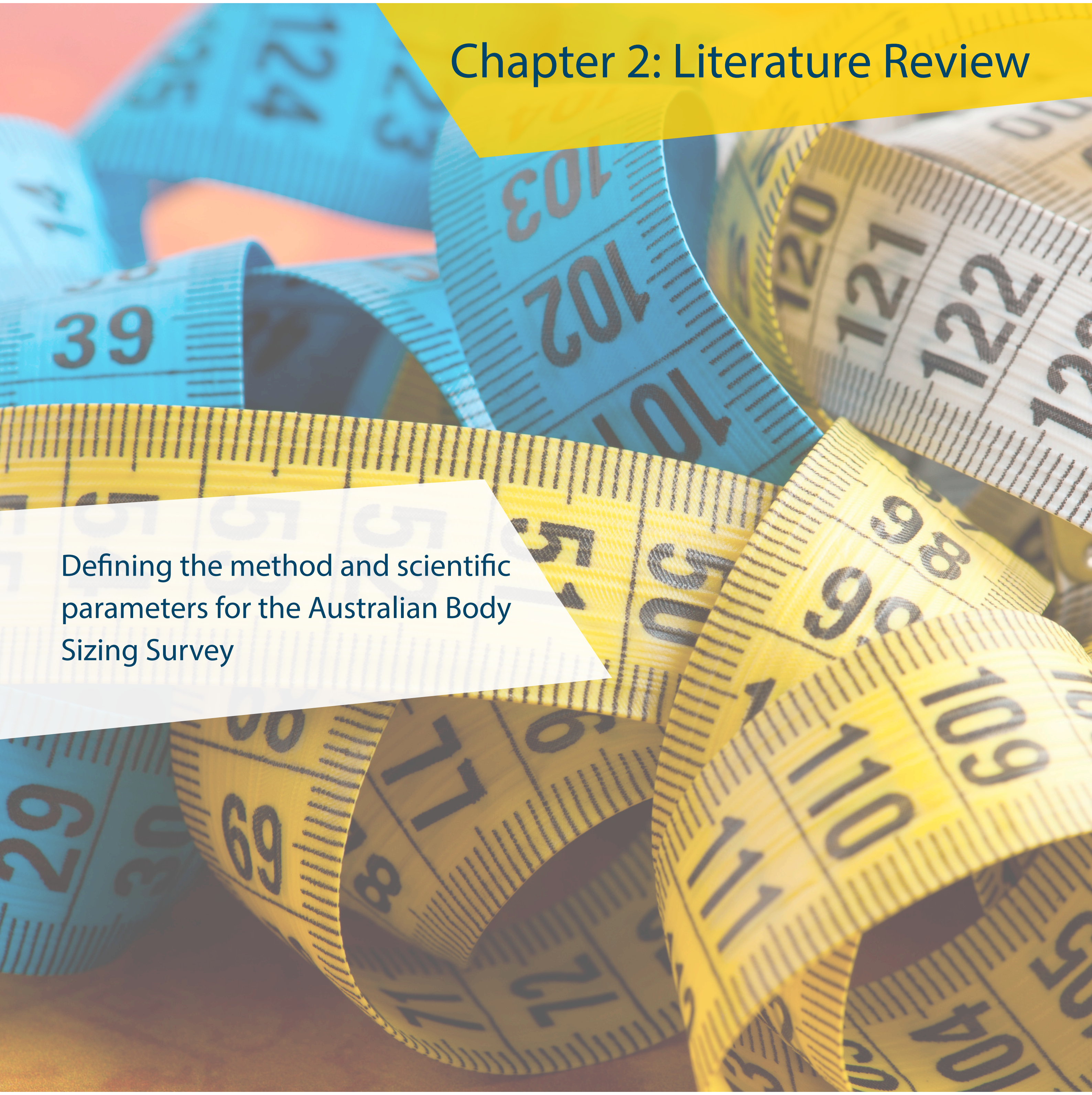
SIZING UP AUSTRALIA
- THE NEXT STEP



Chapter 2: Literature Review

Defining the method and scientific parameters for the Australian Body Sizing Survey

December 2013

This report was commissioned by Safe Work Australia.

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Suggested citation

Veitch, Fitzgerald et al. (2013). Sizing Up Australia – The Next Step. Canberra: Safe Work Australia

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ISBN 978-1-74361-297-2 [PDF]
ISBN 978-1-74361-298-9 [DOCX]

Executive Summary

Safe Work Australia is a national policy setting body whose key role is to improve work health and safety and workers' compensation arrangements across Australia. Key action areas under the Australian Work Health and Safety Strategy 2012 – 2022 are to promote the role of safe design in eliminating and minimising risks to work health and safety, and research and evaluation.

In January 2009 Safe Work Australia published an independent report entitled *Sizing Up Australia: How contemporary is the anthropometric data Australian designers use?* (*Sizing Up Australia*) (Veitch, Caple et al. 2009). *Sizing Up Australia* identified a need to conduct an Australian Body Sizing Survey to make available anthropometric data that could be used to design safer workplace equipment and workplaces. It proposed making this a public infrastructure project to maximise the use of the data, as even given base data, design and testing are still expensive for designers and manufacturers. A summary and update of this has been published (Veitch, Blewett et al. 2012).

This research project builds upon the previous work commissioned by the ASCC, now Safe Work Australia (SWA), in the 2009 report, *Sizing Up Australia – How Contemporary is the Anthropometric Data Australian Designers Use?*[1]. The report stated,

> Increasing emphasis on the designer's OHS responsibilities is engendering concern because this group does not have the necessary information available to it to make informed design decisions…an up-to-date, relevant, Australian anthropometric database….needs to be available…[this] will enable …safer, better designed workplaces for all Australians.

Sizing Up Australia took a design engineering perspective, clearly demonstrated the gap and the need for high quality Australian anthropometric data. This gap can only be filled by a well-constructed and well-executed anthropometric measurement survey of a representative sample of Australian people. *Sizing up Australia* did not define the method and scientific parameters for such a survey, but this step is crucial to producing a high quality sizing survey that meets the needs of stakeholders. This research project aims to define the best way to fill the gap by establishing the method and defining the scientific parameters for the conduct of an Australian Body Sizing Survey to ensure that it achieves a high quality, useful dataset that is developed as a national resource that would be accessible by all. This project is the next step in the process as illustrated in Figure 1:

Sizing up Australia	**This project**	**Next project**	**Final step**
Demonstrated the need for an anthropometric survey	Determine the method and minimum scientific parameters for the Australian Body Sizing Survey.	Identify stakeholders, test parameters against their needs and address their concerns. Finalise method and scientific parameters.	Conduct the Australian Body Sizing Survey by collecting raw data according to the agreed method and scientific parameters.

Figure 1: Where this project fits in the planning for an Australian Body Sizing Survey

In this project, we need to ask basic questions, such as: What should an anthropometric survey deliver? What components make it useful? Aspects of the project need "measure of goodness" tests – will it work? Will it be fit for purpose? Given that once established, the Australian Body Sizing Survey will need to be maintained over successive generations, this initial planning phase has critical implications well into the future.

[1] D. Veitch, D. Caple and V. Blewett, 2009, *Sizing Up Australia: How contemporary is the anthropometric data Australian designers use?* Research Report http://www.safeworkaustralia.gov.au/ .

A review of international literature has been undertaken to enable us to:

1. Establish the characteristics of a "good" measurement
    a. Give examples of technologies that can produce this quality
    b. Permit any technology that can produce this quality
2. Describe a process for sampling that is based upon error estimates from past studies
    a. Estimate sample size and locations
    b. Propose a random, unbiased, or other subject recruitment method for which bias can be estimated
3. Estimate the amount of time we believe we can take per subject
4. Estimate the number and type of measurements/demographic/fit variables within this time frame
5. Estimate the data collection team(s) size
6. Agree upon a process for selecting (down-selecting) measurements/poses/landmarks once stakeholders are on-board

The report is in three Chapters. Chapter 1 summarises the whole report including how budget and resources would be estimated. Chapter 2 is the international literature review and includes a discussion of the afore-mentioned six points related to the literature. Lastly Chapter 3 defines the scope of the sizing survey with an expansion of the key features, recommends stakeholder input and how this shapes the range and type of measurements to be obtained and describes the engineering systems model used to develop the testing required to finalise a method and costing. The chapter develops possible sizing survey methods and recommends sampling method, recruitment strategy and data management.

The key findings of the report are:

1. A good database with 1-D and 3-D representing the relevant user population used in the right way enables two important things. First, it enables safer design for new products and environments, eliminating and minimising risks to health and safety from design related faults. Second, knowledge-based evaluation enables the identification of the risks posed by existing designs of environments, furniture and equipment to certain groups because of aspects of their body size so these can be identified as priorities for improvement or avoidance.
2. The literature contains many examples of good designs that have increased workplace safety. For good design it is necessary (but not sufficient) to have access to raw data, a method to search it, preferably online, knowledge how to use it effectively and product specific analysis. That is, while good, available data and the skill to use it can equip the designer to design with safety as a primary objective, other priorities (eg cost and profit) may get in the way. But without the data, designers cannot design for the user population, even with the best will in the world.
3. From Safe Work Australia reports on the costs of work related injuries (NOHSC 2004, Driscoll, Harrison et al. 2005, Safe Work Australia 2012) it is clear that there is a large economic and social cost experienced by the nation for work injuries that are the outcome of poor design. The Australian Body Sizing Survey could assist in reducing this economic and social burden for a relatively minimal cost.
4. A survey conducted in the right way will enable better design and safer and healthier work places and practices.
5. Australian Body sizing data that is delivered from the survey should be readily accessible to the public and not be locked away or shielded from general use. Accordingly, the Australian Body Sizing Survey should be conducted as a public infrastructure project.
6. Many other countries including Korea, USA and The Netherlands have sizing surveys of their populations that enable not only safer and more effective design but assessment of workspaces for health and safety. Australia with its unique population also needs one. In the form of a publically owned national infrastructure resource would mean that designers and manufactures of products could freely access the

survey to create safe designs for the Australian market. This knowledge base provides an edge for Australia to be a leader in our region.

7. Stakeholder engagement is essential to develop and test parameters against their needs and address any concerns. The scientific parameters, method and budget cannot be finalized without this.
8. A systems engineering design process needs to be applied to the development of the final survey method, which includes iterative pilot testing of all the processes. This will take time and resource.
9. 3-D and 1-D have different uses, strengths and weaknesses. Both are essential for maximum usefulness of the survey.
10. Which 1-D measurements can be reliably and accurately collected from 3-D scans requires testing and validation. 1-D measurements that prove to be unreliable and inaccurate when extracted from 3-D need to be collected in the traditional way. The traditional way is reliable and accurate.
11. Fit and accommodation information are essential to characterize the relationship between models and the environment.
12. Recent developments in 3-D scanning technology, where the time for image acquisition is very fast, offer the possibility of rapidly acquiring high quality additional scans in sequence to characterize movement including reach/accommodation information in a very cost efficient way. This would increase the usefulness of the database to workplace applications, and
13. An International Technical Committee, consisting of technical experts, would be established to provide technical input and act as an arbiter when technical decisions are being made. The project would need to assemble a multidisciplinary team at the outset and adopt this approach for the planning and co-ordination of resources and logistics. The committee will assess technical risk and establish quality management systems for the methods to run the Australian Body Sizing Survey project to ensure effective and efficient outcomes.

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Abbreviations

AGARD	Advisory Group for Aerospace Research and Development
AMI	Anthropometric Measurement Interface
ARIS	Anthropometric Resource Information System
ASTM	American Society of Testing and Materials
CAD	Computer Aided Design
CAESAR	Civilian American and European Surface Anthropometry Resource
CAM	Computed Aided Manufacture
CODATA	International Council for Science: Committee on Data for Science and Technology
CT Scan	Computed Tomography Scan
CV	Coefficient of variation
DHM	Digital Human Model
ICC	Intra-class Correlation Coefficient
IEA	International Ergonomics Association
ISO	International Standards Organisation
KATS	Korean Agency for Technology and Standard
MDS	Multi-Dimensional Scaling
NATO	North Atlantic Treaty Organization
NMI Institute	National Metrology Institute also known as National Measurement
PCA	Principal Component Analysis
PDS	Pattern Design System
PPE	Personal Protective Equipment
PPC	Personal Protective Clothing
SAE	Society of Automotive Engineers
SD	Standard Deviation
SWA	Safe Work Australia
TEM	Technical Error of Measurement
USAF	United States Air Force
WDN	WEAR Data Network
WEAR	World Engineering Anthropometry Resource
XML	Extensible Mark-up Language

Introduction

About this report

This is Chapter 2 of a 3 Chapter report. Chapter 2 is an international literature review.

Chapter 1 summarises the project and provide recommendations for action.

Chapter 3 defines the scope of the Australian Body Sizing Survey. It addresses the key features of stakeholder engagement and how this will determine the range and type of measurements to be obtained. It also describes the systems engineering model that will be used to develop the testing required to finalise the survey method, business plan and costing. It also discusses possible sizing survey methods including sampling method, recruitment strategy and data management.

Acknowledgements

Our thanks go to Dr John Field for statistical advice, Mr Eric Ennis, Dr Jeff Hudson and Dr Greg Zehner for provision of some images and literature, and Mr David Summerhayes for the preparation of the graphics for publication. We greatly appreciated the general support that Griselda Raisa Susanto provided to the project.

1. Background

1.1 Scope

The focus of this literature review is to build on *Sizing Up Australia* by looking at the methods used to conduct engineering anthropometric surveys to then determine a method for an Australian Body Sizing Survey that is contemporary, relevant to Australia's needs and could be used to drive workplace design and improve work health, safety and wellbeing.

Firstly, this report provides the necessary background to explain why we make the survey design decisions that we do. Secondly, it explains why this survey needs to use the experience of past surveys and relevant ISO standards to develop an up-to-date survey method that maximises the developments in technologies used for surveys and the new directions in human modelling that are supported by high quality body size survey data.

1.2 Method

The members of the project team for this report are Ms Daisy Veitch, Mr Chris Fitzgerald, Mr Steve Ward, Associate Professor Verna Blewett, Professor Kathleen Robinette and Dr Chang Shu. The collection of relevant literature began with literature already known to the project team – this included publications authored and co-authored by team members as well as the extensive international collections of books, articles, technical reports, standards and conference proceedings compiled by team members and cited in their own research outputs. In particular, Dr Kathleen Robinette, Ms Daisy Veitch and Dr Chang Shu have provided reference material compiled in the course of their own work over many years of research and publication in anthropometry for design, and digital human modelling. Thus, our personal holdings provided the grey literature necessary to this project.

This literature was augmented by a database search through the University of New South Wales' library for the most up to date peer-reviewed publications relevant to the project. The search was conducted across multiple indexing databases including Science Direct and Scopus. The large number of results returned from the search was filtered for publications later than 2005 and then a selection based on titles and abstracts was made to find those relevant to this project. Publications that were clearly outside the scope of this project were removed from the list and full-text copies of the remaining selection were obtained. Databases of Australian and international standards were searched for relevant documents and to ensure that we had the current versions in our collection.

Publications finally selected for inclusion in this literature review were those that most closely aligned with the aims of the project. Priority was given to work that was recent, recognised as scholarly or authoritative (usually peer-reviewed), and relevant to design and safety.

The collected literature can be divided into seven categories:

1. Introduction
2. Anthropometry
3. Referential Standards for sizing surveys
4. Anthropometric surveys
5. How anthropometric data are used in industry?
6. Technical detail in methods – body sizing surveys
7. Lessons learned from past surveys
8. Conclusions and implications for an Australian Body Sizing Survey
9. About the research team
10. References

These 10 categories provide the overall outline of the literature review.

Papers on anthropometry focussed on specifically assisting public health, sports science, or anthropological fields were regarded as outside the scope of this review.

1.3 Background

1.3.1 AGARD - Advisory Group for Aerospace Research and Development

The NATO Working Group 20 was formed in 1993 comprising of a multi-disciplinary team to investigate the then emerging technologies in the field of 3-D surface anthropometry. In 1997 the Advisory Group for Aerospace Research and Development (AGARD) prepared an advisory report reviewing 3-D surface anthropometry technologies (Robinette, Vannier et al. 1997). This report established a referential basis to use emerging 3-D scanning technologies, in combination with traditional forms of measurement of 1-D data to establish the first large scale, international civilian sizing survey, the Civilian American and European Anthropometry Resource (CAESAR) project.

1.3.2 WEAR - World Engineering Anthropometry Resource - Group

The World Engineering Anthropometry Resource (WEAR) is a group of interested experts involved in the application of anthropometry data for design purposes. The members and partners are from around the globe. WEAR is a non-profit organisation registered in Europe (WEAR Members 2013).

The goals of WEAR are to provide high quality data, including Anthropometry, Tools and Applications (see Figure 2) for end users in a self-sustaining way and to provide an educational forum with which to expand the user base of anthropometric data for design purposes.

WEAR was proposed in 2000 at an International Ergonomics Association (IEA) meeting. The strategic plan was drafted at the first working meeting in Paris, France in 2002. The first workshop was at the IEA in Seoul Korea in 2003. Since then there have been working meetings and symposiums in USA, South Africa, Brazil, China, Australia, Canada, The Netherlands, Japan, New Zealand and Spain. WEAR gained support from the International Council for Science: Committee on Data for Science and Technology (CODATA) in Berlin, Germany in 2004. The first WEAR short course was held in Paris in 2008. The website launch of the beta version of the online WEAR resource was at the IEA Congress in Beijing in 2009.

To create a searchable resource like WEAR has been a mammoth undertaking. A standardization procedure was required to make more than 120 different anthropometric databases searchable and comparable. These databases often had different measurement collection methodologies that have not always been described in great detail – sometime in languages other than English. To achieve this the Anthropometric Measurement Interface (AMI) was created (Ennis and Robinette 2011). A detailed description of AMI is in section 2.3 of this report.

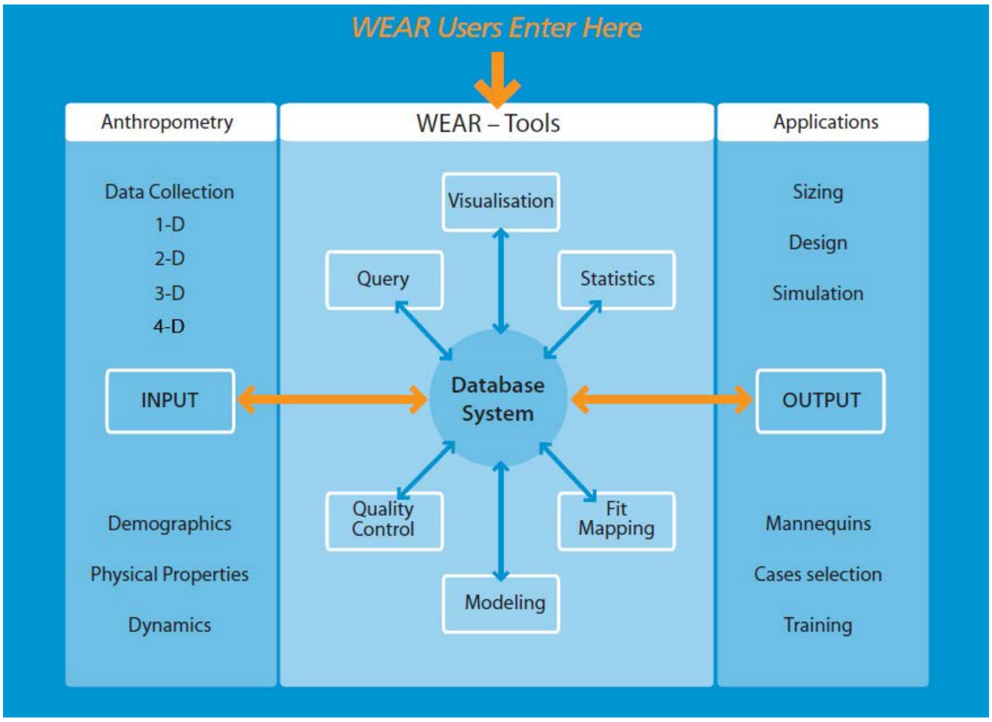


Figure 2: WEAR diagram to represent where Data Types fits into the scheme of things - how Anthropometry interacts with Tools to create Applications

1.3.3 CODATA

The International Council for Science: Committee on Data for Science and Technology CODATA is an organisation devoted to encouraging "the compilation, evaluation and dissemination of reliable numerical data of importance to science and technology" (CODATA 2013). It supports increased awareness, direct cooperation and new knowledge relating to "data activities". CODATA's website describes their objectives as:

- The improvement of the quality and accessibility of data, as well as the methods by which data are acquired, managed, analysed and evaluated, with a particular emphasis on developing countries
- The facilitation of international cooperation among those collecting, organizing and using data
- The promotion of an increased awareness in the scientific and technical community of the importance of these activities
- The consideration of data access and intellectual property issues

In short, the reason for CODATA is to help foster and advance science and technology through developing and sharing knowledge about data and the activities that work with data.

This is particularly important for WEAR because,

> …in this time of increasing importance of data because of computer-based modelling and the Internet. Today more and more data sources of unknown quality and origin are becoming easily available, via the World Wide Web. CODATA provides a home for international data experts needing to address data quality and data access issues to turn the Information Revolution into a positive force for the future. Today's data become the products and processes of tomorrow. CODATA is prepared to help science and technology achieve a better tomorrow through better data today.

2. Anthropometry

2.1 What is anthropometry?

Anthropometry may be most simply and comprehensively defined as the conventional art or system of measuring the human body (Hrdlička 1952). It has been recognised for more than 60 years that there are different uses for anthropometric data. Some of them include:

1. Biological anthropology (often used for researching human evolution),
2. Sports science (often used for assessing athletes or potential athletes),
3. Medicine and public health (often used for assessing the health of individuals and/or populations)
4. Forensic anthropology (for identifying age, cause of death, disease presence etc.) and
5. Engineering or design anthropometry (used for design and assessment of worn products and built environments)

The end use or purpose determines the suitability of each data set. Thus not all anthropometric data are suitable for engineering and design purposes. This is outlined in detail in *Sizing Up Australia* (Veitch, Caple et al. 2009) and summarised in (Veitch, Blewett et al. 2012).

There is an emerging field called Medisign – which is the design of product for use in medicine (Medisign 2013). Sometimes those products are not on the surface of the body. For example a CT scan was used to design a small device that was fitted into a baby's trachea so he could breathe without assistance and saving his life. Another example is the design of a life-like breast model to help train medical students to detect breast cancer (Veitch, Dawson et al. 2011). Although CT, Magnetic Resonance Imaging (MRI) and 3-D sonograms are not suitable for a large scale survey, a small scale study that quantifies the relationship between surface scans and sub-surface anatomy could be very valuable. The large-scale anthropometric survey captures population breadth or cross-sections while smaller studies tie into this with details in targeted areas.

An anthropometric database is defined as a "collection of individual body measurements (anthropometric data) and background information (demographic data) recorded on a group of people (the sample)" (International Standards Organisation (ISO) 2010).

2.2 Anthropometric measurement types

2.2.1 Overview

There are many ways to measure the human body and new tools are continuing to be developed, but there are four main measurement types for engineering anthropometry: one-dimensional (1-D), two dimensional (2-D), three-dimensional (3-D) and 3-D motion, sometimes called 4-D with the fourth dimension being time.

A 1-D measurement provides one number only, e.g. waist circumference is 750 mm. This provides a size value for the measurement, but no specific location information in either 2-D or 3-D space. Once the subject is gone it is impossible to know where in 3-D space the waist measurement was, neither how high it was, nor how far fore or aft of the spine nor how angled or level etc. 1-D provides only the size for that one measurement. Trying to reconstruct a 3-D person from 1-D data is mostly guesswork and is very unreliable.

A 2-D measurement provides two numbers and typically provides 2-D location in a plane. This might be a point location extracted from a scaled photograph, extracted from a photographed silhouette of a person with a background grid or it might be a two dimensional point location measured using a head box, a foot box, or a hand box (specialist measuring equipment). Typically in the past these measurements only captured key landmarks, such as the x,y coordinates to the Menton (a point on the chin) in the head box. Because 2-D measurements contain some location information it is possible to get somewhat comparable measurements on a subject under different conditions and to begin to capture some fit or product interface information. For example, the Menton location might be measured both with and without a helmet to give an indication of the chin strap length needed. If the measurements are taken from a photographic silhouette it is also possible to capture contour type shapes by collecting 2-D measurements, or points, all along a silhouette contour. The limitation is that the location of the 2-D plane with respect to the 3-D person is missing. This leads to error when trying to reconstruct a 3-D person from 2-D measurements.

A 3-D measurement provides three numbers and provides location information in 3-D as well as size.

3-D data points have been collected using a point and click device like a Faro Arm, using stereo photograph pairs (Chandler, Clauser et al. 1975, McConville, Churchill et al. 1980, Young, Chandler et al. 1983) as well as
3-D laser scanners, Computer Tomography (CT) scanners, Magnetic Resonance Imaging (MRI) scanners, and more. Typically a 3-D data set contains many 3-D data points all in the same reference axis system. Some of the points are pre-marked or otherwise detectable and named reference landmarks. Others are just surface points often called a "point cloud" that forms an electronic copy of the surface of an object or person. Each data point in the file has 3 co-ordinates, x, y and z that exactly pinpoints its location in relation to every other point. Because the 3-D locations are known, 3-D data has high capability for measuring the relationship between the individual human body and the apparel he or she is wearing or the built environment within which he or she is living or working. Essentially 3-D enables us to measure the geometry of fit and accommodation for the first time.

4-D measurements consist of 3-D points that are tracked sequentially over time, capturing the body in motion. This is sometimes called dynamic or biodynamic data. Dynamic data are important because it is not only static poses in a workstation that matter - it can be the work process or the activity that requires critical examination. The two most commonly used 4-D data collection systems currently are produced by Vicon and Motion Analysis Corporation. Typically a relatively small number of points are tracked (30 to 60 3-D points per subject), but they define an underlying skeleton for understanding and comparing the motion of different individuals. When combined with 3-D surface scanning, 4-D motions provide a powerful modelling capability for workplace ergonomics (Fullenkamp 2007).

Sizing up Australia found that although 1-D data was the most commonly used, it is perceived as the least useful, while 3-D data were perceived as the most useful.

There are advantages and disadvantages to each type of data and *Sizing up Australia* contains a discussion about their strengths and weaknesses. We include a brief summary here with some definitions.

2.2.2 1-D measurements

The strength of traditional 1-D measurement is that they have been used for hundreds of years, are well- established, abundant, easily collectable, readily available (Robinette, Vannier et al. 1997) and easy to use. Because 1-D measurements provide relative size information they are good for comparing samples of populations in a general way. They are also useful for identifying the relative location of a subject in a population for a few key dimensions and therefore helpful for selecting subjects, cases or fit models. They are also easy for common people to collect on themselves so they can be useful for selection of the size of best fit or to communicate relative size information.

However, there are also significant weaknesses. First, while the strength of 1-D is the ability to understand relative size, it is also the weakness, because the relative size only applies to the dimension that has been measured. The use of 1-D data for design purposes in aggregate form, such as averages or percentiles, can potentially be dangerous (Robinette and Hudson 2006). In 1952 Gilbert Daniels demonstrated that there is no average man (Daniels 1952), that is, there is no one who is average for every dimension. Robinette and Hudson (2006) explained that products designed for the aggregate average of all the 1-D dimensions will often be too small for everyone.

Robinette and McConville (1982) further demonstrated that percentile are worse because they do not add up—that is, the sum of the 5th percentile measurement values does not equal the 5th percentile of the sum. When the assumption is made that taking the 5th to 95th percentile accommodates the remaining 90% of the population, this is only true for one measurement. As soon as a second measurement is added, an additional 10% can be excluded. Each new measurement accommodates fewer and fewer people. This reduction in the accommodation range when adding a second 1-D measurement is illustrated in Figure 3 using stature and weight data and statistics. In this case, the 25th to 75th percentiles for stature are shown in the vertical axis and for weight (body mass) in the horizontal axis. The women who fall within the 25th and 75th percentile for stature (seen in the horizontal band) include many women who fall outside the 25th and 75th percentiles for weight. The women who fall within the 25th and 75th percentiles for weight (seen in the vertical band) contain many women who fall outside these percentiles for stature. As a result when using both measurements, instead of 50% of the population being included an unintended additional 25% of the population is eliminated, leaving only 25% of the population remaining in the sample. Any further addition of measurements in the design continues to eliminate more people until eventually no one is left.

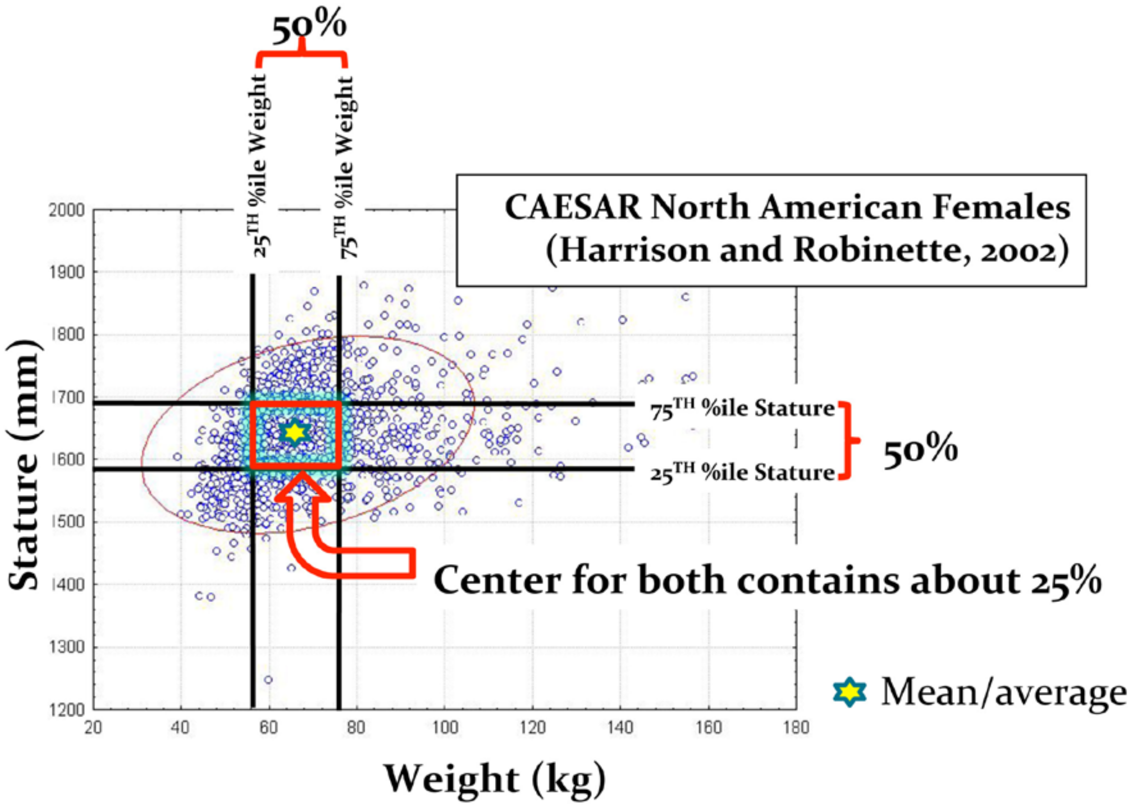


Figure 3: Reduction in accommodation percentage when adding a second measurement.

2.2.3 2-D measurements

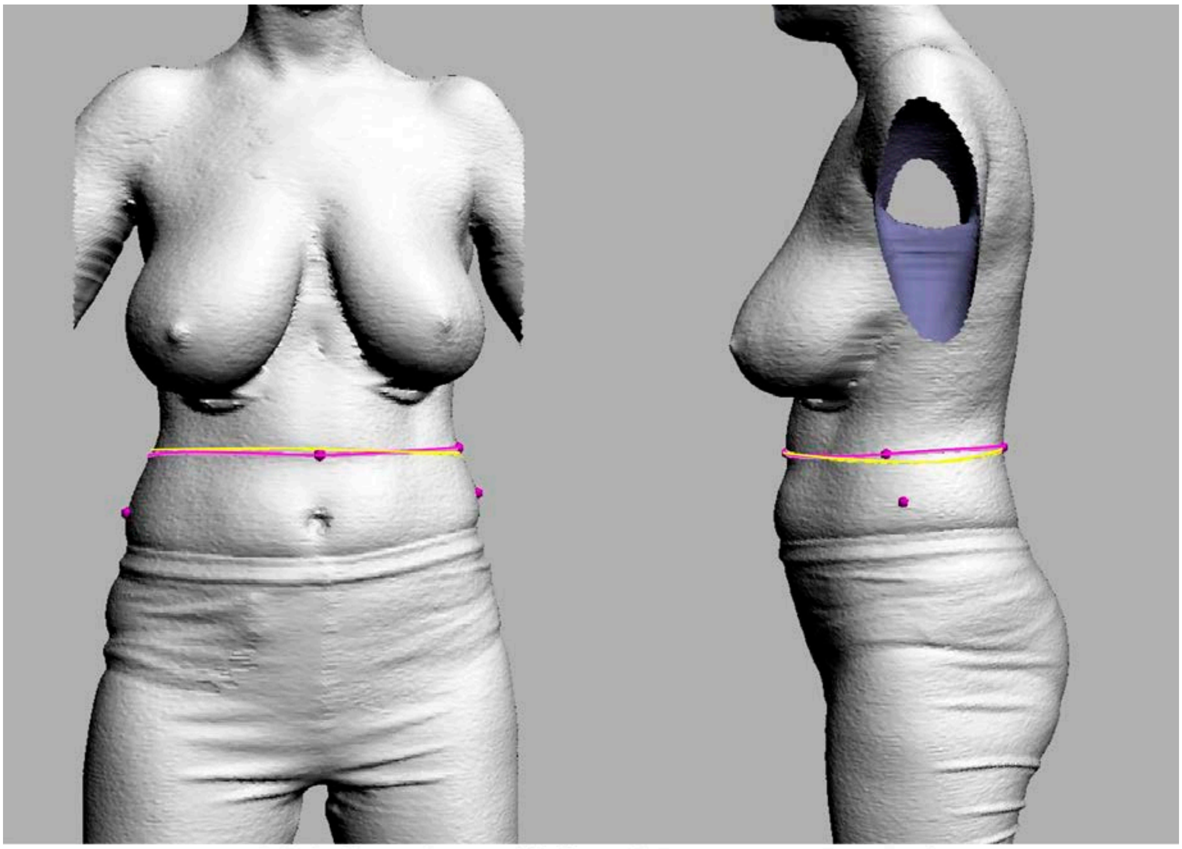
2-D measurement might be considered the worst of both 1-D and 3-D. They are not as good at providing relative size information as 1-D because the missing third dimension in the calculation of distances results in additional random error. They are not as good as 3-D in providing location information because the missing third dimension results in additional random error. Furthermore 2-D requires specialized equipment, boxes, and or grids that add expense in the collection of data. 2-D templates and silhouettes can accurately be produced from 3-D data but 3-D shapes cannot be accurately be produced from 2-D. However, there are some new 2-D tools being generated for capturing 2-D distances using digital photographs that might have potential for getting measurements at home for on-line shopping. Perhaps there will be some practical use for 2-D data in the future.

2.2.4 3-D measurements

The outstanding strength of 3-D measurement is the ability to capture a complete 3-D copy of the subject. This copy can be used to describe the contour shape, the proportional shape, extract 1-D measurements for relative size, extract 3-D skeletal landmarks for biodynamic modelling, and more. Two copies of the same person can readily be compared for examining changes over time due to pregnancy, ageing, growth, or the impact of a load on the posture, or the location of apparel when functioning properly, etc. Copies of two or more different people can be compared to visualize how to accommodate them all effectively. These things can all be done long after the data capture for the study or survey is over. In short, 3-D enables the measurement of many characteristics that are not captured in either 1-D or 2-D measurement. In addition, accurate 1-D or 2-D data can be extracted if you have a 3-D file, but an accurate 3-D form cannot be made from 1-D or 2-D.

One weakness of 3-D is that no matter how accurate they are not the same as 1-D data captured with different tools, such as calipers, anthropometers or tape measures. This means that they are not very good for comparing the sample to historic databases for examining population trends or differences. For that purpose the traditional tools are needed.

There is a common misconception, usually seen in the apparel industry, where the current trend is to rely on
1-D measures which have been automatically extracted (without human intervention or viewing) from a 3-D scan. Highly accurate 1-D measurements are possible to extract as Robinette and Daanen demonstrated (Robinette and Daanen 2006), but not without pre-marking the body and manual intervention and screening. The presumption by many is that automatically extracted data are at least equivalent to traditional-style 1-D circumference measurements taken with a tape measure; for example bust, waist and hip. Unfortunately, 1-D data extracted from a 3-D scan, even highly accurate data, are not the same measurement and are therefore not comparable to the traditional measurement taken on a live person. A study of 90 women showed that scan-derived automated waist circumference measurements were not the same as traditional-style measurements for a particular subset of the population. In addition the definition of the waist chosen affected the measurement location (and thus the final measurement) in a subset of the adult female population (see Figures 5 and 6). For a definition to include everyone, including difficult to measure individuals, a traditional-style waist measurement was taken and the CAESAR preferred waist was able to measure all individuals in the sample (Veitch 2012).



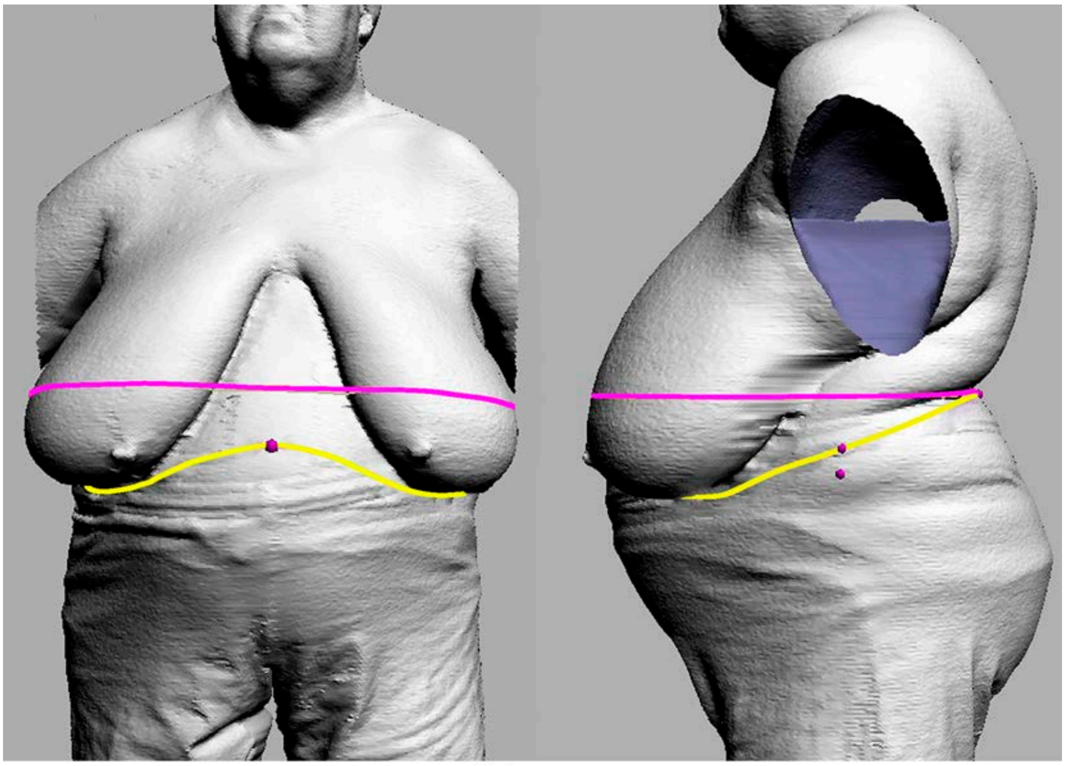
Pink line shows ISO waist - scan extracted
Yellow line shows CAESAR Preferred waist - scan extracted

Figure 4 shows a "normal" women with two different definitions of waist circumference – note that the pink and yellow lines are in the same location.

The Figures 4, 5 and 6 illustrate three different adult female human anatomical variations. The yellow and pink lines show the locations of two different waist definitions: ISO 8559, 2.1.11, and CAESAR, Waist Circumference preferred. The different waist definitions are as follows.

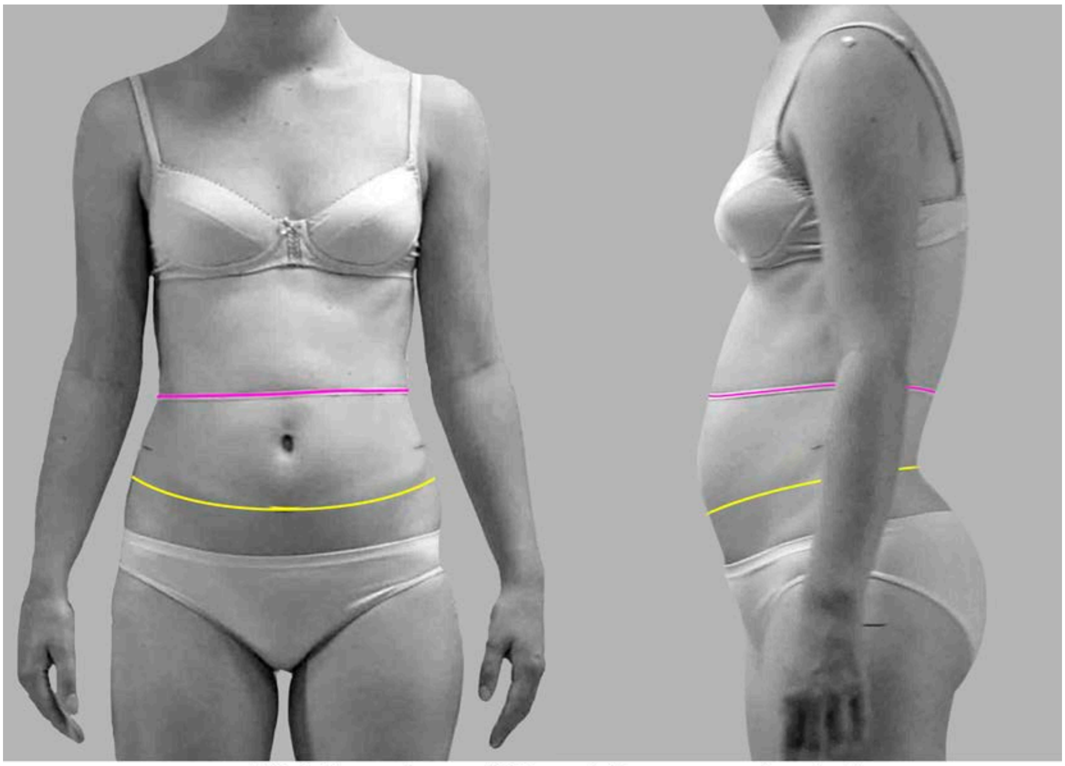
1) —**ISO 8559:1989 Garment construction and anthropometric surveys — Body dimensions** …2.1.11, waist girth: The girth of the natural waistline between the top of the hip bones (iliac crests) and the lower ribs, measured with the subject breathing normally and standing upright with the abdomen relaxed (see figure 7).

2) —**37. CAESAR Name:** WAIST CIRCUMFERENCE PREFERRED,
ISO Reference No. N/A,
Description: Maximum circumference of the waist at the subject's 'preferred' waist level. **Method:** subject stands fully erect with the weight distributed equally on both feet and the arms hanging freely downwards. The subject's feet are placed in foot-prints adhered to the standing surface (the foot prints are positioned approximately 10cm apart at the heels and rotated 33 degrees at the toes). The subject's preferred waist level is marked by using an elastic band.
NOTE: Preferred waist level is established by the subject, who places an elastic band at the level he or she would prefer to wear the waist of their pants. **Instrument:** Steel tape measure



Pink line shows ISO waist - scan extracted
Yellow line shows CAESAR Preferred waist - scan extracted

Figure 5 shows a subject with two different definitions of waist circumference – note the pink and yellow lines are in different locations.



Pink line shows ISO waist - scan extracted
Yellow line shows CAESAR Preferred waist - scan extracted

Figure 6 shows another example of a subject with two different definitions of waist circumference – note the pink and yellow lines are in different locations.

The picture referred to in the ISO shows a horizontal waist. Figure 4 is “normal” - this is the body shape the developers of ISO had in mind when they were thinking about the definition. She has a horizontal waist and her ISO and CAESAR preferred waist are the same.

Figure 5 illustrates an anatomical variation where the bust occludes the waist, called breast ptosis. The waist is clearly not horizontal. In addition, it is impossible for the scanner to capture the waist measurement as it is in part covered by the bust. Substantial discrepancies between the results from these two scan-extracted location-definitions were found – here more than 300mm (more than 6 clothing sizes). However the CEASAR waist (yellow line) scan-extracted is much closer to the real waist although still different. The only way of capturing this waist circumference is by traditional-style tape measure passed under the breasts. She would never wear a waisted garment in the location of the ISO pink line – over her bust!

Figure 6 illustrates another anatomical variation where the waist is *below* the iliac crest (in contrast to the ISO definition which states it must be above) caused by her low lumbar lordosis location. If the ISO waist definition shown by the pink line were to be followed here it would result in location errors not only for the size of the waist, but also when the waist is used as a landmark for another 6 ISO defined measurements, such as crotch length, body rise, back waist length etc. Again she couldn’t wear a waisted garment in the ISO defined location. Lower garments would slide to her lumbar lordosis causing a fit problem. The validity of the pink ISO line for clothing construction must be called into question.

In all 90 cases the CAESAR preferred waist, taken with a tape measure, was robust enough, but the scanner extracted, especially the automated scanner extracted ISO waist measurement was not. (Veitch 2012). 3-D only captures the surface it sees and not the hidden areas. To get at those 1-D measurements are still needed. However without the scan we would never have been able to visualise the problem, so the 3-D was also essential here. This shows the strength of 3-D, because the shape differences and measurement location errors are readily observable. A significant number of measurements need a human operator to intervene if the full range of human variation is to be captured accurately.

Any measurement technology used for an Australian Body Sizing Survey needs to be robust enough to be able to cope with the range of human variation likely to be present in the working civilian population.

Another weakness is that 3-D data are complex, relatively new and require a specialised skill base, software proficiency and statistical knowledge, to use. Although 3-D data are readily captured its analysis is complex (Shu, Wuhrer et al. 2012). In addition, the 3-D search tools are still under development making it time consuming to compare scans.

2.2.5 4-D measurements

The strength of dynamic or 4-D measurement is that it captures people doing the activities of interest and enables an understanding of the effect of age, load, apparel, etc. on the ability to live and work safely and effectively. The weakness is that only a relatively few points (approx. 150) can be tracked and the motion is tracked using markers that move when the skin moves causing some confounding error. There is now one 3-D scanner on the market that has very rapid image acquisition time (3dMD) and it shows promise for combining full surface scans with motion capture in the near future.

2.2.6 Summary

When weighing strengths and weaknesses it might be helpful to think of an analogy. Which is better – a hammer or a screwdriver or maybe a drill? If the goal is to put a nail in the wall clearly the hammer is best. If the goal were to put in a screw, the screwdriver would be best or even an electric drill. The tool needs to be fit for the task in hand. That is why it is crucial to plan carefully and ensure the data type is the best one for the purpose. Thus it is crucial that end users of data are clearly identified through stakeholder engagement.

All types of anthropometric data have advantages and disadvantages. An Australian survey should review the latest developments to weigh up strengths and weaknesses in data types and technology to deliver the most useful combinations for the stakeholders involved in project within the practical limitations of the survey design. This approach will deliver an effective survey that represents value for money.

Through the exploration of the disadvantages of 1-D data the missing link - the relationship between anthropometric data and design - is revealed. This essential link is the "fit" of products. 3-D data provide powerful information, but they are complex to analyse. 1-D is easy to use but insufficient, especially for complex design. For the best of both data types an Australian survey should collect both, however because data are specific to the end use we will not know what specific measurements to include until we have engaged the stakeholder group. If a stakeholder has needs for 4-D, or dynamic data, the survey design needs to be flexible enough to allow the future project to satisfy stakeholders' needs, which may also include Digital Human Modeling (DHM). The ability to compare with other datasets will mean some ISO measurements should be included. Past experience, in combination with current needs and the outcomes of testing, will influence the final detail of an Australian survey in terms of the specific data to be collected.

2.3 What is a well-defined 1-D measurement? Database structure and making data searchable on-line

The purpose of taking measurements in a survey is to be able to compare people, and understand differences and variability. For this purpose a well-defined measurement is one that is unique and unambiguous enough so that it can be considered the same and comparable from person to person and from one time to the next. Things that must be clearly defined include:

- The type of measurement; such as a circumference or a point-to-point distance, an angle, a volume, etc.
- The location including:
  - point, line and planar surface landmarks (both anatomical and environmental)
  - any trajectories or paths to follow
  - side of the body
- Body posture including:
  - the angles and directions of all relevant body segments
  - the respiration level
  - methods to ensure posture is maintained
- Instrument used; such as anthropometer, tape measure, caliper or scanner, and
- Apparel worn, such; as fitted shorts for measuring, uniforms, protective gear etc.

A number of problems exist with collecting and later accessing anthropometric data:

- Data collection can be expensive,
- Datasets are distributed in databases around the world,
- Data are sometimes referenced in languages other than English,
- Methods used in data collection and data quality can vary greatly,
- Methods are not always described in detail and
- Measurement descriptions are not standardized so the same measurement might have different names in two surveys or different measurements might have the same name.

These issues make direct comparison of data difficult.

It was in part to overcome these and other limitations that the World Engineering Anthropometry group (WEAR) was founded in 2003. The WEAR group has developed a method to make data comparable and searchable on-line. In addition, for the need to measure in a comparable and consistent way, comparability of measurement description is essential for comparing datasets. Cheng and Robinette (2007), founding WEAR members, developed a naming convention to alleviate this problem, and it has been implemented in an on-line tool called the Anthropometric Measurement Interface (AMI) by the WEAR Association to assist people in creating measurement descriptions for new anthropometric surveys. The WEAR Data Network (WDN) is the data repository of members of WEAR. It is where members of the group share and view data with other members worldwide.

As illustrated in Figure 7, through WDN raw data can be retrieved that corresponds to AMI descriptions from more than 130 different databases and the user can use tools such as extensive statistical analysis to provide information to answer queries. (Ennis and Robinette 2011). This important feature, the access to raw data, allows the user the flexibility to build queries to answer a specific design question. This solves the previous constraint that summary statistics had of being unable to tailor the population to the application.

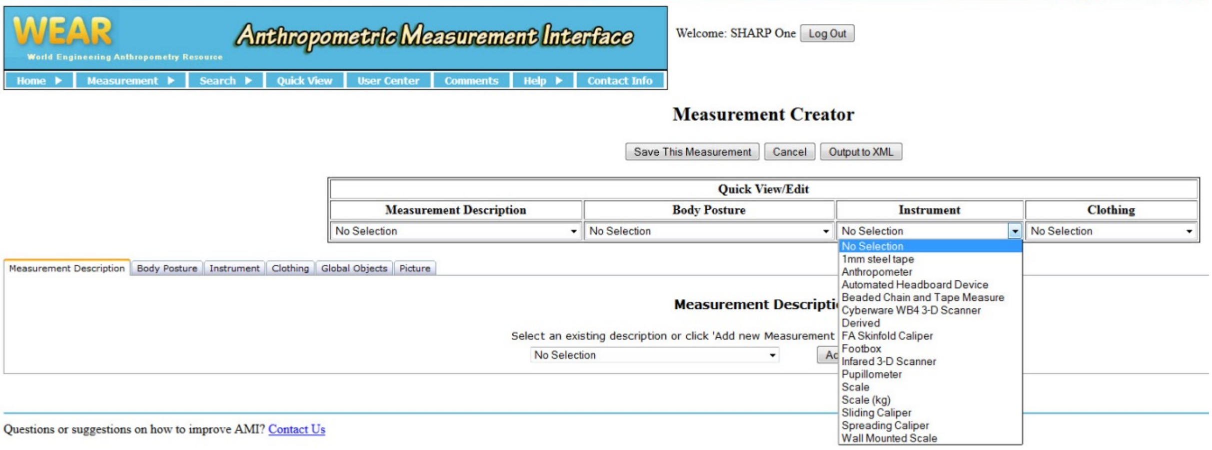


Figure 7: Example of building a unique measurement identifier in AMI – note the detail in the measurement, such as body posture, instrument and clothing worn during measuring to standardise measurements for the purpose of comparison of international data. Each section has a drop-down menu with pre-loaded detail.

AMI is a web-based interface that allows the user to create measurement descriptions and thus facilitates a step-by-step process to standardise data entry. At the end of the process the software creates a unique XML file of the measurement (digital descriptor), a unique measurement descriptor and saves this for future reference (Cheng, Robinette et al. 2007). In addition AMI allows the user to select pre-loaded measurements from ISO- 7250 or CAESAR to help facilitate using existing measurements.

Digital descriptors are used as identifiers and when these are applied to measurements, even those created in other languages, the computer can rapidly identify which measurements are the same.

Robinette and Cheng describe how a standard XML schema can be used as a type of Rosetta stone to translate the anthropometric data into a universal format and then link the databases using a web format so data can be searchable online (Cheng and Robinette 2007) see Figure 8.

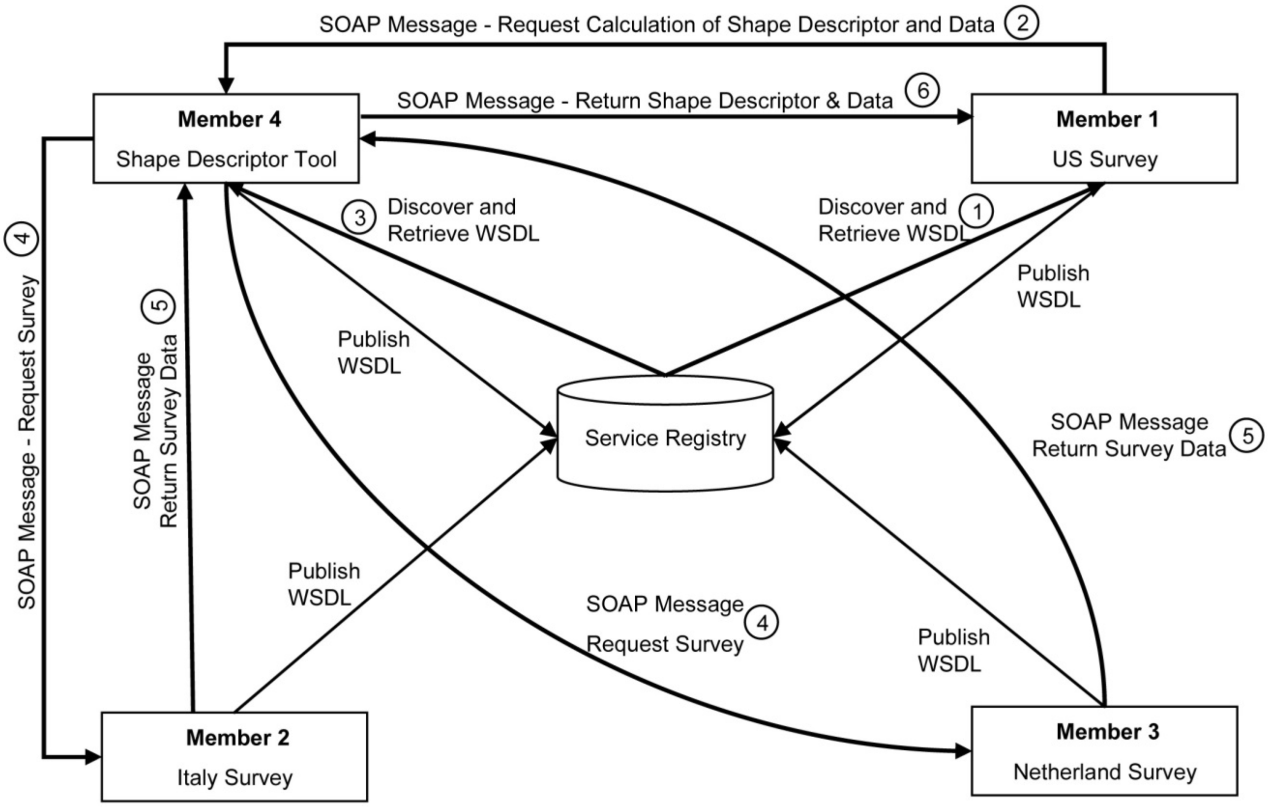


Figure 8: An example of XML web service of WEAR integration

This has some major advantages. Not only are data from different databases universally represented, searchable and comparable, but also collaboration is greatly simplified and assistance in defining new anthropometric studies is facilitated. This also demonstrates that the web service integration of WEAR can serve as the data feeders to the analytical tools required by general public and private industries for solving engineering anthropometric problems (Cheng and Robinette 2007). So to make an Australian Body Sizing Survey useable it needs to be searchable, comparable to other national surveys and compatible with tools so users can get the information they need in an efficient way.

2.4 Brief history of engineering anthropometry, body sizing surveys and human models

Anthropometric data have been used in the design of apparel, in particular for bespoke tailoring, for centuries. Engineering anthropometry has a history dating back nearly a century when human size data were used in the development and improvement of aircraft and automobiles. Table 1 outlines the chronology of significant events and publications in the world of engineering anthropometry.

Historical context - timeline	Topic	Comments
Last few hundred years to present	Abundant 1-D data collected	Used for tailoring and other design purposes
These papers are a sample of publications on the use of 2-D templates: 1926, Hugh Lippman pre WW11, Captain H.G Armstrong 1946, Randall 1961, Alexander, Zeigan et al. 1970's, Ken Kennedy	2-D and 3-D templates or engineering design manikins developed often using percentiles	Used to improve aircraft and car safety History outlined by (McConville and Churchill 1976)
1952, Churchill and Daniels	Published a technical note titled: "The Average Man"	Showed use of percentiles create percentile body forms that are statistically impossible
March 1967 **(Hertzberg 1968)**	Conference on Standardization of Anthropometric Techniques and Terminology was held in the Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, USA	Recognition that there was a separate branch of "engineering anthropometry" that applies anthropometry to designs (used in industry) (Hrdlička 1952) as distinct from other uses including classical anthropometry (used in biological anthropology). Acknowledged need to standardise.
1970, Hertzberg **(Moroney and Smith 1972)**	Published "Average Man is a Fiction: Range of Sizes is Key to Work Places" and "Misconceptions in Design and Use of Anthropomorphic Dummies" Hertzberg 1970	Documented in history outlined by (McConville and Churchill 1976)
1976, Kroemer and Eberhard	Presented "COMBIMAN – Computerized Biomechanical Man Model"	First attempt at a Digital Man Model now called Digital Human Models (DHM)
1952 to Present **(Diffrient, Tilley et al. 1974, Kothiyal 1996)**	Percentiles method explained, a warning given but with no alternative statistical methods presented - recommends testing assumptions in a physical mock-up. No distinction is made between the use of percentiles for single variables - which works - and the use of multiple variables in design - which does not.	Despite the 1952 proof of limitations - the use of percentiles is still a broadly described solution and commonly used method to help solve complex design problems using multiple variables, but they are found wanting.
(Roebuck, Kroemer et al. 1975, McConville and Churchill 1976, McConville, John et al. 1978, Robinette and Hudson 2006)	Alternative scenarios presented for the correct use of statistics for applying anthropometry in design	Roebuck used punch cards and early computers to create multiple correlation coefficients, McConville published regression equations, and Robinette wrote a book chapter summarising the correct use of anthropometry in design
(Mellian, Ervin et al. 1990, Robinette, Vannier et al. 1997)	Ground breaking work in fit-mapping done in Sizing Evaluation of Women's Navy Uniforms	Alteration rate reduced from 75% to less than 1% with the same number of sizes in women's uniforms resulting in improved efficiency and cost savings, estimated at $2.5 million USD

Historical context - timeline	Topic	Comments
(Robinette, Vannier et al. 1997)	A written for NATO titled, “3-D Surface Anthropometry: Review of Technologies” AGARD AR-329	Written in 1997 this report was used as a foundation for the work done in CAESAR. The first Chapter is as relevant today as it was in 1997.
(Blackwell, Robinette et al. 2002, Harrison and Robinette 2002)	Civilian American and European Surface Anthropometry Resource (CAESAR). Final Report 2:	First fully planned, and largest anthropometric survey that used both 1-D and 3-D body scanner. More than $6,000,000 USD were spent in 1999 and the first high quality 3-D scanner was purpose built for the project. There were more than 50 partners from industry.
2003 2009	World Engineering Anthropometry Resource (WEAR), a not for profit organisation was established in 2003. The beta version of the resource was launched to the public in 2009 at the IEA Congress in Beijing	The first networked and searchable data repository accessible online able to compare different anthropometry studies was established. See Fig. 1
2006**(CODATA 2013)**	An Anthropometric Data and Engineering Task Group was established by CODATA, the Committee on Data for Science and Technology. This is an interdisciplinary Scientific Committee of the International Council for Science (ICSU).	CODATA provides funding to assist the WEAR project in acknowledgement of the high quality of the work of WEAR and its data. This is important because data sources of unknown quality and origin are becoming easily available and WEAR only accepts high quality data.
(Mochimaru and Kouchi 2000, Allen, Curless et al. 2003, Ben Azouz, Rioux et al. 2004, Ben Azouz, Shu et al. 2006, Xi, Lee et al. 2007, Hasler, Stoll et al. 2009, Wuhrer, Xi et al. 2013)	Processing 3-D data to build statistical shape models: Use of a generic mesh for registration (shape correspondence); Use of a volumetric method for registration; Principal Component Analysis (PCA) and Multi-Dimensional Scaling (MDS) were used; Tools for interactive visualization of shape variability were developed; Landmark prediction and fully automatic registration were proposed.	Uses a generic mesh to fill holes and to establish correspondences among the data models. Because it uses landmarks for alignment it is much more accurate. This is important because statistical shape analysis can reveal pattern changes in human shape. This is powerful for visualising which is an intuitive activity for designers
Present time onward **(Meunier, Shu et al. 2009, Shu, Wuhrer et al. 2012, Wuhrer, Shu et al. 2012)**	Development of design tools using statistical shape models.	A few attempts have been made, but effective use of 3-D statistical shape tools for design remains a research problem
(Allen, Curless et al. 2006, Cheng and Robinette 2009, Hasler, Stoll et al. 2009, Wuhrer, Ben Azouz et al. 2010, Wuhrer, Shu et al. 2011) Present time onward	Analysing shape computer models (DHM) in different postures which allows a dynamic environment remains a research problem	Although some work has been done this is emerging work. This is needed for future work in motion prediction

Historical context - timeline	Topic	Comments
(Oudenhuijzen, Zehner et al. 2009)	Training of digital human models (DHM) also called Human Modeling Systems (HMS) to create libraries. This was an extension of work done in 2002 which showed a mismatch between real subjects and their corresponding manikins, sometimes as large as 95mm.	Human case studies have been used to create reach envelopes which in turn have been used to artificially force CAD DHM's to have correct reach allowances for the first time. This can be used as a temporary fix while waiting for accurate dynamic DHM to be developed
(International Standards Organisation (ISO) 2008, International Standards Organisation (ISO) 2010, International Standards Organisation (ISO) 2012)	International Standard organisation (ISO) technical standards are published covering anthropometry in design	How to take measurement and landmarking are defined. Some summary statistics for individual ISO populations are listed. A basic guide to the establishment of anthropometric databases is outlined.
(International Standards Organisation (ISO) 2010)	ISO 20685 3-D scanning methodologies for internationally compatible anthropometric databases	A very comprehensive and useful standard has been published to guide use of 3-D scanners in sizing surveys
(Mellian, Ervin et al. 1990, Robinette, Vannier et al. 1997, Hudson, Zehner et al. 2003, Robinette and Hudson 2006, Choi, Zehner et al. 2010)	Fit-mapping is extended, described and published	Solutions developed of how to successfully apply anthropometric measurements to design. These methods work very well but require real people. At the moment they are not in predictive computerised models.

Table 1: Historical timeline highlighting important developments

3. Referential standards for sizing surveys

3.1 International standards

Over the history of the collection of anthropometric data, standards for the collection of population data for engineering purposes have been developed. These have been consolidated and defined in international standards, published by the International Standards Organization (ISO), Geneva, Switzerland. Some of the international standards that are relevant to undertaking a large scale sizing survey include:

1. ISO 7250-1 Basic human body measurements for technological design. Part 1: Body measurement definitions and landmarks. Geneva, ISO: 25.ISO (2008).
2. ISO 7250-2 Basic human body measurements for technological design. Part 2: Statistical summaries of body measurements from individual ISO populations. Geneva, ISO: 53.ISO (2010). (International Standards Organisation (ISO) 2010)
3. ISO 20685 3-D scanning methodologies for internationally compatible anthropometric databases (International Standards Organisation (ISO) 2010)
4. ISO 15535 General requirements for establishing anthropometric databases (International Standards Organisation (ISO) 2012)
5. ISO 8559 Garment construction and anthropometric surveys – Body dimensions (International Standards Organisation (ISO) 1989)

ISO 7250-1 provides a description of anthropometric measurements which can be used as a basis for comparison of population groups, the basic list specified in this part of ISO 7250 is intended to serve as a guide for ergonomists to provide the anatomical references and anthropometrical bases and principles of measurement that might be applied in the development of solutions for design tasks. It is not a reference on how anthropometric measurements should be taken.

ISO 7250-2 intends to serve as a continually updated repository of the most current national anthropometric data. It is intended to make current and updated anthropometric data available for inclusion by reference in the various ISO product standards requiring anthropometric data.

ISO 20685-3 is a highly specific approach that is recommended for groups undertaking anthropometric studies that extract 1-D data from 3-D scans. It intends to ensure comparability of traditional-style body measurements (usually measured with traditional anthropometric instruments such as tape measures and callipers) specified by ISO 7250-1, but instead measured with the aid of 3-D body scanners and measurement extraction software. It is further intended that by conformance with this International Standard any data extracted from scans will be suitable for inclusion in international databases such as those described in ISO 15535. This approach does not recommend replacing traditional-style measurements without validation. It recommends the use of a validation study using manual methods to determine if it will be feasible to collect the required data from the 3-D scanning methods.

ISO 15535 specifies general requirements for anthropometric databases and their associated reports that contain measurements taken in accordance with ISO 7250-1. It provides necessary information, such as characteristics of the user population, sampling methods, measurement items and statistics, to make international comparison possible among various population segments. The population segments specified in this International Standard are people who are able to hold the postures specified in ISO 7250-1.

Whenever possible an anthropometric survey should follow ISO standards in order that data can be used and compared across populations. For example, ISO 7250-1: 2008 (updated from the previous edition of 1996) lists commonly used measurements (International Standards Organisation (ISO) 2008) however in the Scope section of the standard it recommends that ISO 7250 should be used "in conjunction with national or international regulations or agreements to assure harmony in defining population groups". Furthermore it is anticipated that in “various applications, …the basic list will be supplemented by specific additional measurement”. Whenever possible landmarks and measurements should be cross-referenced with ISO 7250 nomenclature (Blackwell, Robinette et al. 2002). When a landmark or measurement has no ISO reference this should be stated and in all cases adequate records, including photographs or detailed sketches and measurement procedures documented (4.2.3 (International Standards Organisation (ISO) 2012)) for quality assurance and comparison purposes. An example of suitable documentation is that published by Civilian American and European Surface Anthropometry Resource (CAESAR), Volume 11: Descriptions (Blackwell, Robinette et al. 2002). Population sampling strategy needs to be decided for an Australian survey but the ISO 15535: 2012 Section 4.3.2 (International Standards Organisation (ISO) 2012) recommends random or stratified sampling. An example is given in 6.1.1 later in this report.

In summary ISO standards provide a basic template for the development and delivery of a large scale body-sizing survey and how data should be stored for common use, however the standards are not sufficient to define all aspects of the survey. The contribution and missing sections of these ISO standards are outlined below in Table 2 and Figures 9 and 10.

	Relevant ISO Standard	Topic
Who/where	ISO 15535	Database description - Sampling methods
What	ISO 7250-1	Terminology and methods - Measurements to be taken/stakeholder (user/sponsor) input
What or how	ISO 15535	Database description - Storing and presenting measurement data
What or how	ISO 7250-2	Data content - Existing summary statistics
How	ISO 20685-3	Terminology and methods and some validation

Table 2: Summary of relevant ISO standards

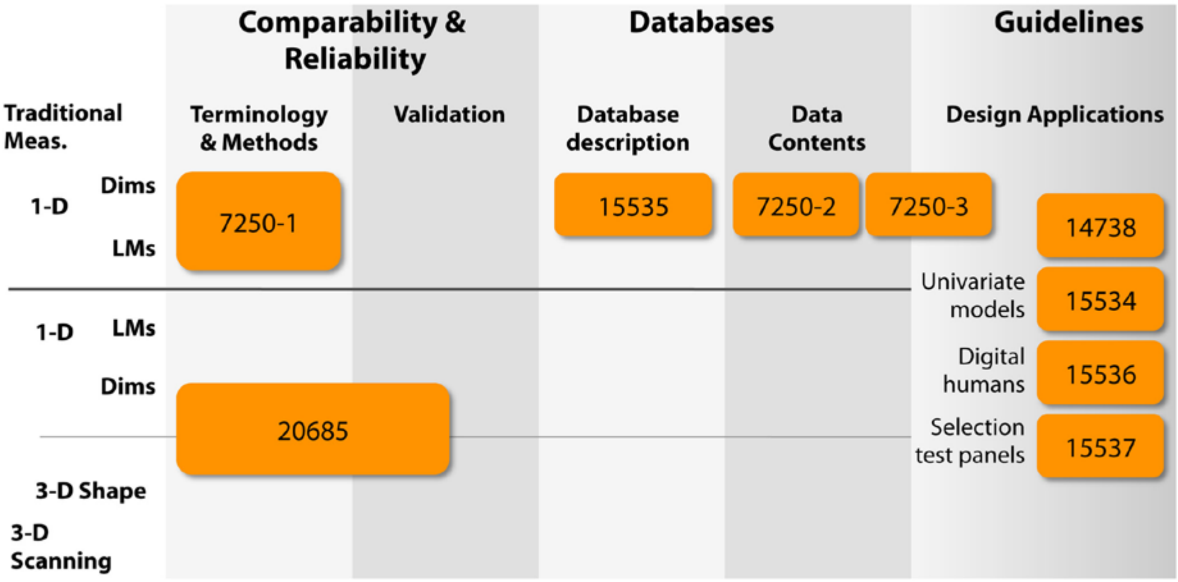


Figure 9: Established standards in ISO/TC159 “Ergonomics” . LM stands for Landmarks and Dims is dimensions.

ISO has established New Working Items (NWI) and is in the process of developing validation protocols because these are currently missing from the standards. ISO/TC 159 has been established for this purpose - see Figure 10. In the meantime a future Australian survey must still be validated, so lessons learned from past surveys and new tools such as AMI must be used to supplement the standards. See Figure 7.

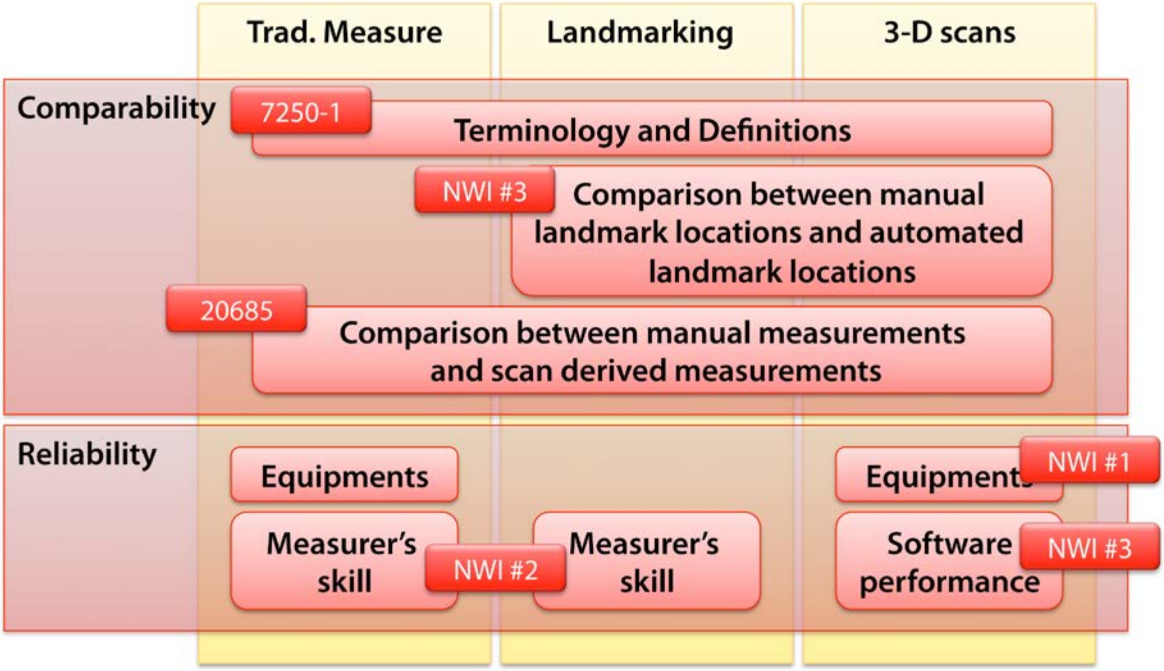


Figure 10: shows New Working Items in red have been formed to create standards for comparability and reliability. This diagram is from the ISO159 strategic plans for ISO projects - anthropometry (Mochimaru 2012).

3.2 Demographic data

Demographic data are a necessary accompaniment to a body sizing survey as they tell the user about non-body size/shape details about the sample that may be critical to design. The ISO defines demographic data as “background information (such as sex, dwelling or working place, occupation, education) that is used to describe members of the user population and/or population segments”, (International Standards Organisation (ISO) 2012). This same standard goes on to provide specific guidelines on the numbering of items and measurements:

7.1.1 Item 1 Subject number.

7.1.2 Item 2 Sex: M for male subjects, F for female subjects.

7.1.3 Item 3 Exam location: country, ISO 3166-1 and location.

7.1.4 Item 4 Exam date: ISO 8601 method yyyy-mm-dd (for example, 2003-05-23 for 23rd of May, 2003).

7.1.5 Item 5 Birth date: ISO 8601 method yyyy-mm-dd (for example, 2003-04-05 for 5th of April. 2003).

7.1.6 Item 6 Decimal age: subject's age calculated after the exam in accordance with the method described in Annex D.

7.2 Recommended background data
Additional background data items such as birthplace, school, occupation or population segment may

also be included, depending upon the purposes of the study.

The Australian Body Sizing Survey should comply with the ISO requirements in the interest of international comparability, however, stakeholders may request additional information that will add richness to the dataset.

3.3 Landmarks and their uses

A landmark is “a point of correspondence on each object that matches between and within populations” (Dryden and Mardia 1998). Landmarks are used for multiple purposes:

1. To define the anatomical reference points for body measurements, joint centres and segmented body scans (Burnsides, Boehmer et al. 2001, Blackwell, Robinette et al. 2002, Robinette and Daanen 2006, Xi, Lee et al. 2007, Ball 2009, International Standards Organisation (ISO) 2010).
2. Anatomical correspondence between two different body scans (Kouchi, Mochimaru et al. 2011, Shu, Wuhrer et al. 2012).
3. Creating homologous models (Mochimaru and Kouchi 2000, Allen, Curless et al. 2003).
4. Statistical analysis and reconstruction of variation in human shape (Mochimaru and Kouchi 2000, Allen, Curless et al. 2003).
5. To locate specific anatomical locations for design purposes, such as the pupils relative to the design goggles (Burnsides, Boehmer et al. 2001).
6. “Many anthropometric distances can be calculated from the co-ordinates of anatomical landmarks. Some additional points may be necessary to obtain circumferences” (International Standards Organisation (ISO) 2010).

The CAESAR project used 72 anatomical landmark locations (Blackwell, Robinette et al. 2002) and one seated surface landmark for the 3-D scan data. There were additional landmarks used for the traditional/manual 1-D measurements that were not used in the 3-D scans. ISO 20685 3-D Scanning methodologies for internationally compatible anthropometric databases lists 21 landmarks (International Standards Organisation (ISO) 2010).

Landmarks are either manually placed, which means having an anthropometrist (expert) pre-determine the location of a landmark (usually by palpation) and place a sticker or 3-D bumper on the person prior to scanning. The landmarks can be viewed and exactly matched later on the 3-D digital scan. Alternatively landmarks can be automatically placed, which means allowing computer software to place landmarks automatically.

For manual landmarking, time prior to the scan is required to identify, locate and place landmarks and to remove them from the subject after the scan. The manual location of landmarks also introduces the potential for error when one might be omitted, be dislodged or knocked off during movement of the subject or not be accurately located and applied. In addition, the scanned image (may) need to be checked as soon as it is obtained to confirm that the landmarks are detectable within the image and to record the detail of each landmark.

To simplify and streamline this process and reduce the risk of inter-rater and intra-rater error a study was conducted to determine if it is possible for these landmarks to be automatically detected via the 3 D scan image. This study found that, while a small number of landmarks could be consistently and automatically detected, it was not possible to consistently detect a sufficiently high proportion of anatomical landmarks to eliminate the need for manual landmarking. These results found a mean error of 20 mm across scanned landmarks; a benchmark error of less than 10 mm was sought (Wuhrer, Xi et al. 2013). Current state of the art still relies on the use of landmarks and their application by an expert anthropometrist (International Standards Organisation (ISO) 2010). Automatic landmark detection is not sufficiently accurate to be relied on for measurement purposes. Manual application of landmarks on subjects is needed to reduce error and achieve correspondence to then be able to develop paramatised/homologous models.

3.4 Traditional Style measurements

Until the advent of laser scanning technology, anthropometric measurements were taken manually in the physical world using tape measures, weighing scales and a range of purpose-built tools: the anthropometer, sliding calipers, and spreading calipers. The term “Manual measurements” was applied to these measurements but now this term has broadened to include some measurements taken in the virtual world – see 3-D scanned measurements below 3.3.2. Their terminology and methods have been standardised by the ISO in ISO 7250 -1, Section 3 (International Standards Organisation (ISO) 2008).

Now that 3-D scanners have become a measuring tool the new term used to describe anthropometric measurements taken without a 3-D body scanner is “Traditional Style measurements “. They also comply with ISO 7250-1. Specifically, Traditional style measurements are those complying with ISO 7250 -1, section “3 Measuring conditions and instruments”(International Standards Organisation (ISO) 2008). In this section “3.2 Instruments”, says, “the standard measuring instruments recommended are the anthropometer, sliding calipers, spreading calipers, weighing scale and tape measure.”

ISO 15535: 2012 Section 7 has guidelines on the numbering of these measurements. Items with ISO 7250-1 measures being recorded as Items 11-56 and missing variables from 11-56 being recorded as 9999. There is a provision in the standard for complementary data, which are additional measurements not present in ISO 7250-1. The recommendation is that they are recorded as data items 57 and higher, in alphabetical order.

3.5 ISO 20685 – 3-D scanned measurements

Since the advent of the 3-D scanner a whole standard has been dedicated to the topic of measurement using
3-D equipment and data storage. This is ISO 20685:2010, “3-D scanning methodologies for internationally compatible anthropometric databases”(International Standards Organisation (ISO) 2010).

The standard defines two different features of measurement extraction from a 3-D scan in Section A.4.5. These are measurements taken using a software extraction method. They can either be manually (A.4.5.1) or automatically (A.4.5.2) extracted.

Section A.4.5.1 defines Manual measurements as giving the user the ability to identify points from the scan and measure, such as extract a distance from the vertical plane at the most posterior part of the body, and calculate different types of measurements, such as point-to-point (ISO 20685:2010:19).

Section A.4.5.1 defines Automatic measurements as, “the software may give the user the ability to define a measurement in terms of landmarks and procedures (e.g. a horizontal circumference or a point-to-point distance), and then extract that dimension automatically.

Very importantly this standard outlines procedures that should be followed for testing accuracy and hence which measurements might be suitable to be collected in each different hardware and software combination. This would then inform which measurements would need to be taken in traditional style.

3.6 Other data (eg strength)

A Body Sizing Survey may include data other than measurements of a sample of the population and their demographic data; in particular, data on strength may be collected. ISO 7250-1:2008(E) lists other data as “4.4 Functional Measurements”, and have three related to grip measured using a 20mm diameter rod (International Standards Organisation (ISO) 2008).

4. Anthropometric surveys

Until 2001, large-scale anthropometric surveys were mostly conducted with military populations - see Figures 11 and 12 for some examples. These gave them an inherent bias against females and towards males with the physical attributes needed to pass the threshold values of physical recruitment tests. They also tend to include people within a limited age range. These inherent biases mean that military populations cannot be regarded as representative of the more inclusive civilian working populations where there are more women, a wider range of fitness levels and broader age range.

The following sections describe population surveys that have been conducted recently. This includes the WEAR project because it already has collected together more than 120 different anthropometric surveys. WEAR only includes datasets that have the functionality of raw data. Thus not included in WEAR are those datasets that only provide summary statistics. These include the surveys listed in ISO 7250-2, Size USA and Size UK.

Surveys that collected 3-D scans only should be differentiated from those that combined 3-D scans and traditional anthropometry due to their usefulness. 3-D scans with 1-D traditional style measurement surveys are more useful as they provide the additional functionalities of 1-D data: ease of use and comparison with older data collected in the same way. In addition 1-D traditional style measurement provides an opportunity to cross-check the quality of scan-extracted measurements and provides comparable data for survey comparisons. 1-D measurements extracted from 3-D scans are comparable for point-to-point measures when the landmarks are pre-marked by experts (Robinette and Daanen 2006) but not circumferences (Perkins, Burnsides et al. 2000), especially the waist measurement for a particular sub-section of the female population (Veitch 2012). In addition there is a potential confounding error in a resulting body dimension due to taking a measurement on the wrong place on the body (Kouchi, Mochimaru et al. 2011). This is only a problem with automated landmarks. Automated landmarks may differ from those placed by an expert by 20mm, which is good enough for shape comparisons but not measurement extraction (Wuhrer, Xi et al. 2013).

Recent high quality surveys that combine 3-D scans and traditional style anthropometry include CAESAR (2002), Size Korea (2003-) and Size Japan (2006). Further information is below in 4.1, 4.2 and 4.3.

Recent surveys that used 3-D scans only include Japanese survey (early 1990's), Size UK (2001), Size USA (2003), Size China (2008)(which was also heads only), Spanish Sizing Survey (2007) and Size Germany (2009).

The 3-D only surveys are not discussed in this literature review due to the known and documented limitations regarding the accuracy of 1-D scan-extracted circumference measurements discussed above. In addition there is very little published information about the quality of these surveys. This could be because the main way to check quality is to cross check with 1-D traditional style measurements. Thus if traditional style 1-D measurements are not collected it is impossible to verify the quality. Validation studies done in advance on these studies are also missing from the literature. Size China scanned heads only which made it an exception.

The least useful are surveys that only collect 3-D scans and then only provide 1-D measurements automatically extracted from the 3-D scans (no 3-D scans provided and sometime 3-D scans are not even saved). Recent examples include surveys conducted by the clothing retailer, Target, in Australia in 2012 which includes ongoing collection by the privately owned Chinese-based company Alvanon (Target Australia 2012), and the US-based company me-ality (me-ality 2013). If the user is only provided with a summary of these 1-D measurements this further degrades the usefulness. Not only does the user have to contend with the limitations of 1-D data but the automated scan-extracted 1-D data collected are different to traditional-style
1-D data collected – although confusingly the measurement might have the same name and

no definition. Currently there is no systematic translation to compare these data. Lastly the absence of individual 3-D scans with matching 1-D data means there can be substantial errors in the realm of 300 mm in the waist (6 clothing sizes) as illustrated in Figure 5 with no capacity to visualise what the problems might be. This creates the tendency to delete these subjects as outliers instead of understanding the underlying problems causing the errors (no capacity to understand and solve potential measurement issues). Ultimately this defeats the purpose of a survey as the goal would be to capture the full range of human variation not just those people who fit the pre-conceived notion of what someone should look like. Thus, these surveys are not covered in this literature review.

4.1 CAESAR

The Civilian American and European Surface Anthropometry Resource (CAESAR) project was the first large-scale, international anthropometric survey to collect demographic, 3-D and traditional 1-D data. It included North America, (USA and Canada) and the European populations of the Dutch (tallest) and Italians (shortest). In addition, it covered the civilian population including both males and females to provide a survey of contemporary populations with diverse make up and an anticipated greater range of body sizes than had previously been achieved. The project used purpose built 3-D laser scanners to capture data over a two-year period. It was published in 2002. The number of subjects measured were: North America = 2375; The Netherlands = 1225; Italy = 801; Total = 4431. (Robinette, Blackwell et al. 2002)

The development of the plan for the survey was an iterative process initiated in 1993 with the formation of a NATO working group, Working Group 20: 3-D Surface Anthropometry (Robinette, Vannier et al. 1997) referred to as the AGARD Report.

The group members for CAESAR originated from 6 different countries and included various technical experts from the fields of physics, medicine and applied design. It involved engagement of stakeholders at the outset to identify their requirements for anthropometric data and the initiator, the United States Air Force (USAF) Research Laboratory, collaborated with the Society of Automotive Engineers' (SAE) G-13 Committee and the American Society of Testing and Materials (ASTM) D-12 Committee. In addition to the international nature of the project, this brought stakeholders from different industries such as aerospace and apparel under one umbrella for a common goal. This was reported by the stakeholders themselves as an integral part of the success of the CAESAR project. This approach enabled the project group to establish early funding commitments so they could then proceed to finalise the design so it captured the data sought by sponsors and then implement the survey.

The project used many standardised protocols including versions of the current ISO standards (International Standards Organisation (ISO) 2008, International Standards Organisation (ISO) 2012) and expanded and rigorously documented their methods and detail of the project in two publications (Blackwell, Robinette et al. 2002, Robinette, Blackwell et al. 2002). In addition, the project produced a series of technical research papers describing how various decisions were made, what was tested, and the advantages and disadvantages of the choices that were made (Blackwell 1993, Brunsman, Daanen et al. 1997, Daanen, Brunsman et al. 1997, Rioux 1997, Robinette, Vannier et al. 1997, Perkins, Burnsides et al. 2000, Robinette 2000, Burnsides, Boehmer et al. 2001, Robinette and Daanen 2003, Robinette, Daanen et al. 2004, Robinette and Daanen 2006). As a result this is the highest quality and most studied anthropometric database that combined 1-D manual and traditional style measurements, with 3-D scans.

The high quality 3-D scans, combined with manual landmarking, gave the ability to cross check measurements with traditional style measurements. This important feature has enabled the research community to build applications for use by industry as outlined in Section 5. Australia is well placed to learn from and improve on CAESAR in its own body sizing survey. We have the benefit of the outcomes of CAESAR and other surveys to inform our own survey and achieve the best possible outcomes for our specific population, which will lead to the development of the tools and knowledge to directly apply the findings to industrial applications.

4.2 Size Korea

The following extract is from a personal communication (email) between Daisy Veitch with Lee-Young Suk (a member of the WEAR group) from her unpublished paper on Size Korea, which she has translated from Korean.

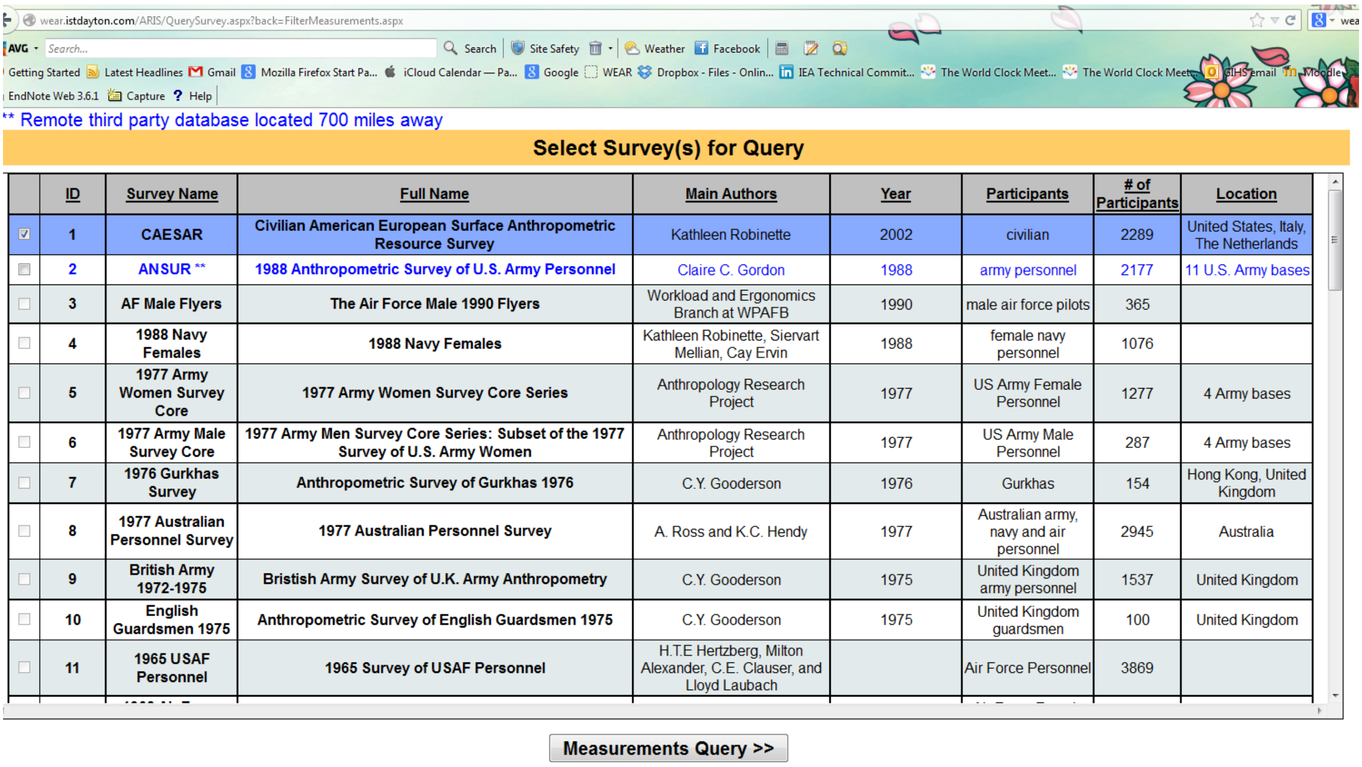
> "In Korea, the first national anthropometry survey was conducted in 1979 by a Korean government division, the Korean Agency for Technology and Standard (KATS 1979). At the time, data were collected concerning 17,000 samples residing in various parts of the country aged between six and fifty. A total number of 117 measurement dimensions were taken using calipers and tape measures. Thanks to these data, the KATS established 46 items defining Korean standards concerning clothing, furniture, desks and chairs. Forty-one of them (KSK 0035 to KSK 0096) were associated with the size designations of men's wear, women's wear, brassieres, socks, etc.
>
> Following this survey, the Korean government has been presenting a national anthropometric survey every 5 or 6 years. The surveys of 1986, 1992, 1997, 2003 and 2010 were performed according to the following sequence: The survey was performed with the traditional measurement method (2-D) using an anthropometer, somatometer, caliper and tape measure. The 3-D body scan data collection (Body Line Scanner, Hamamatsu Co.) method (3-D) was also adopted in order to obtain a good compromise and to modernize the fit and construction of their garments for the 2003 and 2010 surveys. All body dimensions were measured with the method defined by the ISO (ISO 3635 1981; ISO 8559 1989)."

Surveys	**1st**	**2nd**	**3rd**	**4th**	**5th**	**6th**
Years	1979	1986	1992	1997	2003	2010
Sample	17,000	21,650	8,800	13,000	14,000	14,000
Age Range	6-50	6-50	6-50	0-70	0-90	7-69
Dimensions	117	80	84	120	359	139
Methods	1-D + 2-D	1-D + 2-D	1-D + 2-D	1-D + 2-D	1-D, 2-D + 3-D	1-D, 2-D + 3-D

Table 3: Summary of Size Korea surveys from 1979 – 2010.

4.3 Other surveys

WEAR has a collection of more than 120 other databases from around the world. These have been included in the WEAR database by WEAR members who include various researchers, companies and universities. In the main these databases are subsets of populations that have been taken for specific design purposes. A subset of Australian 1-D data for 1250 women are included in ERGODATA (Henneberg and Veitch 2003). Figure 11 illustrates how WEAR draws the surveys together.



** Remote third party database located 700 miles away

Select Survey(s) for Query

	ID	Survey Name	Full Name	Main Authors	Year	Participants	# of Participants	Location
☑	1	CAESAR	Civilian American European Surface Anthropometric Resource Survey	Kathleen Robinette	2002	civilian	2289	United States, Italy, The Netherlands
☐	2	ANSUR **	1988 Anthropometric Survey of U.S. Army Personnel	Claire C. Gordon	1988	army personnel	2177	11 U.S. Army bases
☐	3	AF Male Flyers	The Air Force Male 1990 Flyers	Workload and Ergonomics Branch at WPAFB	1990	male air force pilots	365	
☐	4	1988 Navy Females	1988 Navy Females	Kathleen Robinette, Siervart Mellian, Cay Ervin	1988	female navy personnel	1076	
☐	5	1977 Army Women Survey Core	1977 Army Women Survey Core Series	Anthropology Research Project	1977	US Army Female Personnel	1277	4 Army bases
☐	6	1977 Army Male Survey Core	1977 Army Men Survey Core Series: Subset of the 1977 Survey of U.S. Army Women	Anthropology Research Project	1977	US Army Male Personnel	287	4 Army bases
☐	7	1976 Gurkhas Survey	Anthropometric Survey of Gurkhas 1976	C.Y. Gooderson	1976	Gurkhas	154	Hong Kong, United Kingdom
☐	8	1977 Australian Personnel Survey	1977 Australian Personnel Survey	A. Ross and K.C. Hendy	1977	Australian army, navy and air personnel	2945	Australia
☐	9	British Army 1972-1975	Bristish Army Survey of U.K. Army Anthropometry	C.Y. Gooderson	1975	United Kingdom army personnel	1537	United Kingdom
☐	10	English Guardsmen 1975	Anthropometric Survey of English Guardsmen 1975	C.Y. Gooderson	1975	United Kingdom guardsmen	100	United Kingdom
☐	11	1965 USAF Personnel	1965 Survey of USAF Personnel	H.T.E Hertzberg, Milton Alexander, C.E. Clauser, and Lloyd Laubach		Air Force Personnel	3869	

Measurements Query >>

Figure 11: some of the 52 surveys currently available in WEAR – ARIS

N°	Survey	Date	Content: Males Females	Content: Age (min,max)	From
-	AUSTRALIA_02_F	2002	1275 females	15 to 96	SHARF

SOUTH AMERICA

N°	Survey	Date	Content: Males Females	Content: Age (min,max)	From
-	BRAZIL_01_M	2001	231 males	- to -	INSTITUTO NACIONAL DE TECNOLOGIA INT MINISTÉRIO DA CIÊNCIA E TECNOLOGIA
-	BRAZIL_01_F	2001	106 females	- to -	
31	BRESIL	1976	249 males	- to -	BRESIL, Thèse de sciences, Rio.
50	BOLIVIENS	1974	152 males	14 to 32	BOLIVIE, Anthropologie Appliquée.
53	VENEZUELA	1983	151 males 149 females	7 to 14	Vénézuela, enfants vénézueliens, Anthropologie Appliquée.

NORTH AMERICA

N°	Survey	Date	Content: Males Females	Content: Age (min,max)	From
-	USA_98_MF	1998 2000	1127 males 1264 females	18 to 79 18 to 69	CARD We Put The FIT in FLIGHT
-	CANADA_98_MF	1998 2000	147 males 86 females	20 to 65 19 to 63	
30	CANADIENS	1974	565 males	17 to 50	CA. Militaires Canadiens, DCIEM Canada.
1	AFW68	1968	1905 females	18 to 56	U.S.A. (Air Force Women), Aerospace Medical Research Laboratory.
12	FLY67	1967	2420 males	21 to 50	U.S.A. Pilotes, Aerospace Medical Research Laboratory.
13	AFM65	1965	3869 males	17 to 59	U.S.A. Air Force (Men), Aerospace Medical Research Laboratory.
55	NCHS	1962	3091 males	18 to 79	U.S.A. Civils adultes, National Center for Health Statistics

Figure 12: some of the 68 surveys available in WEAR – ERGODATA

5. How are anthropometric data used in industry?

Understanding and differentiating effective from ineffective practices in using anthropometric data in industry will ensure survey data are suitable to enable better design practices in the future. It will answer the question “how does your market differ from populations in another country?” and enable assessment of products designed for other markets that end up being used in the Australian market. Some case studies that illustrate the practical use of anthropometric data by industry follow.

5.1 Worn things/apparel sizing

5.1.1 Understanding your target market

A goal in industry is to understand your target market so that it is possible to fit the maximum number of consumers into the minimum number of product sizes in a safe, functional and aesthetic way. A good example of this is found in the apparel industry. Historically, the apparel industry used bespoke tailoring to fit individuals, but a more cost effective production method is based on the mass production of garments. Mass production has been developed largely using trial and error and feedback from retail i.e. what sells best. It is often assumed that the best-selling items are the best fitting and often someone is employed by the retailer as a fit model, whose job it is to try on potential apparel for the purposes of determining if the buyer wants to commit to purchase. The selection of the fit-model can be a very subtle process based on the look of the person, rather than an objective, scientific basis. Consequently there is significant variation in the size-labelling and fit of retail clothing. Additional sizes are usually created automatically from the base size pattern using a process of shifting various points in the x-y plane to make them bigger or smaller in a process known as grading. Apparel retailers often have a size chart with 1-D measurements such as bust, waist and hip that they refer to. There are significant problems with these methods. The first is there is no indication about the location of the fit model in relation to the general population, so the fit model may be an outlier. The second is that grading often doesn’t match the changes in shape that accompany body growth.

1-D data can be very useful in addressing some of these issues especially when used in combination with 3-D. Veitch and Robinette used 3D, 2D and 1D anthropometric data in the selection and design of bio-fidelic (life-like) apparel fit manikins. The resultant manikins are copies of real people; one is a regular size and the other is a large size female. The selection process uses bi-variates and multiple regressions from the key variables for apparel sizing, as defined by past testing (Mellian, et al., 1991). Databases used included CAESAR data, SHARP Dummies National Size and Shape Survey (Australia), other anthropometric data sources and apparel industry feedback (Veitch and Robinette 2006). Each dot on the bivariate chart in Figure 13 represents a woman measured in the CAESAR survey. Any potential fit model and clothing manikin should be located on the solid red line, which is the line of best fit for this population. The red dotted line shows where the most people cluster at different sizes – the so called “sweet spot” of grading. The green dots show the location of current industry measurement charts and grading (source Robinette). Just by moving the fit model to the centre of the distribution and adjusting the grading to match body growth, an extra 14.7% of people could be accommodated in the same number of sizes. To quantify this, if the population of adult females in the US in 2000 was about 123 million then 15% is roughly 17.5 million people who don’t fit in the sizes because of basic statistical errors.

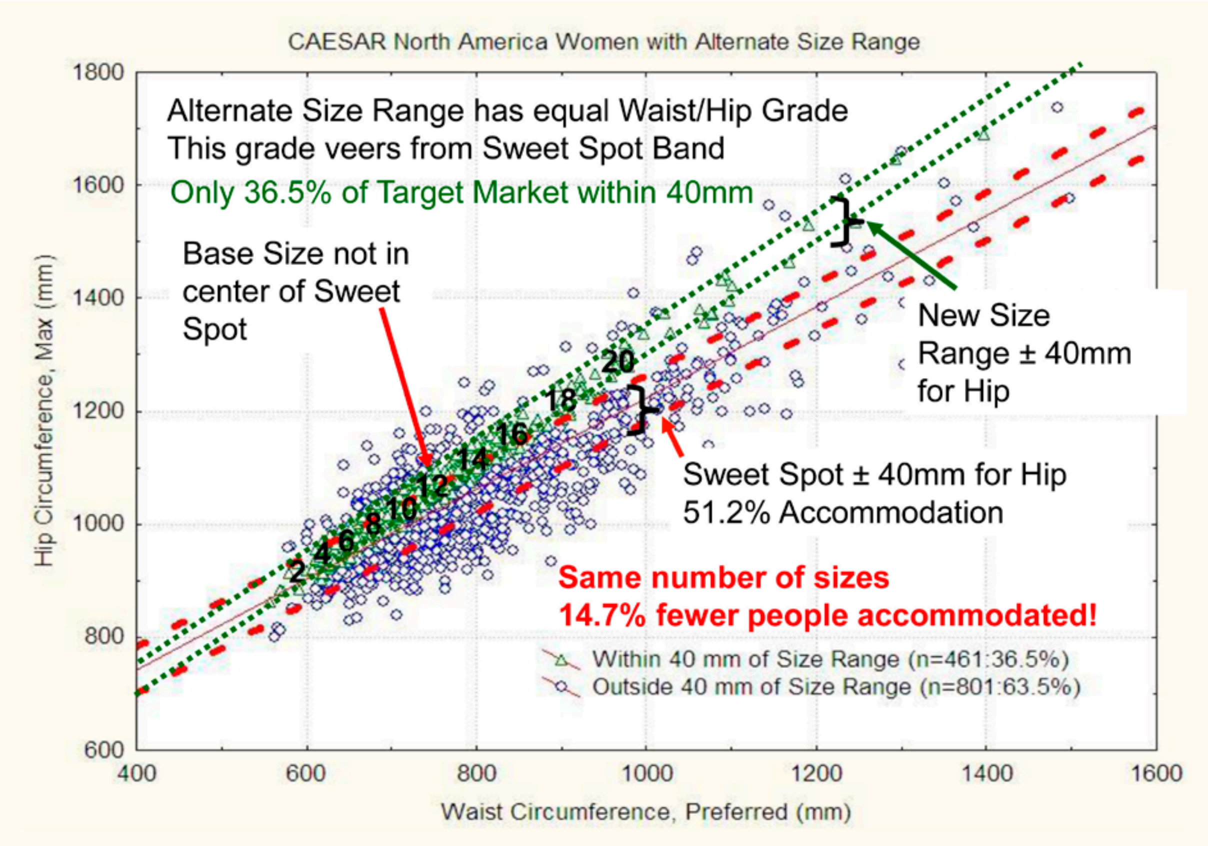


Figure 13 shows a bivariate plot of 1D hip vs waist data (North American CAESAR Women).

Subj	Stature	Crotch Ht	Bust Circ	Below Bust	Hip	Waist circ	Waist Front	Thigh Circ	Total Crotch	Cross-should	Fitness	Pants Size	Blouse Size
ASTM Size 10	65.5	29.5	36	n/a	38.5	28	14.5	22.5	28	15.38		10	10
233	66.42	30.28	36.69	30.79	38.39	28.03	15	22.79	26.26	16.52	>10	8	10
383	64.49	29.57	33.66	29.02	39.19	27.95	14.57	22.36	25.39	14.8	0-1	6	10
1736*	66.50	29.96	36.1	29.65	38.9	28.03	14.8	21.57	26.57	14.34	4-6	7	7

Table 4 shows basic measurement chart comparing ASTM sizing in inches, with 3 people measured in CAESAR, subject number 233, 383 and 1736 and their measurements.

To select the right candidate from the sample population for making a life-like manikin, suitable 1-D measurements were selected such as waist, hip and stature as described in Table 4. The sample was truncated at plus and minus 25mm (or 1 inch for the US) then some candidates from within that box were selected and their scans were viewed. A subject selection was made using a visual assessment of symmetry and posture as illustrated in Figure 14.

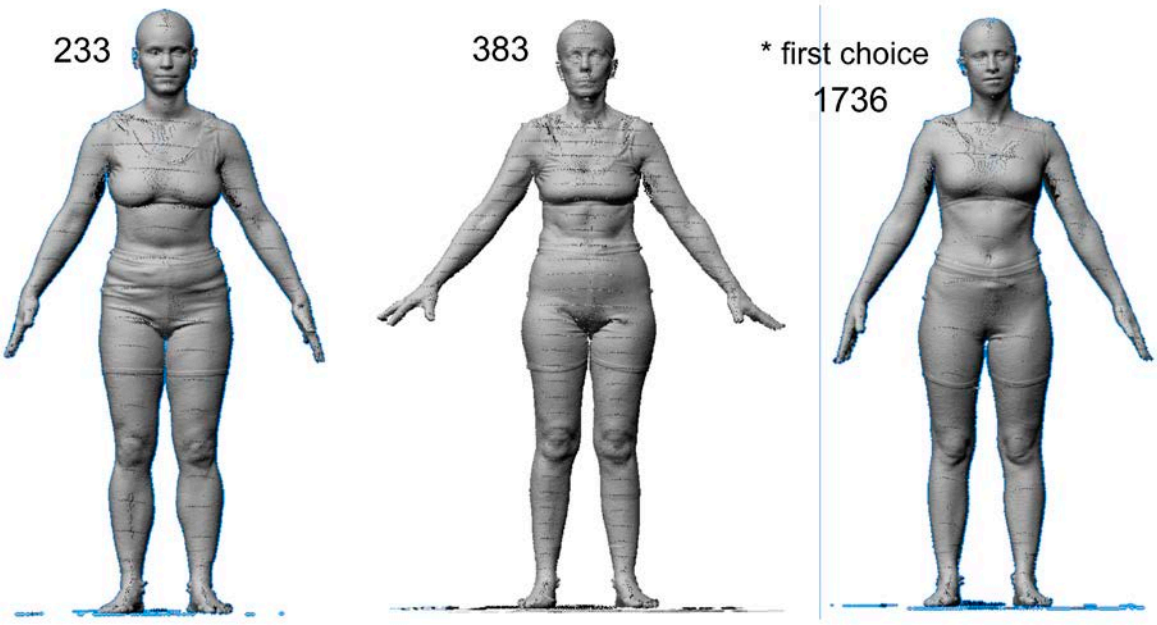


Figure 14 shows front view of the selected candidates.

The selected candidate's data was cleaned and processed. The data were then milled and a manikin produced. See Figure 15.

Figure 15 An apparel manikin made from a 3-D body scan.

This whole process was repeated for a large size manikin as shown in Figure 16. The process described above was then repeated but in this instance for a special population. The population was restricted to women whose weight was between 80 and 85 kgs. The woman selected best representing this group was 82 kgs and matched the other criteria outlined above for the normal population. The goal of this was not only to make a manikin representing the most commonly occurring size and shape in this special population but also to understand how changing body shape with size relates to pattern grading.

Figure 16 shows an example of an overlay of scanned data shows clearly how the body grows. This can inform an understanding of grading (the creating of different sizes from a base pattern). Existing grading practice can be arbitrary. For example the existing practice of traditional grading in Australia has no negative growths. This means that there is an underlying assumption that as the body grows in size *all measurements will stay the same or increase*. Figure 16 illustrates that this assumption is *not true* in the sweetspot band. It is immediately apparent from Figure 16 that the growth of bust height in relation to waist height is negative. That, is the bust point is closer to the waist in large sizes. This means the designer can now easily detect likely errors using intuitive visualisation of 3-D scan data and change grading to match body growth, providing increased control and understanding. The ability to use 3-D to overlay shapes and compare is a powerful tool for the designer to understand body shape change in relation to increased weight while keeping stature constant.

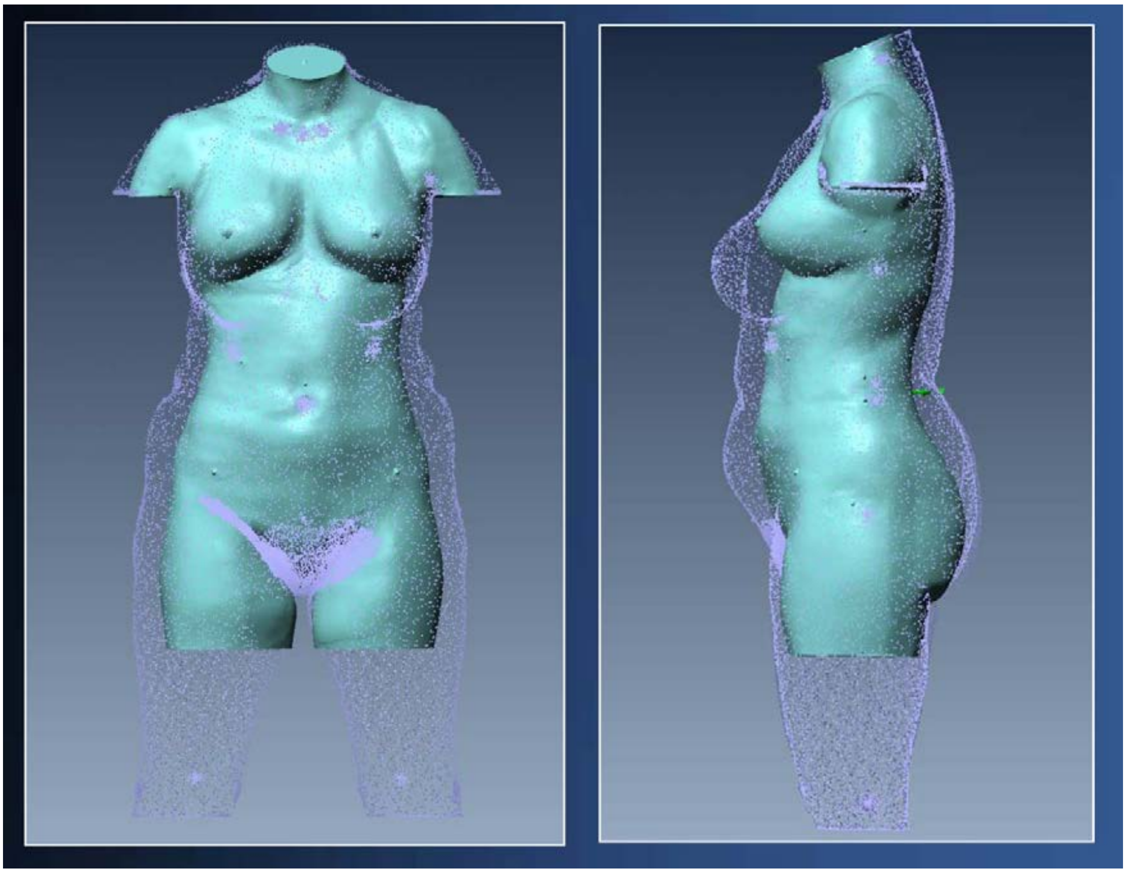


Figure 16 an overlay of two digital scans showing body growth. Note the change in bust point on the larger female.

These case studies show the power of using 1-D individual or raw data (raw data are the individual measurements that are taken). After statistical analysis they become aggregate data, sometimes called summary statistics. Ideally the ASTM measurements would be derived from real data.

Raw data are essential for use in design because they allow the selection of data subsets, such as certain age groups or gender or ethnicity, which may be suitable for specific applications. Summary statistics then can be built upon specific search criteria that are relevant to the immediate need. In this example the 1-D data were matched to 3-D data files that were single scans used for visualisation.

In an Australian example, if the entire Australian raw data were loaded into the WEAR resource, the users could select a subset relevant to their immediate search criteria, such as, measurements/s: stature, gender: females, age range: 39-50, ethnicity: white (of course this search would vary depending on the range of the original data collected and the requirements of the user). The user would receive an Excel spread-sheet with all raw measurements selected for their specific user population as per the query criteria specified above, including Subject identity number, along with summary statistics of mean, standard deviation, minimum and maximum values. The user then could select subjects who look representative of their user group and view pictures and scans. This is what our planned survey needs to provide.

In addition, Australian data could be used for population comparisons, such as the one below that compares Anglo-Saxon (black) countries to Scandinavian (red) to Oriental (green) etc for buttock-knee length vs eye-sitting height. The graph below illustrates that there are population differences and that people from oriental countries are not only smaller/shorter overall but also they have proportionally shorter buttock-knee length compared to their eye-sitting height. This might be important for car design.

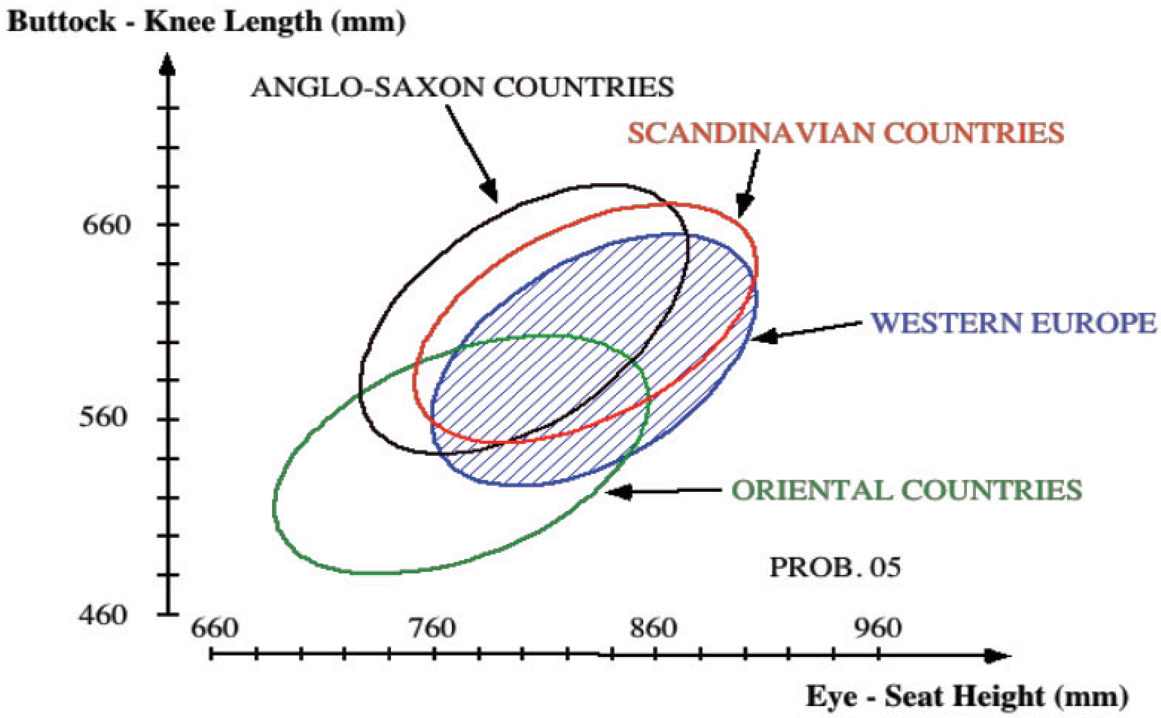


Figure 17 show a bivariate graph comparing two 1-D measurements for different populations.

Percentiles are suitable for comparing one or two dimensions between populations, as Figure 17 illustrates, but, as explained earlier they are inadequate as a statistical tool to use in engineering anthropometry when the design requires several anthropometric measures used together.

5.1.2 Personal Protective Equipment (PPE)

A common application of anthropometry to working populations is the fit and function of personal protective equipment (PPE) and clothing. The development of uniforms, helmets and gloves and protective equipment for the head and face has been the focus of numerous studies (Mellian, Ervin et al. 1990, Blackwell 1993, Choi, Zehner et al. 2010). For many items of PPE the calibre of the fit is tied to its function. Also where multiple items of PPE need to be worn the effectiveness of fit for one item can impact on the quality of fit, and ultimately operational effectiveness, of other items of equipment worn, whether they are operational items of equipment or other items of PPE such as helmets combined with goggles.

Fit cannot be predicted without measuring accommodation, but more about that later in 5.3 and 5.4

5.2 Built Environments – Accommodation – workplace design and the built environment

The use of anthropometric data by designers and ergonomists to establish design parameters for built environments varies in effectiveness. Examples are given here that reflect both: effective use - good understanding of the accommodation of target groups in the design; and less effective applications - where the target groups may not even be well defined, let alone sufficiently accommodated in the design. Good design involves an iterative design cycle where a range of potential users tests the product/environment against a set of performance criteria (see Figure 18). Ideally the range of users will cover the full scope of human variation likely to occur in that population for the dimensions critical to the design of that particular item/set up.

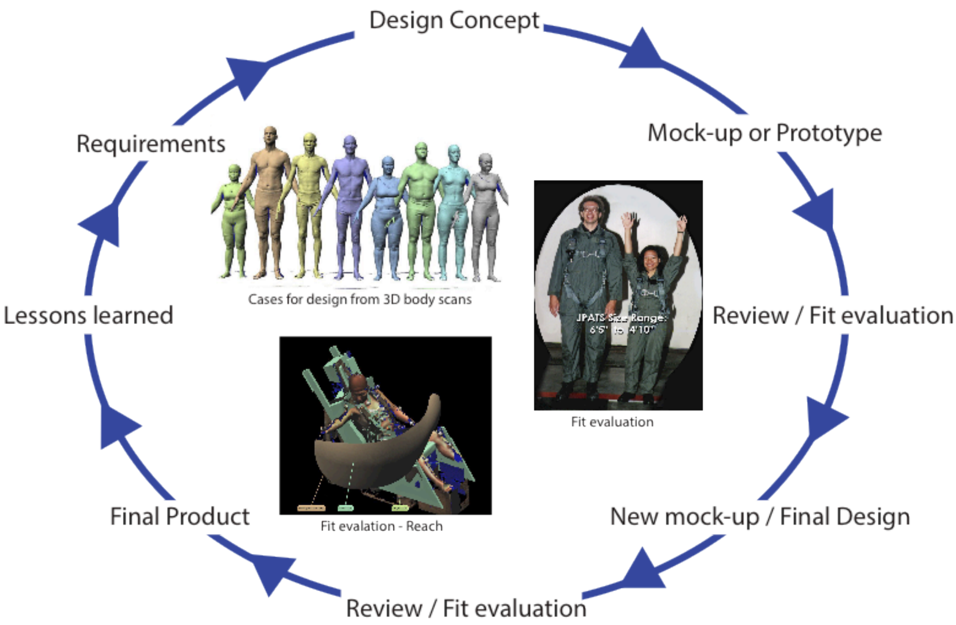


Figure 18: shows the concept of fit-evaluation applied in the design concept stage to improve the design before production

The applications of anthropometric data in workplaces have largely been derived from 1-D data. 1-D data in ergonomics-influenced design relates to the accommodation of people within spaces and environments or how people physically interact with plant, furniture, equipment and tools (Diffrient, Tilley et al. 1974). For example, defining the knee height range for a seated person can be used to determine the vertical range of a height adjustable computer workstation to accommodate the range of adults who would use it and who need to fit their knees under the workstation without compromising their posture.

These 1-D data describe heights, lengths, widths, depths and circumferences of different body segments. They are used to establish clearances for the accommodation of people and their movement in workspaces as well as to determine (estimate) reach distances. 1-D reference data are an essential part of design and assessment. However the type and complexity of the design dictates which is the appropriate use of those data.

For example, if in the process of design a designer requires information about more than one key human measurement to satisfy the need for good fit, the designer cannot effectively rely on 1-D or 2-D data. Instead the designer needs to use realistic human models to explain how the range of human variation can be accommodated in the design. This is required to adequately test the product or space. This is because the human body is complex and changing multiple variables simultaneously makes the change very hard, if not impossible to visualise when only using 1-D. Visualisation, which leads to greater understanding, is achieved by using *cases*, a form of advanced statistics. Cases are defined as a combination of body measurements, such as a set of measurements from a sample, a 3-D scan of a person, or a 2 or 3-D human model.

Robinette and Hudson (2006) have defined the procedure for selecting cases using multivariate statistics, principal component analysis (PCA). PCA allows the user to compress multivariate data that would normally occur in high-dimensional data space (1 axis per variable) into a lower dimensional space that is easier to visualise. It can help the user understand the relationship between different variables by reducing the number of dimensions.

5.2.1 Cockpit example – Part 1

An excellent example is USAF cockpit design work that includes workplace assessment of new recruits based on their body measurements in relation to minimising risks to their safety when operating various aircraft. This work is in two parts: case selection using PCA (described here) and fit-mapping (described in Section 5.4.2).

An important reason for this work was a change in attitude away from restricting recruits based on body size towards a more relaxed entrance requirement. This allowed the development of a user-centred, inclusive-design view where smaller people (primarily women) and larger people could become pilots (Zehner 2001, Zehner and Hudson 2002). The method developed can be applied to a variety of design applications where fitting a human into a work system needs assessment.

Important considerations include the pilot's seat location: high enough to have a clear field of view versus low enough so legs do not interfere with the controls; forward enough to reach the controls yet far back enough that their abdominal adiposity does not interfere with the free movement of the steering controls, and; back enough so that knees and feet do not hit the controls during a seat ejection.

The USAF cockpit example uses a specific type of case, called boundary cases. Boundary cases are cases that occur on the boundary of a bi-variate graph of a principal component shape. In this example six variables determined to be important for the cockpit layout were reduced to two principal component variables that explained nearly 90% of the total variability for all six (Zehner 2001). The first principal component (PC1) is interpreted to be related to overall size and the second principal component (PC2) is interpreted to be limb versus torso height contrast. Then representative cases/body combinations were selected from around the 95% boundary for the two PCs to account for the important variation relevant for this design.   These can be seen in Figure 19 (blue dots).

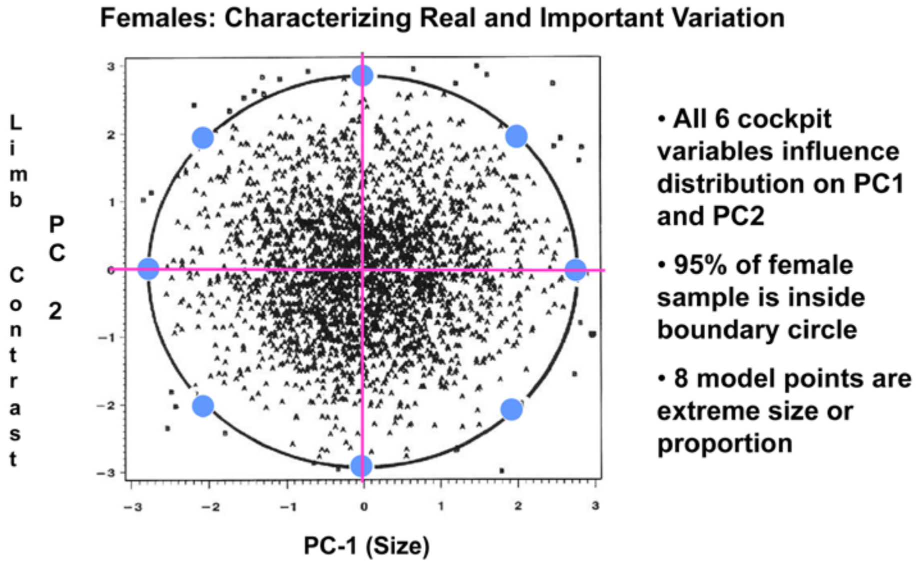


Figure 19: shows limb contrast as Principal Component 1 (PC 1) and Principal Component 2 (PC 2). The blue dots represent the “boundary cases” and each black dot is a person in the population. Source Greg Zehner.

The boundary cases around the ellipse (or circle) are examples of different body shape combinations that are representative of the outer ranges, or extreme sizes, for the combination of body parameters being considered within each of the principal components. In Figure 19 above, eight boundary cases, shown by blue dots, have been selected to represent the different extreme combinations that reflect variation in shape and size for these principal components. These cases were used in the specification of the U.S. Air Force’s Joint Primary Air Training Systems (JPATS) system and are now commonly referred to as the JPATS cases (Zehner 2001). Different combinations of small and large can be identified and matched with 3-D real cases (shown in Figure 20), and specifically considered within the design process.

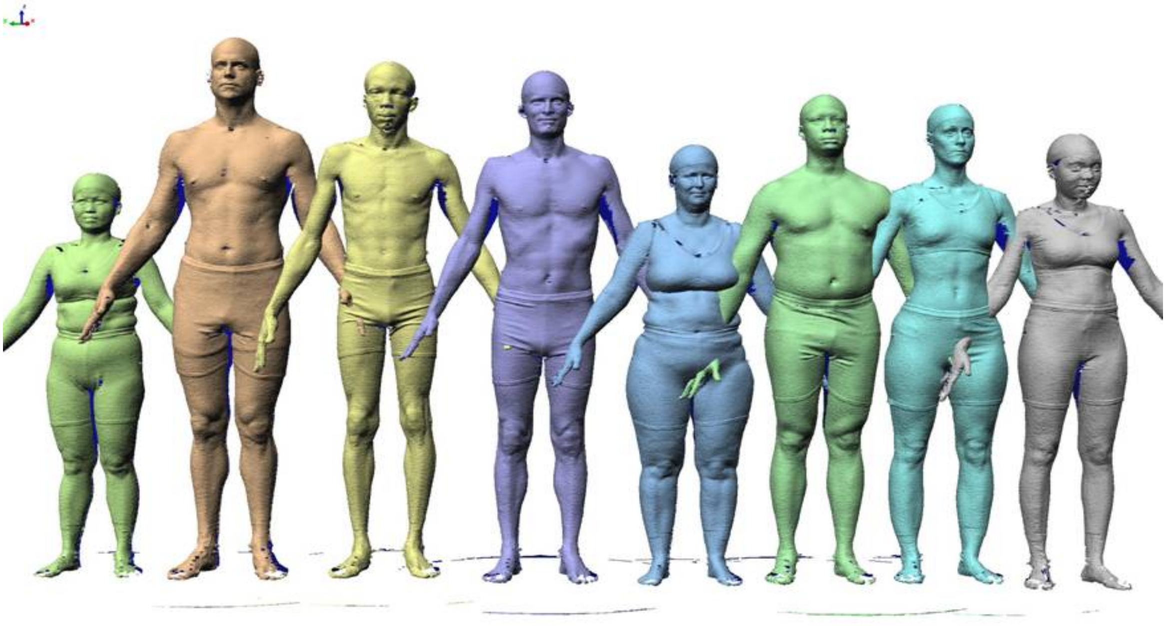


Figure 20: Cases for design, from 3-D CAESAR body scan data showing the range of human variability needed for design of a product – source Greg Zehner

By the use of these special extreme body measurement combinations that occur on real people, useful information about design problems can be tested and solved.

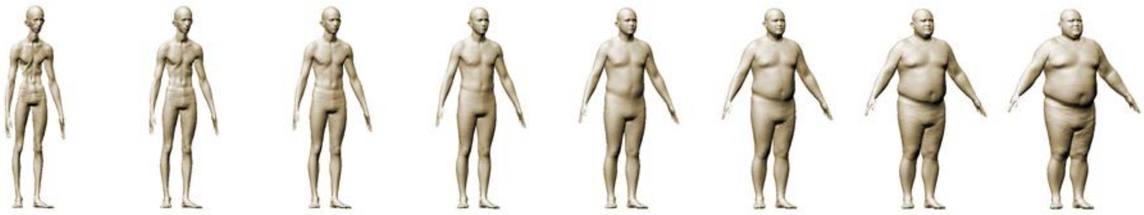


Figure 21 images extracted from an animated gif using CAESAR scans to illustrate a possible PCA1 – size component of males only. Female and outnumbered ethnic groups need to be characterized separately and the results compared. Source Shu

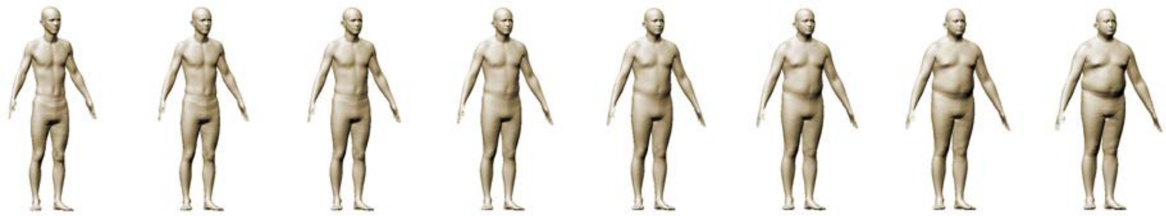


Figure 22 images extracted from an animated gif using CAESAR scans to illustrate a possible PCA2 – limb contrast – males only are shown. Source Shu

A visualisation for a PC1 (often related to size) is constructed in Figure 21 and emphasizes overall size. PC2 is usually related to a shape variable – in this case appears to represent a limb versus torso contrast. That is measurements relating to the contrast in limb length in relation to the body length. A visualisation is shown in Figure 22. Female and outnumbered ethnic groups need to be characterized separately and the results compared (Zehner 2001) to drop redundant cases and ensure minority groups are adequately represented. A method for using PCA with mixed samples is outlined by Zehner (2001). In addition, the summary of Zehner's report describes when it might be appropriate to use extreme values in addition to PCA thus simplifying the analysis. Underlying assumptions including that moveable components in the workspace can be adjusted in sufficiently small increments are also discussed.

The second section of this example occurs in the application of these cases during fit-mapping and is discussed in Section 5.3.2.

It should be noted that the statistical process for constructing PCA cases is specific to the product and the design issues (Hudson, Zehner et al. 2003, Robinette 2007). This is due to the fact that PCA results differ dependent upon the measurements used. The USAF cockpit example above used six variables that they had determined were relevant to their product and design issues. Those variables are not suitable for apparel and not necessarily for other types of vehicles or even non-ejection seat aircraft. Also, boundary cases are suitable for products that have continuous adjustability from small to large, but not suitable for things such as apparel that are adjusted using discrete sizes. Boundary cases for apparel would result in sizes for the extremes but nothing to fit the majority of the population who fall in the middle! <u>This is important because it means that good design requires raw data and product specific analysis.</u>

5.2.2 Other examples

An example of less effective design from Australia is shown in Figure 23 where meat workers of different body dimension are working side-by-side in an abattoir. This is just one of many examples where raw data was not available and the range of variability was *not* designed in from the start creating a problem that has to have an expensive retrofit to address the needs of the workers. Leaving it as is might result in work injuries.

Figure 23: A shared fixed height workstation in an abattoir that attempts to accommodate three workers of different heights.

In the absence of our Australian database it is common in Australia to use aggregate 1-D data because these are readily available from a range of different data sets printed in books (Peebles and Norris 1998, Pheasant and Haslegrave 2006). They are usually expressed as a percentile and a specific value for that percentile. Different values are provided for males and females. When the standing shoulder height is expressed as a percentile value, say for a 95th percentile male, there is an inherent assumption that this will be the representative shoulder height for a male that is also the 95th percentile for standing body height. The same assumption is applied to other 95th percentile 1-D data variables for males as it is for other percentile values for both genders. That is, this representation assumes that measures such as forward reach distance, seated knee height or even seated body height for a 95th percentile male will be the same for all 95th percentile males. This is simply not the case. Males who are the same body height will not have the same values for all other 1-D body segment dimensions. If this were the case, all people of the same height would have almost identical appearances and physiques. This failing in the interpretation of 1-D data is described earlier, in section 2.2.2 about 1-D data limitations, where we discuss how percentiles are not additive. It is also found in the earlier report, *Sizing up Australia* (2009).

In addition to these types of limitations with 1-D data, the availability of these references provides scope for interpretive error. To demonstrate the risks of misinterpretation a practical example can be drawn from one of the Chief Investigator's direct experiences in the simplistic use of 1-D data. In designing fire-fighting vehicles the anthropometric design benchmark was to identify the reach requirements for lockers and fire-fighting equipment around the perimeter of the vehicle. Traditionally this has used an average (50th percentile) Anglo-Saxon male height value. This not only under-represents the needs of shorter males when reaching upwards and for taller males when having to reach to lower levels around the vehicle, but provides no reference to the increasing numbers of females and persons from non-Anglo-Saxon backgrounds who are enlisting as fire-fighters. Such data do not identify how they might be affected by a vehicle designed for the average Anglo-Saxon male (Fitzgerald 2004).

In an attempt to rectify this, a second benchmark reference model was introduced by the designers – one representing an average female body height. This model was, as expected, shorter than the average male body height. While this provided some attempt to represent females in the design, it still failed to represent the broader population of individuals who are required to operate these vehicles under emergency, and often time-critical circumstances. While 1-D data can provide a starting place for this design it cannot effectively deliver the quality of results shown in the USAF example. The assumptions underpinning their use need to reflect the population of likely users; assumptions that can be very inaccurate. In this case, fire-fighters of both genders and varied ethnicity are more or less left out. The actual required raw data and information to effectively test this design *is not known*, so even if designers attempted to use newer methods to test the design they would not have the base line data to do so with confidence.

In this example the 1-D data has not been used appropriately for this design scenario because, as already outlined in Section 5.2.1, good design requires raw data and product-specific analysis – that is, the measurements used should be relevant to the design. Specifically the use of stature as a sole variable is inadequate to represent the range of tasks required to be performed by fire-fighters in the truck - overhead reach and other measures would have to be included. In this example the 50th percentile male doesn't represent the full range of possible workers. Section 5.2.1 shows that to achieve a user-centred, inclusive-design view where smaller people (primarily women) can be accommodated in the design approach, they must be considered as potential users. In addition, the correct method for use of data must be appropriate for the design - boundary cases developed and tested – not aggregate percentiles that are inadequate for the purpose.

5.2.3 Impact of design issues on work-related injuries in Australia

Work-related fatalities and total and permanent disablement (defined as "serious injury") can be the extreme outcomes of poor workplace design. In the 2000-2002 study of the causes of work related deaths "Seventy seven of the 210 workplace deaths (36.7%) definitely or probably had design-related issues involved" (NOHSC 2004). This report also describes that design-related issues possibly contributed to 50.5% of work-related fatal injuries and at least 30% of serious work-related injuries involving:

- all machinery and mainly fixed plant
- self-propelled plant, semi-portable plant and other mobile plant
- all powered equipment, tools and appliances
- ladders, mobile ramps and stairways and scaffolding.

The contributing factors in a number of these fatalities related directly to the use of plant where inadequate fit or absence of barrier protection across the expected range of use of the item was found to be the main source of risk and ultimately the cause of death. These examples included poor guarding design and people being able to access hazardous situations or positions (Driscoll, Harrison et al. 2005). The use of anthropometric data through a fit mapping process across all anticipated aspects of use of these items of plant may have resulted in a higher focus on user-centred design and ultimately a less hazardous design.

The more recent Safe Work Australia report on the cost of Australian work related injury and illness (Safe Work Australia 2012) highlighted that "the total economic cost for the 2008/09 financial year is estimated to be $60.6 billion, representing 4.8% of GDP for the same period".

Economic costing and analysis are not exact sciences and estimates are derived from multiple sources that may vary in their collection methods and definitions, so an attempt to attribute the cost impact of poor design on these fatality and injury rates has not been made in this report. However, at these levels the personal, financial, social and organisational impacts are likely to be high and warrant new strategies for design based improvements to reduce these levels of death and serious injury.

Anthropometry is not the only influence on better design of products; but it is a critical one. That is, it is necessary, but not sufficient. Examples of other influences are cost, profitability, aesthetics and meeting the design brief. However, the increasing legal requirement for designers, manufacturers and suppliers of plant to establish safe designs will create a greater need for the ability to define the population of users and create designs that use body size information about these users as key influences in the design process and outcomes (Safe Work Australia 2013). Anthropometry supplies this necessary information.

In the absence of ergonomists and designers seeking and using newer and more methods of applying body size data to understand the dimensional and functional requirements (often dynamic and not static) of those who will use or be exposed to these designs, the designer is left with an uncertain level of responsibility; an uncomfortable place to be in an increasingly litigious society (Veitch, Caple et al. 2009).

5.2.4 Summary

In summary, in applications such as design and assessment of workspaces the more advanced and effective techniques of design use a combination of 3-D and 1-D methods. Without the appropriate database Australia cannot develop applications like these for our population.

There are many good examples of the correct application of statistics based on CAESAR data. The high quality of the data and accompanying documentation has allowed the development of well-documented design applications. There are many applications and they range from the USAF cockpit example to developing 3-D statistical shape analysis tools, to the development of life-like apparel manikins for the apparel and medical simulation industries (Allen, Curless et al. 2003, Hudson, Zehner et al. 2003, Ben Azouz, Rioux et al. 2004, Anguelov, Srinivasan et al. 2005, Allen, Curless et al. 2006, Ben Azouz, Shu et al. 2006, Veitch and Robinette 2006, Xi, Lee et al. 2007, Cheng and Robinette 2009, Veitch, Dawson et al. 2011, Wuhrer, Shu et al. 2011, Wuhrer, Shu et al. 2012, Wuhrer, Xi et al. 2013).

For 1-D data – sometimes using the actual measurements is appropriate and sometimes using PCA might be appropriate and sometime both may be used in combination. For 3-D data – raw data might be in the form of pictures and 3-D body scans. These can be matched with the 1-D data to create cases. At this stage 3-D scans cannot be presented as meaningful means, standard deviations and percentiles in themselves, although tools are under development to make the scans more readily usable. 3-D scans can be compared using shape analysis tools and the next generation of digital human models (DHM) are under development; these are discussed further in Section 5.3.1.

5.3 Fit/accommodation mapping

5.3.1 Digital human models

Digital Human Models (DHM) are computer representations of humans used for characterizing the relationship between the modelled humans and the environment. Current DHM consider three aspects: size, shape and biomechanics. The human being is among the most complex systems in nature; therefore creating realistic DHM is a challenging problem. The key to building useful DHM is to create physically real models in terms of size, shape and functionality, but at the same time being computationally feasible. Two important but neglected aspects of current DHMs are: 1) the lack of fit or human/system interface measurements and 2) lack of data on the equipped or encumbered person. Not only does the human body have size and shape variability, but the way the body deforms when occupying a seat or doing different activities is also highly variable and for the most part, this variability is not measured or known so it is neglected in the visualization. In addition, apparel, particularly bulky apparel such as PPE and encumbrances such as a harness, backpack or shoes, can dramatically affect the space occupied, the posture, and functional performance, but the DHMs are formed from unequipped body measurements. If we don't know how the person sits in the seat, with what apparel, with what type of harness, if any, it is not possible to predict fit and reach with any kind of accuracy without measuring the interface and accommodation. These data must be collected in such a way that they are referenced back to the original baseline sizing survey data. The new capability of the 3dMD scanner might provide, for the first time, a cost-effective way to do this because it can capture the whole person in motion with and without different encumbrances. This section discusses the application of DHM and how to acquire the accommodation data required for validating it.

DHM can be created from 1-D data but these have the same limitations described in *Sizing up Australia* for 3-D data created from 1-D. These simplified shapes do not realistically represent the human body, which is a biological structure of complex form. Linear measurements alone have too many 3-D interpretations with no way of determining which interpretation is realistic. Current commercial DHMs do not come with verification data and are untested by their developers. Efforts have been made to "train" the 3-D models by forcing the reach data to match real data (see Figure 24) creating a "digital library" of real reach values in the context of the F-16 fighter plane (Oudenhuijzen, Zehner et al. 2009). This produced excellent results, reducing errors in the digital models but this is a "work-around" or stop-gap fix. Even with real scan data superimposed the DHM cannot be posed properly as the correct segments in the spine to allow the real shape to be replicated are missing. DHM need to evolve considerably before they can reliably represent real values.

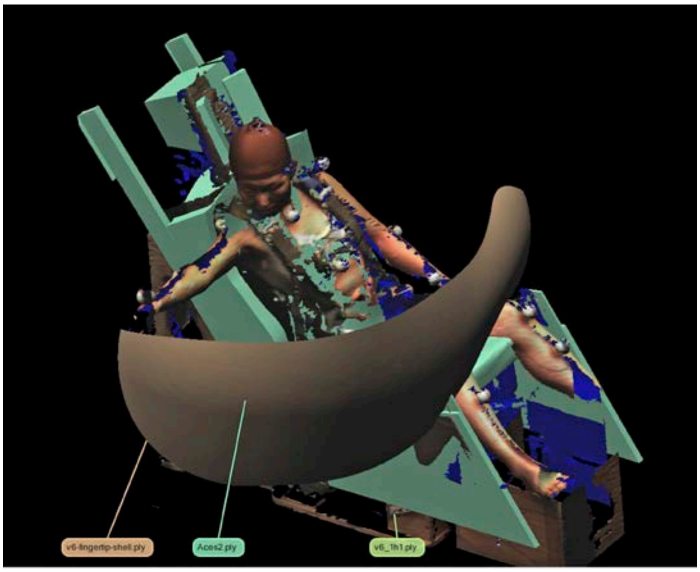


Figure 24: used a real case to validate the reach of a DHM built from 1-D data in an F-16 seat. Source Greg Zehner.

DHM's representing small subjects were found to have especially large errors (up to 95mm difference) predicting the subject's capacity to reach, when in reality the subject could not reach the controls. This error creates a situation where the anthropometry indicates a match between the work environment and subject when there is not a match in reality. This has consequences including two design related gaps:

- not altering the design to accommodate the maximum number of potential subjects, and
- creating a restriction on who can safely operate in the space in real life, or if not properly assessed, creating a potentially catastrophic consequence (work hazard).

3-D anthropometric data have brought new opportunities for creating realistic DHM, because the 3-D scans capture accurate and detailed shape information. Integrating 3-D anthropometric data into DHM will drastically improve the accuracy of the human shape model. However, raw scan data are seldom usable, because they are noisy and incomplete.

For example, due to occlusions in the scanning process, the data in the crotch and underarm area are missing. In addition, if dynamic and 3-D motion data are required they can be captured but only in comparatively low resolution (only a few dozen data points versus hundreds of thousands points per image). These techniques only capture the movement, not the shape change. If both are required the motion must be painstaking matched with high-resolution scan detail frame by frame. Considerable processing is necessary before the models can be imported into 3-D CAD systems. Currently there are no rapid acquisition, high-resolution scanners available, thus there is a technology gap. As soon as a scanner of sufficient quality becomes available then this capability will bring with it an increased cost-effective way to rapidly advance the quality of DHM.

In the past 15 years, much work has been done on building statistical shape models using 3-D data to characterize the variability in human shape. This is an effort to realize the full potential of the 3-D data. Tools drawn from computer graphics, computer vision, and geometry processing were used. A statistical shape model allows describing the shape space using a small number of parameters. One of the most effective approaches is to apply Principal Component Analysis to the 3-D data. PCA can reduce complex human shapes to fewer than 50 key parameters, with the majority of the variability represented by the first 5 components (Ben Azouz et al. 2004, Shu et al. 2013). Multi-Dimensional Scaling is also used for statistical shape modelling (Mochimaru and Kouchi, 2000), achieving similar dimension reduction.

Unlike statistics for 1-D data, where the variables are the linear measurements, the variables for the statistical analysis of 3-D data are the coordinates of the 3-D points. This requires that every model has the same number of points, and furthermore, for each point on a model, we need to know its equivalent points in all the other models. This problem is known as correspondence or surface parameterization. The goal is to create a point-to-point homologous matching across the population. An effective method for solving the correspondence problem is deforming a template model to each data scan (Allen, Curless et al. 2003). Often landmarks are used to guide the deformation. The results of this process not only establish the correspondence across the models, but also clean up the models, smoothly filling the holes and thus making them “watertight”.

Once a statistical shape model is built, we can use it to “learn” a map between the traditional measurements and the 3-D shape space. This map allows computing realistic 3-D models efficiently. Since the models are drawn from the space of human shapes, they represent statistically realistic humans.

One unique property of statistical shape models is that the shape parameters control directly the 3-D shapes. Using modern graphics hardware, efficient tools can be built to navigate the shape space and visualize the shape variability in an intuitive way (Shu et al. 2013). Representative or boundary cases can be generated by exploiting the relationship between the shape parameters and the traditional measurements, bridging the gap between 1-D and 3-D data (Meunier, Shu et al. 2009, Wuhrer, Shu et al. 2012). Here, the generated models (cases) do not necessarily correspond to any scanned human subjects, but they are real human shapes because the statistical shape model represents a continuous shape space and it can be sampled at any point.

The statistical shape models can also be used for comparing different populations, which is useful for making design decisions for products targeted to different demographic groups. This technique was used to compare Chinese and Caucasian head shapes (Ball, Shu et al. 2010).

The next generation of models that is under development will be able to accommodate shape data from real people but the models will only be as good as the input data. That is why a diverse range of high quality, raw 3-D, 1-D and physical landmarking/segmentation data is so important to the validity and hence usefulness of the tool. In addition, their usefulness depends on understanding and characterising the relationship between the models and the desired environment, including motion and encumbrance. It is not sufficient to know how they might be aligned – to have confidence the designer must be able to measure how they *are* aligned (Robinette, Vannier et al. 1997). This needs to be quantified by fit-mapping.

5.3.2 Fit-mapping

Fit-mapping is a process that characterizes the fit relationship between the product being tested and its target population (Choi, Zehner et al. 2010). For apparel or worn products a goal of fit-mapping is to provide design guidance that in the end enables the streamlining of sizing, dropping sizes where there are overlaps, creating sizes when they are missing for segments of the user population to improve the accommodation range, as well as providing design and reshaping recommendations (Robinette and Hudson 2006). An outcome of fit-mapping is to develop a sizing chart or size roll that assists people to identify the size that will most likely fit them. The use of fit-mapping can have profound effects on sizing resulting in significant production and inventory cost-savings as shown in Figure 25.

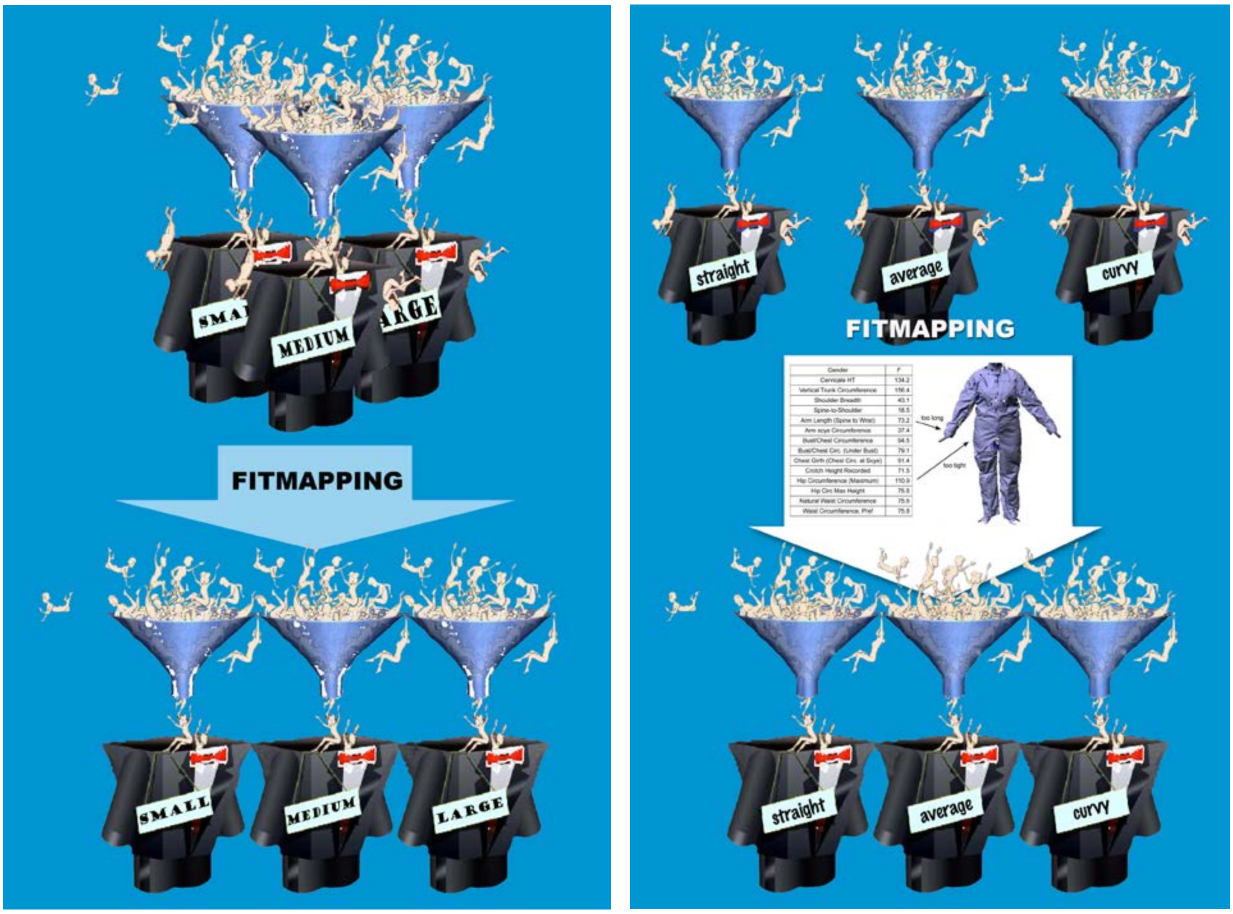


Figure 25: sizes can be overlapping (shown on left) and missing (shown on right).

The goal of optimal sizing is to fit the maximum number of people into the minimum number of sizes. This minimises the stock that needs to be kept and improves efficiency as well as making it easier to find the right size. Sometimes this doesn't happen in an optimal way. The same people could be funnelled into more than one size which is confusing for them and costly for the holder of inventory. This is known as overlapping sizes. The solution is to make the size funnels further apart, reducing the number of sizes. See the left set of funnels in Figure 25 at the top. So, after fit-mapping the funnels are wider spaced - fitting a broader range of different sized people with the same number of sizes – see Figure 25 at the bottom.

Alternatively the funnels could be too widely spaced, see Figure 25 on the right side at the top. This is a problem of missing sizes or possibly missing body shapes. Here women who have an average hip –waist ratio may be accommodated (sometimes in overlapping sizes) but women of different body proportions, waist to hip ratio of “straight” or “curvy” might not be catered for at all. Ideally after fit-mapping the missing sizes would be created accommodating many more women – see Figure 25 on the right side at the bottom.

These problems can occur in isolation or simultaneously.

Fit-mapping extends the process of fit-testing to make iterative design improvements using traditional methods augmented with 3-D scanning. It uses a functional and measurable definition of fit for each item so even non-experts can perform these evaluations with the right methods and tools (Choi, Zehner et al. 2010). At the moment this requires human subjects who fit and who don’t fit to define the boundaries of fit and measures relevant to fit. The population data is needed for determining the range of sizes and adjustments once the fit range is known. Population data should represent the broadest variability (even broader than the target population is okay) (Robinette and Hudson 2006). One goal for a future study might be to have enough basic information about fit to create guiding principles to allow Digital Human Models to predict fit (CODATA 2013) and share this information but at the moment this has not been successfully done.

US Navy example

A famously successful example of fit-mapping was the US Navy women’s uniform study (Mellian, Ervin et al. 1990) which resulted in reshaping recommendations that reduced the number of major alterations from 75% to less than 1%. In addition it recommended dropping overlapping sizes and introducing missing sizes for different hip-waist ratios improving the accommodation rate of the women from 23% to 99%, with the same number of sizes – similar to that shown in Figure 25. Obviously this has a large financial implication; especially since the women had to pay for their own alterations.

Without fit-mapping the designer has access to limited information about the body’s surface, that it, about shape and size, making it difficult to test for error or determine which of the multiple solutions is best. Anecdotally, people complain about trying on garments labelled with the same size but that have decidedly different shape and fit.

Other examples

There are also documented case studies about the design of personal protective equipment (helmets and night vision goggles) that describe how design errors occur and what happens as a result (Robinette, Vannier et al. 1997). A summary of work done over a 5-year period, 2002-2007, by the USAF which documents anthropometry, methods for measuring the quality of fit and methods for relating the two has been published by Robinette (2007). This document helpfully has a chapter on transferring anthropometry out of the lab and gives summaries of further case studies.

Cockpit example – Part 2

For cockpits or built environments Zehner (2001) refers to fit mapping as accommodation mapping. The use of PCA for case selection was outlined in the Cockpit example – Part 1 in Section 5.3. Once the 8 boundary cases were identified they were used to select human subjects for cockpit accommodation mapping. The accommodation mapping was used to produce tools including a body clearance/size requirement chart to identify the possible career track of a potential recruit based on their individual measurements.

Live subjects were selected to represent the cases and tested in situ against performance criteria. Criteria included escape clearance, minimal operation clearances including ability to reach emergency controls and external visual field. Real people were used as a type of measuring tool in the cockpit and used to map safety in various environments to the body size space. This information was then used to create a pilot career path tool identifying the body sizes and proportions that could safely operate the various aircraft in the career pipeline. Failure in any one of the accommodation criteria could make the pilot unsafe to fly an aircraft (Zehner and Hudson 2002).

The tool allows an individual person's body dimensions to be interpreted in each individual aircraft in terms of safety/risk of injury. Figure 26 shows for an example. An accommodation fail is marked in red, a pass in all accommodation criteria is shown in green and borderline (requires further testing for that person) is shown in yellow. So if a potential recruit were measured and they have an eye sitting height of 30.79 inches, Buttock-knee length of 39.92 inches and arm measurement of 63.35 it could be seen that although they could safely fly the fighter plane, F-117 plane they would be unable to safely fly the required training aircraft T-38. A green path for a recruit means they can safely work in all the environments required to gain their skill set (learn to fly). Any red areas represent a blockage where it is *not safe* for various reasons. So it is immediately apparent that this individual has only one green path where body measurements show they can safely train and perform the task they are trained for.

This chart has two major economic advantages. First the air force can see they need to design the T-38 differently in the future so all future pilots who could safely fly the F-117 can safely train, and second, they avoid mishaps and accidents which cause injuries. Also with a good database they not only can keep their existing workforce safe from design related accidents but also know how to redesign their planes to have the maximum accommodation thus fitting the most people for the future.

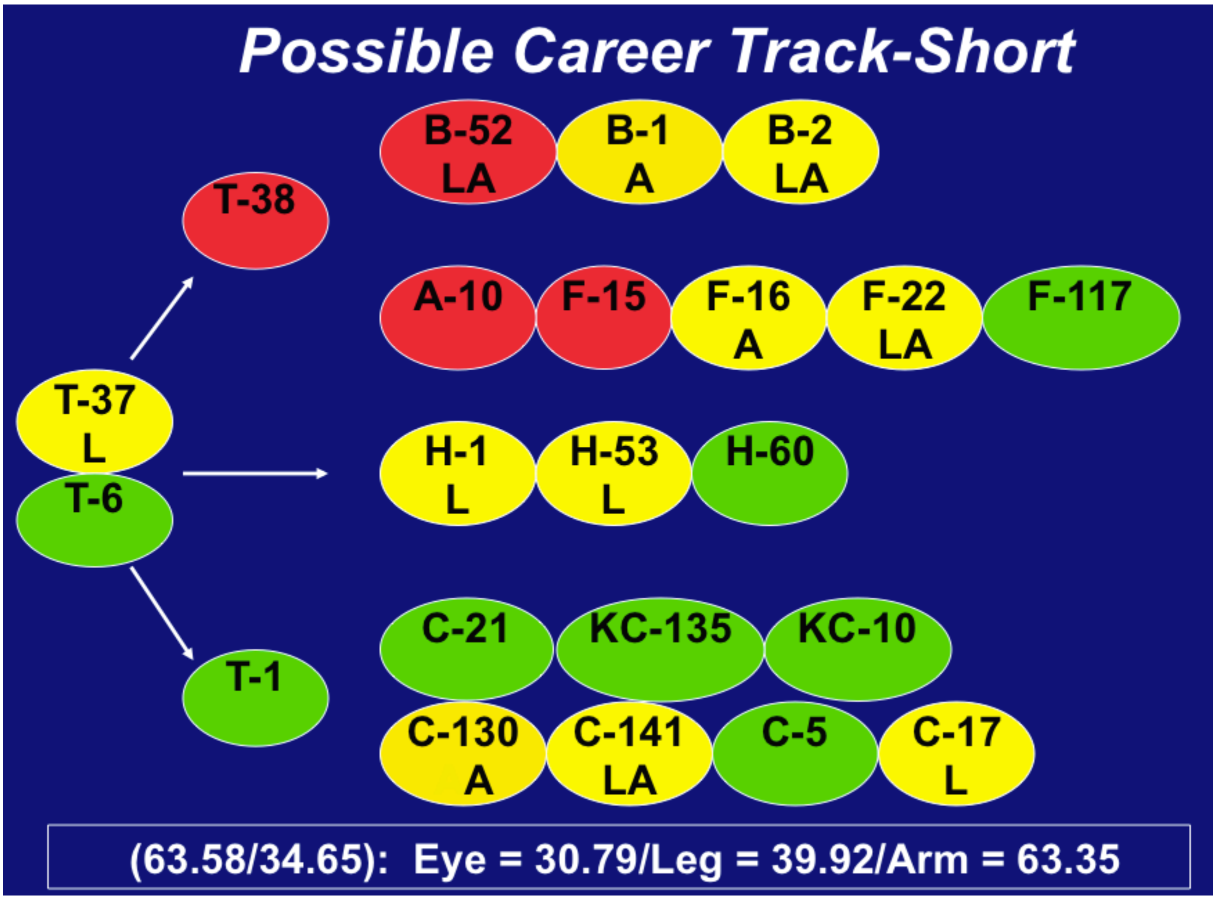


Figure 26: shows aircraft arranged in order of mandatory training left to right. Red indicates this person is unsafe to fly, green is safe to fly and yellow means that person would need an additional assessment before being judged safe or unsafe to fly that plane. H = helicopter, T = trainer, F = fighter jet, C = cargo plane. The number is the identity of the aircraft. Source Zehner

In this example very cost effective tools were designed to avoid accidents and improve future design. This example of very effective use of anthropometry and fit-mapping is just one example of what could be achieved in the broader context of occupational health and safety.

5.4 Conclusion

> Task performance or the potential for injury (either acute or by repetitive stress) may be impacted by how well a person is accommodated by his or her work environment or life support equipment. (Robinette 2007)

Using the knowledge of the correct statistical analysis tools and processes to solve design problems, we need to design an Australian body survey to provide us with the most appropriate 3-D and 1-D raw data for the future. This will also require education to transition from ineffective practices to better ones and in the process use the new capabilities. It is easy to collect anthropometric data, but it is not easy to balance all these needs and to design a survey to collect useful anthropometric data that fulfils future requirements. That is why iterative testing of the survey method is needed to fine-tune it in conjunction with the stakeholders' input. The design needs to be flexible to allow for future applications of the next generation DHM and fit-mapping.

In this section we demonstrated that a survey conducted in the right way will enable better design and safer and healthier work places and practices.

6. Technical detail in methods - body sizing surveys

6.1 Survey methods

6.1.1 Population sampling strategies

ISO 15535 General requirements for establishing anthropometric databases, Geneva (International Standards Organisation (ISO) 2012), pp.3 recommends sampling techniques described below

> 4.3 Sampling techniques
>
> 4.3.1 The demographic characteristics of the population shall be indicated as clearly as possible in the report. In the event that the population is divided into several subgroups, e.g. exam location and dwelling location for either sampling or statistical reporting, this shall be stated in the report.
>
> 4,3.2 It is desirable that random or stratified random sampling methods be used. However, if this is impossible, the report shall indicate the sampling method used.
>
> 4.3.3 It is desirable that the number of subjects needed for a database be established using a statistical power formula based on the accuracy of results desired by the investigator (see Annex A). However, in reality, the selection of subjects is often influenced by various factors, such as population size, number of people who agree to participate, and cost and period of time required for the investigation.
>
> From annex g
>
> G.2 If new data are required, determine an appropriate size and develop a sampling strategy.
>
> For example, an appropriate stratified sample might include strata such as geographic area, age and sex.
>
> Considerations should be given to sample acquisition methods, in order to ensure a representative sample in each sample stratum.

6.1.2 Sample size

The method required for estimating the number of subjects needed in a sample is summarized in a straightforward and detailed manner in ISO 15525: 2012 Annex A. In conclusion, the minimum number of randomly sampled subjects, N , needed to ensure that a database 5th and 95th percentile estimates the true population 5th and 95th percentiles with 95 % confidence and a percentage of relative accuracy is calculated using the following formula:

$$n \geq \left(1{,}96 \times \frac{CV}{a}\right)^2 \times 1{,}534^2$$

where

n	is the sample size
CV	is the coefficient of variation
a	is the percentage of relative accuracy desired

Example:

	Mean	SD	CV
Stature	175,6	6,7	3,8
Chest circumference	99,1	6,9	7,0
Shoulder (bideltoid) breadth	49,2	2,6	5,3

Table 5: examples of mean, standard deviation and coefficient of variation for 3 measurements.

Entering this data into the above mentioned formula will result in the following:

Stature	$N = \left(1,96 \times \frac{3,8}{1}\right)^2 \times 1,534^2 = 130,5 = 131$ **subjects**
Chest circumference	$N = \left(1,96 \times \frac{7,0}{1}\right)^2 \times 1,534^2 = 443,0 = 443$subjects
Shoulder (bideltoid) breadth	$N = \left(1,96 \times \frac{5,3}{1}\right)^2 \times 1,534^2 = 253,9 = 254$subjects

Table 6: Minimum sample size for 95 % confidence and 1 % relative accuracy

CAESAR used a stratified sampling plan with equal sample size in each cell according to the recommendations of ISO 15535. (Robinette, Blackwell et al. 2002)

Strata might be by age, gender and ethnicity.
For example:

3 Age Strata	**18-29,30-44,45-65 years**
2 Gender Strata	Male and Female
3 Ethnic Group Strata	White, Black, and Other

Total = 3*2*3=18

Table 7: shows an example calculation for strata used in CAESAR

The total number of subjects is calculated by multiplying the number of sampling cells (strata) by the number of subjects in each cell, so for example is the total number of sampling cells is 18 and if the number of subjects in each cell was 188 then the total number of participants in the survey would be 3384.

6.1.3 Quality of Traditional-style measurements

Anthropometrists in the project should have appropriate training to minimise any inconsistency in the measuring techniques employed by the team. Due to the nature of anthropometry and measuring something as changeable as a human body (e.g. breathing and posture variations) there are acceptable levels of precision for most anthropometric variables used to evaluate performance, both intra and inter measurer. These are described in an excellent chapter written by David Pederson and Christopher Gore titled, Chapter 3 Anthropometric Measurement Error (Pederson and Gore 1996) that outlines the measures of precision and reliability – technical error of measurement (TEM) and intraclass correlation coefficient (ICC). This report does not seek to repeat this work but instead recommend that the expert anthropometrists employed in a future project be trained and tested according to the quality guidelines outlined in the chapter.

In addition the method of scribe and measurer working together is described on p28 (Norton, Whittingham et al. 1996), the anthropometric equipment p29-32 and standardised ways of holding the equipment etc should be followed.

Although this anthropometry comes from a different field – sports science – it is appropriate to use these guidelines because the technical methods for collecting the traditional style measurements are the same in both fields. The actual measurements collected may not be the same and the applications will be different. The measurements will be fit for purpose and appropriate to engineering anthropometry and will be decided in conjunction with the stakeholders in the future survey.

There should be additional systems in place to improve quality. For example in CAESAR all data were recorded on paper as well as on the computer. When the data were entered in the computer it would beep when an outlier appeared to alert the investigator about any potential errors. There was a system for determining the range of outliers based on previous surveys. The 3-D data files were checked at the final measuring station to ensure they were correct and for the right subject. The 3-D land marking had a heuristic checking system. There was a final check of all traditional style measurements (including scan extracted measurements) using a regression outlier analysis. For a full description of the statistics used see Chapter 11; Experimental Design (Robinette, Blackwell et al. 2002).

6.1.4 Quality requirement for purchasing of Scanner (Hardware)

At the moment there is no ISO standard to define the terminology and methods and validation of 3-D scanner hardware or software. However there is a New Working Group NWG1 for ISO 159 assigned to develop this – see Figure 10. In the meantime a proposal was put forward to the ASTM by Kathleen Robinette in 2005. A set of purchasing criteria was developed to select and test the whole body scanners using the following requirements:

- safety: eye and skin safe,
- high speed: avoid movement effects,
- data output type is point cloud: allows viewing and calibration of raw data,
- data output format in public domain (not proprietary): allow freedom to choose a third party software if required,
- resolution of 1mm in all directions (or similar): closeness of 3-D points to each other,
- precision: high accuracy of 3-D points, - ease of calibration: allows adjustment of raw data to fine tune accuracy,
- field of view at least 2m x 1.5m x 1.2m or close: accommodates large subjects and seated scans
- good surface coverage: avoids holes in the field of view (minimal occlusion),
- good landmark recognition capability: ability to recognize flat markers, and
- warranty and support.

(Robinette 2005)

A protocol for evaluating the accuracy of 3-D body scanners and software should be followed. At the moment there is not an ISO Standard for this, although this is new work item currently underway in ISO159 strategic plans, see Figure 10. Until this becomes available test object/s to make objective and standardised comparisons of quality parameters should be used (Kouchi, Mochimaru et al. 2012).

In addition, overall features such as portability and durability might be considered.

7. Lessons learnt from past surveys

The majority of body sizing surveys that have utilised 3-D scanning that were found in the literature focused on the method and results. Only one publication was found that reflected on the process and outlined things that worked well and things that could be done differently (Robinette and Daanen 2003). This reference provides an honest appraisal of how the CAESAR process went, with no attempt to conceal any of the shortcomings or pitfalls. It provides practical and detailed insights for those planning to conduct a similar survey.

With Dr Robinette being part of this project team it was also possible to interview her directly about these experiences. Her elaboration on the importance of testing all elements and phases of the survey and measurement processes and planning for errors and mishaps to occur is an invaluable contribution to this review and project.

In addition, the ISO standards, in particular ISO 206585 (International Standards Organisation (ISO) 2010) were found to provide clear definitions to support the preparation, testing phase and delivery of a survey and the development of an anthropometric database.

7.1 Using a systems engineering approach

For the complex and large scale CAESAR project, much of the success of being able to collect 3-D body scan and traditional measurement data for over 4,000 subjects with more than 13,000 scans, using 2 different types of scanners in 3 different countries stemmed from good planning and organisation and the early and ongoing feedback from stakeholders and those working within the project (Robinette and Daanen 2003).

The CAESAR study took a systems engineering approach to the development, preparation and delivery of this sizing survey and the subsequent consolidation and storage of the data - and the project succeeded. “Systems engineering is an interdisciplinary field of engineering that focuses on how to design and manage complex engineering projects over their life cycles” (Wikipedia 2013).

The implication for an Australian sizing survey will be to utilise a systems engineering approach to maximise the likelihood of effective development and management of the survey as a complex project with many elements that, if not well managed, may jeopardise the project’s success. Success would be defined by how useful the data are to solve engineering anthropometric problems – how fit for purpose the data are? The project would need to assemble a multidisciplinary team at the outset and adopt this approach for the planning and co-ordination of resources and logistics, working with stakeholders to determine the measurements to be obtained and to test and finalise the measurement technologies and methods. Risk management principles would also be applied to establish effective management systems and methods to run the Australian Body Sizing Survey project.

7.2 Developing and maintaining quality criteria for the survey method

The quality and therefore accuracy and usefulness of traditional and 3-D scanned data is paramount to the ability for the data to be used as a predictor in engineering designs. The provisions for obtaining high quality and accurate traditional data has been clearly defined in Anthropometrica, A textbook of body measurement for sports and health courses (Pederson and Gore 1996). This should be used in conjunction with AMI to build or preselect the measurement definitions (Ennis and Robinette 2011) and WDN to provide a database system for the functionality of searchable online and comparability with other datasets (Cheng, Robinette et al. 2007).

For 3-D scanning, the CAESAR project used a number of quality control strategies to minimise error (Robinette, Blackwell et al. 2002, Robinette and Daanen 2003). These included:

- Checking that the electronic file data completeness and assignment to the correct subject at the final data collection station to confirm that the required scan and data had been satisfactorily completed.
- Error trapping the subject landmarking process by issuing landmark stickers in a roll that had the exact number of landmarks needed. Having too few or spare stickers at the end of landmarking would highlight that an error had occurred which would prompt the assessor to find and fix the error.
- In two of the three CAESAR countries the scanned images of a subject were checked within one minute of the scan to ensure they were of good quality and all of the landmarks were visible. If the scans were not good enough then they were repeated until the required quality was obtained.
- An audible beep being generated by the computer when a value that was beyond the range expected for that variable was entered.
- Subjects carrying a clipboard with records of their traditional measurements from station to station in addition to these measurements being recorded on a database so these were available if the computer system failed.

These examples reflect the highly proactive approach that was used to prevent or limit errors across the survey (Robinette, Blackwell et al. 2002).

Part of a systems engineering approach will require quality, safety and accountability measures to be clearly defined against which project management and performance would be measured. A number of these provisions are described in the ISO standards. However, other approaches to prevent or limit error at the measurement and recording phases would need to be bought to the Australian Body Sizing Survey. These approaches would establish systematic training and assessment requirements and criteria for assessors as well as establish smart quality control provisions within data recording systems.

With regards to quality criteria for measurement technologies and obtaining measurements there are currently no standards for 3-D body scanning technology, both hardware and software, and a buyer beware situation prevails. The Australian Body Sizing Survey will need to develop performance criteria for scanners and any scanners being considered for use within the survey would need to be tested against these criteria. It will not be sufficient to rely on manufacturer specifications and promotional material (Robinette 2005).

7.3 Process of selecting the measurements to be obtained

7.3.1 Early engagement of stakeholders to determine the data that will be captured

The CAESAR project engaged stakeholders at the outset of the project. These stakeholders focused on end users of the data and they were given a significant capacity to define their needs and preferences to ultimately define the scope of the project and determine the range of measures that would be obtained. This engagement was fundamental to the success of the project as demonstrated by the original plan to scan only the traditional seated erect pose when the industry wanted a natural seated pose. The industry partners helped to define the natural seated pose and it was substituted for the traditional pose. A second seated pose was added to get additional body surface coverage for modelling after the industry made it clear that most work is done while seated so for built environments seated poses are more important than standing.

This approach seeks to not only ensure that the survey obtains data that will benefit the ultimate users of that data but establishes a platform for stakeholders to provide financial support for the project and maximise its chance of delivering good quality and relevant data.

A priority requirement for stakeholders was data quality. In 2001 a cost benefit analysis for an anthropometry survey was conducted and a survey of stakeholders found that the over whelming need from sponsor stakeholders was for the data to be accurate (55.2 % rating) and then be relevant to their needs (26.8% rating) (Robinette 2004).

The table below describes the possible stakeholder relationship within the components of an Australian Body Sizing Survey. See Figure 2 for a pictorial overview of the interactions.

	Data: 1-D, 2-D, 3-D	Database System	Applications	Consumers
Sizing Survey Components	Anthropometry - raw data	Tools – statistics, queries, visualisations, digital human models	The way data are used: Sizing, design, simulation, Standards and Guidelines	Consumers of the products
Stakeholders	HFESA ABS NMI Scanner manufacturers	Tool developers Universities	Standards Australia Government Industry Unions Service providers	Workers Users of built and worn products

Table 8: Possible stakeholders by category

A range of different stakeholders will be interested in different components of the survey from the raw data to databases of that data and applications to use that data to achieve better designs and ultimately the consumers of those designs. However, early and ongoing engagement will be vital to ensure that the survey is run to achieve best outcomes for all stakeholders.

For any large scale survey, particularly when stakeholders and any sponsors seek to have data collected that is of most interest and use to themselves, input from these groups are likely to be critical to the success of achieving funding, identifying or confirming the data that is to be gathered (Robinette and Daanen 2003) and operating the project.

7.3.2 Minimum measurements to be obtained

The CAESAR project obtained 99 1-D measurements. Forty from traditional measurement methods and 59 from scanned methods (Robinette, Blackwell et al. 2002). It also obtained complete 3-D copies/models of the subjects in three poses, one standing and two seated and 3-D coordinates for 73 landmarks from the standing pose and approximately 50 landmarks from the first seated pose.

The number of 1-D measurements obtained was related to the partner requirements. Many more could have been calculated and some have been extracted from the scans after the survey ended.

A key determinant of the number of measures that can be obtained will relate to how long the subjects will be prepared to participate in the process. The CAESAR project undertook pre survey questionnaires to establish the likely acceptable period and this was set at one hour. If the subjects for the Australian Sizing Survey, via a pre survey questionnaire, indicated a likely willingness to participate for a longer period then a larger number of measurements may be possible. In addition, if the overall efficiency of subject throughput and maximising the number of measurements derived via the scanned data could be optimised, then this might also enable a greater number of measurements to be obtained with an hour or make it possible to involve the subjects for a longer time period, if identified via pre survey testing.

An ultimate goal of the Australian survey would be to maximise the possible measurement outputs from the raw 3-D scanned data, to minimise the number of traditional measurements that need to be taken and maximise the overall efficiency of the survey while optimising quality and accuracy.

With this in mind the relationship between stakeholder engagement to establish the measurements sought by users and the overall capacity of the survey to obtain a finite number of measurements will need to be incorporated into the stakeholder process at a very early stage. Once the total number of measurements possible is established the process would then consider and include measurements on a priority basis according to stakeholder needs, any natural overlap with the minimum recommended measurements as specified in the ISO and any need or preference to include all ISO recommend measurements so the Australian data fully corresponds with the other data sets being established internationally that are in line with the ISO recommendations.

In addition the needs of the anthropometric data application developer will also need to be included in these considerations. Their needs are likely to vary for industry based sponsors but will need to be included and balanced relative to prioritisation of all stakeholder requests for specific measurements. There needs to be a fair and clearly defined method to make sure each stakeholder is accommodated. For example each stakeholder might get to include their top 3 measurements.

These ISO standards also define baseline demographic data which could be included within the Australian survey so they correspond with other ISO anthropometric data bases.

7.3.3 Rationalisation and justification of measures and landmarks

The measurement process that needs to be conducted within a finite period for each subject, installs an inherent limitation on the ability of the project to capture as much measured data as all stakeholders are likely to want (Robinette and Daanen 2003). For example, in the CAESAR development and testing process the time taken to obtain 90 measures was greater than an hour, a survey duration target that had been identified by surveying prospective participants. This number of landmarks needed to be revised down to 72 so the survey period matched the one hour window.

This reality requires the survey method to be designed to maximise the efficiency of subject throughput with the range and number of measures that can be obtained. As a result there will be a need to rationalise and justify the measures that will be obtained in the survey and stakeholders will need to be made aware of this at the outset to ensure that realistic expectations are established and maintained.

A method of managing this process will be to establish a prioritisation and justification table for measures and, consequently, landmarks. The table below provides an indication of how such as list could be used when establishing landmarks.

Landmark (number & name)	**Measurement (number & name)**	**Geometric or palpated**	**Why is it needed? (examples)**	**Priority rating (1= highest, 5 = lowest)**
1 – top of head	1 – Standing head height	geometric	For ISO comparison	1
23 – widest point across the hips	23 – Hip breadth (sitting)	Palpated (flat sticker)	For CAESAR comparison	1
31 – top of femur	31 – Knee height (sitting, right)	Palpated (raised sticker)	For segmental axis system	2
etc	etc	etc	etc	etc

Table 8: shows example of landmark justification table

The rationalisation reference would be progressively developed during consultation with stakeholders and preparation for the survey.

7.4.4 Importance of having a pool of trained and competent assessors

Over the measurement period of the project the needs and health of project assessors will change and may require them to withdraw or not be available. A pool greater than the actual number of assessors will be required to accommodate these changes in availability. For an Australian sizing survey, provision may need to be made to employ assessors among different geographic locations, states, particularly if this supports the maintenance of a high level of quality of the data generator by the assessors.

The training of the assessors is vital to ensure that a high level of intra and inter-rater (sometimes caller interobserver) reliability is achieved. As outlined in the following section, the training of assessors in all aspects of their assessment work and, in particular their inter-rater reliability will need to be assessed. Interobserver error has been studied and there are generally acceptable values of repeatability of different measurements (Gordon and Bradtmiller 1992) that the team can test themselves against. In addition there are standardised procedures to detect and minimise potential errors.

Once poses are decided the positioning of subjects needs to be practiced, so that positioning is exactly repeatable each time.

7.4 Development and testing of the survey method to establish the survey design parameters

7.4.1 The need to test elements of the method to finalise them

A systems engineering approach to the development of the survey method should be applied.

A wide range of elements of the survey method would need to undergo a cycle of testing and retesting where required to consolidate and finalise them (Robinette and Daanen 2003, International Standards Organisation (ISO) 2010, Robinette, Veitch et al. 2013). These would include:

- Data features:
  - Traditional versus scanned measurements.
  - Data capture, validation, storage and back up processes.
- Subject features:
  - Orientation and postures within the scanner volume.
  - Garment sizes, design, material, and colour.
  - Landmark marker size, shape and colour
  - Accommodation within the testing facility, including any subjects with special needs.

- Scanner hardware features – see 6.1.4, but consider the possibility of a very large scan volume for alternative postures and possible 4-D data gathering, portability (tear down and set up time), durability during transport and use and calibration methods and time. Physical space required to accommodate the scanner – check the ceiling height - if the scanner is tall or if the scanner would fit in most normal height rooms.
- Scanner software features, including calibration, accuracy and precision, capacity to see manually placed landmarks, automatic landmarking and measurement extraction.
- Pre - Subject questionnaire
  - Incentives to participate.
  - Acceptability of scanning.
  - Tolerance period (preferred and maximum) for participation at the survey site.
- Logistics:

- o Time taken to construct and deconstruct the scanner at each location
- o Space planning, scanner and change room locations
- o Subject flow from location to location within the survey site, “staggering subjects” see Figure 27
- o Subject throughput and any threats to smooth transition.
- o Team composition (number and genders of team members)
- o Competency requirements for team members for subject management, measurement, landmarking and general tasks.
- o Number of landmarks able to be placed in a certain time
- o Number of traditional-style measurements able to be taken in the time allowed
- o Number of scans - postures
- o Quality control procedures for the survey process and processing and managing data. These would include measuring the inter-rater reliability between team members for both traditional and body scanning measurement methods.

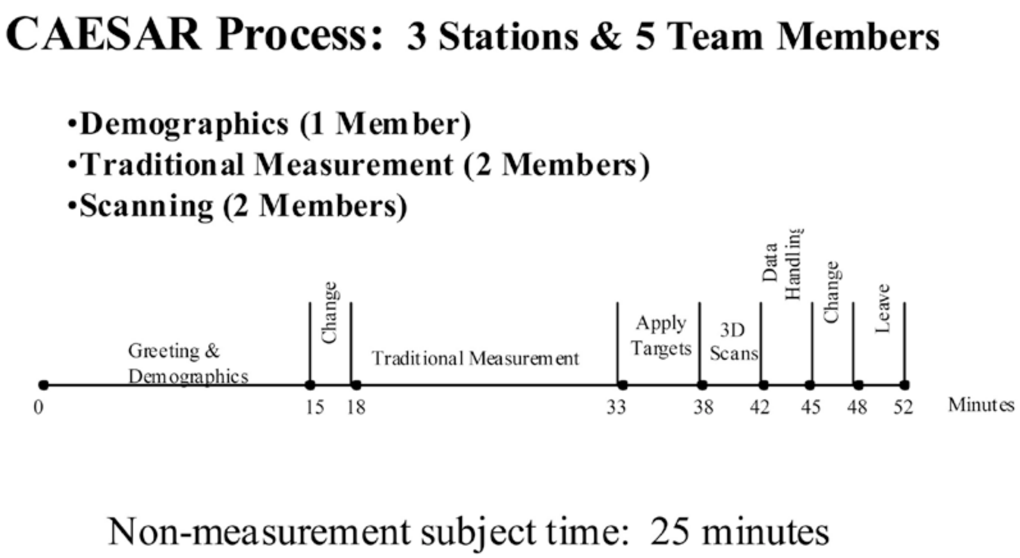


Figure 27: shows the flow of subjects through the different measurement stations and the time frames. Source Robinette

7.5 Population sampling to obtain subjects

ISO 15535 recommends random or stratified sampling. The detail is set out in 6.1.1 of this report.

CAESAR used stratified sampling – see Table 7. In addition to the strata similar to that described in Table 7, height, weight, education and within country geographic region should also be monitored to ensure that the volunteers were roughly matched to the civilian populations as measured in a recent census studies.

Because of the stratified sampling strategy, the overall mean values do not accurately reflect an accurate mean for a given country. In order to achieve a representative sample for a country, the data have to be weighted using the census data (Blackwell, Robinette et al. 2002).

This is explored in more detail in the companion document to this – Chapter 3, Section 6.2, Sample size for the Australian context.

Alternatively random sampling could be used. But this will require many more subjects overall to get the minimum required minority groups.

CAESAR project had some difficulty recruiting enough subjects to fill their minority ethnic groups strata. For this group a financial incentive had to be offered to establish a sufficient sample level and there were advertisements placed written in the language of the group needed –for example an ad placed in Chinese in a local Chinese targeted publication (Robinette and Daanen 2003). While this strategy help to achieve this outcome, this created an unnecessary project delay.

The key learning here was that advance surveying of the targeted sub groups within the broader sample group should help to identify these types of likely responses so plans to work around these limitations to increase response rates across all subgroups is achieved. This should help to keep the survey period for each location on schedule and avoid additional costs and use of resources to have to extend the measurement period to obtain sufficient data to represent specific sample sub groups.

8. Conclusions and implications for an Australian Body Sizing Survey

It is fortunate that in the development of the parameters for an Australian Body Sizing Survey there is an abundance of experience and supporting written reference material that helps to plot the direction of planning for a survey, and these are summarised here.

A combination of ISO standards and the recorded experiences of others provides detailed information about the range of data that can be collected and how it can be collected. However, the ISO standards as a single set of references, while necessary are not sufficient to guide and support the process. The feedback from projects completed in other nations about how their surveys have been conducted and progressed is vital to our efforts and will enable us to limit errors and pitfalls in the Australian survey. It will mean we will be able to develop criteria and standards to fill any shortfalls in the ISO standards. This would include developing criteria for body scanners, a missing link in the current equation for scanning surveys.

3-D scanning provides unprecedented access to data that is collected faster but whichever methods are used they should be tested in line with the recommendation in ISO 15535: 2012. Any measurements that cannot be collected with sufficient quality from 3-D scan extraction methods should be collected using traditional-style measurement methods. For example, using a tape measure to obtain circumferential measurements around soft tissues is important for several reasons. Firstly, for comparability reasons with past surveys. Secondly, because of occlusion where accurate values cannot be obtained from the scanned data, such as a waist with fat folds that prevent an accurate waist circumference being obtained.

Traditional measurements should comply with quality standards of inter and intra-rater reliability. Where necessary, expert anthropometrists should be used to identify and mark anatomical landmarks and obtain measurements. The emphasis should be on the quality of data and its future application. An Australian Body Sizing Survey future survey can learn from the lessons of previous work, in that that an enormous amount of work can be generated attempting to fix problems caused by the collection of poor quality, or limited scans as these create barriers to building high quality applications. These limitations can be avoided by Australia.

Stakeholder involvement is essential to define the scope, final method and hence resources required for a survey that delivers stakeholders needs. Once stakeholders have been engaged and consulted and a resulting list of measurements drawn up, a **trial study** needs to be conducted with the proposed hardware and software. This would be used to test accuracy and consistency in using 3-D scanned data, manual or automated measurement extraction and, when these cannot be obtained, traditional style measurements for some of these dimensions. Pilot testing should cover all aspects of the survey in line with a systems engineering approach.

The availability of 3-D data introduces new requirements to validate data as it is obtained and to process it according to quality standards. It is important to have a good understanding of the limitations and how to manage risks when planning so that good outcomes can be achieved. ISO 20685-2010 gives excellent guidance on how to do this.

An Australian Body Sizing Survey should also line up with the objectives of the International Council for Science: Committee on Data for Science and Technology (CODATA), to provide a high quality data resource that is able to be shared by different disciplines http://www.codata.org/about/who.html.

Input from stakeholders must be obtained from the outset of the project and extensive testing of technologies and the survey method must be conducted to finalise the scope and method of the survey. A pre-survey questionnaire for potential participants should be conducted to determine how long they would be willing to participate in the measuring for (maybe 60 or 90 minutes?) and what incentives might be suitable to gain their participation.

3-D scanning is no longer an emerging technology, but the application of 3-D statistical shape analysis to industry is. We have a strong need to try and fill the gap of accurate digital human models, shape deformation and fit-mapping all of which need a high quality, real data set upon which to base the digital work and predictive modelling that can be used to drive design innovations. Australia has an opportunity to fill this gap.

The Australian Body Sizing Survey presents an opportunity to extend the experience of previous surveys by developing and using the most up to date survey method and using scanning technology to capture high quality raw data.

In conclusion, the first report *Sizing up Australia* (Veitch, Caple et al. 2009) states in the executive summary that, “Anthropometric data are fundamental in the design process. They give designers information about the end-user”. But what has emerged in this report is that this information alone is not enough; being able to define dynamic and functional anthropometric data, such as reach envelopes (Oudenhuijzen, Zehner et al. 2009) and defining relationships between anthropometric data and the fit and function of designs, (Blackwell 1993, Robinette 2008, Choi, Zehner et al. 2010) are also both essential. So for designers, “it is not enough to know how they [the product] might be aligned [to the body], given their size and shape. It is important to be able to measure how they *are* aligned.” (Robinette, Vannier et al. 1997).

In the past, capturing dynamic data had technical problems because the 3-D data collected was either high quality or rapidly acquired, so two different data collection methods needed to be calibrated, which was slow and difficult, but with the advent of the new technologies such as the 3dMD scanner on the horizon the option of rapid, high quality data is emerging as a possibility for the first time. The Australian Body Sizing Survey should take advantage of and permit any technology that can produce this result in a cost effective way. Having such a tool could also mean being able to measure and accommodate small populations with special needs effectively. This is crucial for inclusive design that includes disabled workers and workers from ethnic groups with small populations.

Fit-mapping in a large scale National Sizing survey such as the Australian Body Sizing Survey would break new ground and would be the first instance of this work on a civilian population. The ability of designers to not just use high quality anthropometric data but to understand and, potentially, more accurately predict fit for their populations would be commercially very valuable, help drive innovations in the manufacturing sector to support their sustainability and help create safer and more productive workplaces.

This literature review as introduced new information from the rapidly developing world of anthropometry and its application in design. It builds on *Sizing Up Australia* and helps to set the framework for the development of the Australian Body Sizing Survey such that the end result can be world-leading, effective, value for money and cutting edge in terms of process and application. It could represent a significant competitive advantage for Australian firms in manufacturing, software development, DHM, and the application of these tools to design.

9. About the research team:

Ms Daisy Veitch was a Chief Investigator on this project. She is an internationally recognised Criterion Anthropometrist who directed the Australian National Size and Shape Survey in 2002 (NSSS 2002). In addition she collaborated in 2003 with the University of Adelaide and the University of South Australia surveying 3000 South Australian school children and is now employed in Flinders Medical Centre as an anthropometrist including body scanning (Cyberware WBX).

Daisy is Co-Chair of the IEA TC Anthropometry; Founding Member and Secretary World Engineering Anthropometry Resource (WEAR); Founder and Committee Member of HFESA's ARASIG; Co-Chair, International Council for Science: Committee on Data for Science and Technology (CODATA) Task Group for Anthropometric Data and Engineering. She is the Founder and CEO of SHARP Dummies Pty Ltd. Daisy is currently undertaking a PhD at Delft University of Technology (TU Delft), Faculty of Industrial Design Engineering. She is an Adjunct Associate Lecturer, Flinders University School of Medicine, Clinical Skills and Simulation Unit. Daisy was the principal investigator on *Sizing Up Australia* (2009).

Mr Chris Fitzgerald was a Chief Investigator on this project and the project manager. He is a Certified Professional Ergonomist, Committee Member of HFESA's ARASIG; Founder and CEO of Risk and Injury Management Services Pty Ltd. He is also the Director of Human Factors at the Emergency Medical Services Safety Foundation, New York.

Chris operates in industry with a focus on improving the design of work systems, environments and equipment. Chris has developed ergonomics design guidelines for numerous organisations and industries that include emergency services (fire and ambulance), disability services, food processing and manufacturing. He has extensive involvement in managing large ergonomic projects in these industries. This work in the ambulance industry has extended to North America and Europe. Understanding of the populations affected by these designs, and in particular the body parameters of users, has been integral to the development of these design guidelines. However, the absence of body size information about the Australian population has required these guidelines to be based on non-Australian anthropometry datasets.

Professor Kathleen Robinette was an advisor and mentor to the project, providing guidance and knowledge to ensure the project is able to meet its stated outcomes. Professor Robinette's direct involvement enabled the team to build on the lessons from the gold-standard CAESAR project to ensure that the Australian Body Sizing Survey is world-class and a national asset.

Professor Robinette is one of the leading international experts in engineering anthropometry with more than 30 years of practical experience. She has an extensive track record in the area of research covered by this EOI. During her 30 years with the US Air Force Professor Robinette developed and managed the Computerized Anthropometric Research and Design (CARD) Lab, one of the most sophisticated resources for anthropometric science, technology and information. She organized and directed the CAESAR project, the world's first anthropometric survey to deliver 3-D whole body human models and a multi-million dollar collaborative effort with over 32 companies from 5 participating countries. She planned, organized and managed the joint DoD/DoE development of the world's first automated 3-D anthropometric digitization system, and developed a new process (fit mapping) for efficient sizing of women's uniforms. Professor Robinette is now Head of Design at the Oklahoma State University where she is developing curriculum to teach engineering anthropometry applied to design. She has a PhD in bio-statistics and is currently Chair of the Statistics committee for ASTM (American Standards).

Dr Chang Shu was an advisor and mentor to the project. He contributed technical knowledge of scanning technologies as well as provided an advanced user-perspective in regards to future development in digital human modelling. This input ensured that the method for developing the Australian Body Sizing Survey will lead to a resource that has application for sophisticated future use.

Dr Shu is an Adjunct Research Professor at the School of Computer Science, Carleton University as well as a Senior Research Scientist at the Institute for Information Technology, National Research Council Canada. His research is focused on developing geometric and statistical methods for understanding shape variations in human and other biological forms. He leads the Digital Human Modelling Project at the National Research Council of Canada applying statistical shape analysis to 3-D anthropometric data and developing tools to visualize human shape variations. This research has applications in ergonomic design, medical and biological research, security, gaming, and animation.

Mr Steve Ward supported the international literature review and assisted with report development and writing.

Mr Ward is a lecturer in the Industrial Design program, Faculty of the Built Environment, at the University of New South Wales and is a Chief Investigator in an ARC funded Linkage project LP120100395 (funding commenced 2012) Project title: “Liveable bathrooms for older people: designing out dependence in activities of daily living”. In the Linkage project he advises on protocols for collection of anthropometric data that will inform the design of bathrooms and fittings for elderly Australians. He teaches ergonomics in the Bachelor of Industrial Design program at UNSW and, with a recent UNSW internal research grant, has developed trial tools and methods to assist designers to transfer anthropometric information to problems of design. In his teaching he is passionate about promoting an inclusive approach to design, and supports this with evidence from available anthropometric data. Mr Ward is Chair of HFESA’s Anthropometry Resource Australia Special Interest Group (ARASIG) and is a member of the HFESA Board. He has a broad understanding of standards and methods of data collection as well as a practical orientation, from experience as a designer as well as researcher, to using anthropometric information to design better and safer places for working and living.

Associate Professor Verna Blewett specialises in work health and safety and organisational change at Central Queensland University’s Appleton Institute. She is a Founder and Committee Member of HFESA’s ARASIG and was an investigator on *Sizing Up Australia* (2009). She is a facilitator and ergonomist. She advised the team on the ergonomics of safe design, and assisted with report development and writing.

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