HUMAN FACTORS INTEGRATION

TECHNICAL GUIDE FOR ANTHROPOMETRY: PEOPLE SIZE

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HFI

FOREWORD

Military Capability is a function not just of equipment performance, but depends upon a combination of interacting elements across all Defence Lines of Development, including a significant human component. Defence systems have to be operated under demanding environmental and operational conditions which often impose significant levels of physical and psychological stress on users and maintainers. Therefore, the usability and maintainability of systems within these demanding contexts of use will significantly influence operational capability. Because of this some of the most challenging aspects of acquisition lie in the specification and design of systems that successfully integrate the people and technological components of capability. The process through which the MOD considers the human component of capability within acquisition is known as Human Factors Integration (HFI) and is described in JSP912, Defence Standard 00-251 and in HUFIMS. This Technical Guide (sponsored by Defence Authority for Technical & Quality Assurance (DA4T&QA)) is one of a series of guides that have been produced, or are in the process of being produced, as part of a major revision and update of UK MOD Human Factors Integration (HFI) policy, standards and guidance. While the technical 'design guides' are distinct from defence standards, as they are for guidance and include useful datasets to inform design, they provide policy-compliant business practices that should be considered best practice in the absence of any contradicting instruction.

The principal aims of the Human Factors Integration (HFI) Technical Guides (TGs) are to:

- Enable Requirements Managers to populate the System Requirements Document with relevant HF requirements and measures of performance and support solution providers in deriving Sub-System Requirements, informing design or to flow out to sub-contractors.
- Provide Technical Guidance to inform the development of system (capability, equipment and service) solutions.

The guidance is intended to be independent from any specific development method and from any specific hardware or software environment. The content is intended to be sufficiently general to allow projects and design authorities to apply the guidance without prejudice to particular design solutions. Throughout the HFI Technical Guides, candidate Human Factors System Requirements have been provided alongside the technical guidance and data, these have been collated at Appendix C of each Technical Guide. These should be read in conjunction with Defence Standard 00-251 Part 3 which includes candidate URD and SRD HF requirements. In order to enhance the guidance, throughout the HFI Technical Guides, defence related examples, where available, have been provided. Where a case study provides extant military specific project, programme or platform guidance, this has been included within Appendix B. This document contains human factors technical information that has been tailored from other human sciences literature for application within defence acquisition, as well as lessons identified from in-service equipment with the expectation that they will become lessons learnt in future systems. The guidance does not replace or take precedence over the Health and Safety at Work etc. Act (1974) (HSWA), and the Environmental Protection Act 1990 (EPA), are primary pieces of relevant UK legislation. Nothing contained within this Human Factors Integration Technical Guide removes the responsibility of any Duty Holder to comply with the applicable legislation, Defence regulations and H&S policy, as stated in DSA01.1: Defence Policy for Health, Safety and Environmental Protection. The requirements of this document and of the Health and Safety Regulations are to be seen as complementary.

OWNER

This Human Factors Integration Technical Guide is owned by the Defence Authority for Technical & Quality Assurance (DA4T&QA).

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IMPORTANT

This document contains technical guidance for Human Factors Integration during defence acquisition. The *Health and Safety at Work etc. Act (1974)* (HSWA), and the *Environmental Protection Act 1990* (EPA), are primary pieces of relevant UK legislation. Nothing contained in this Human Factors Integration Technical Guide removes the responsibility of any Duty Holder to comply with the applicable legislation, Defence regulations and H&S policy, as stated in DSA01.1: Defence Policy for Health, Safety and Environmental Protection (Ministry of Defence, 2016).

AMENDMENT HISTORY

Version	Date	Sections Changed	Amended By	Remarks
1		N/A		Initial Version
2	17/09/2015		Gareth Shaw	Dstl review comments addressed
3	11/10/2017	Foreward, References, 3.6	Rob Cummings	Updated to address QQ comments and update JSP references
4.2	19/01/2019	Owner, 4.1.2, 7.2.2, Appendix H, Table 23, Serial 32, Table 22, Serial 6, References	Rob Cummings	Owner, Address updated 4.1.2, 7.2.2, References to Defence Standard 00-970 updated Appendix H, clarification provided that all dimensions listed have been rounded to the nearest mm Table 23, Serial 32 (Hand Breadth Table 22, Serial 6 (Bideltoid Breadth Updated to correct error) References updated
4.3	06/03/2019	Appendix H	Rob Cummings	Anthropometric Data updated to correct errors identified: H.3 - Army – Male (inc. Gurkhas): 5) Foot Length H.1 - All Services & Groups - Male: 12) Inter elbow span H.6 - Gurkha, 18) Vertical functional reach

Version	Date	Sections Changed	Amended By	Remarks
				H.10 - Royal Navy – Male: 16) Elbow functional reach H.10 - Royal Navy – Male: 25) Knee height, sitting

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1 INTRODUCTION

1.1 IDENTIFICATION

The People Size Technical Guide (TG) provides information and technical guidance on the physical size and proportion characteristics of the population of operators, maintainers and supporters for whom the system under consideration should be designed. The document aims to provide the authority and the designer with the necessary guidance to use anthropometric data systematically and effectively, in the specification, design and acceptance of the solution in order to accommodate a target population. This TG draws heavily on the previous Defence Standard 00-250 Part 3, Section 9 and updates it where new data are available. Particular updates include incorporation of data from Version 2 of the Tri-Service Anthropometric Database (Pringle, et al., 2013).

The document has therefore been divided into the following sections:

(a) Background;
(b) Key principles;
(c) Define the target population;
(d) Generate anthropometric requirements;
(e) Structural anthropometry;
(f) Clothing and equipment;
(g) Functional anthropometry;
(h) Anthropometric movement of body parts;
(i) Use of manikins; and
(j) Applying anthropometric data to the design of systems.

1.2 INTENDED AUDIENCE

1.2.1 PROCUREMENT AGENCIES

This Guide is designed so that it may be used as a resource for the procurement/acquisition community. It is envisaged that this TG may be referenced in tender documentation, therefore reducing the amount of detailed HF requirements that need to be included in the documentation. System suppliers may then be asked to document where and why they have not followed the advice in the document (i.e. compliance with the System Requirements Document (SRD)). The Guide also provides advice on how to include objective Human Factors (HF) requirements in the Specification and T&E processes and therefore assist in the procurement/acquisition acceptance process.

1.2.2 HUMAN FACTORS SUBJECT MATTER EXPERTS

This Guide is designed so that it may be used as a resource for the HF Subject Matter Expert (SME) community. It is envisaged that it may be used as reference and guidance material for HF SMEs who are responsible for applying anthropometrics in the design of systems. The information on the system design process should allow them to obtain a greater understanding of the constraints and compromises involved in the design of particular systems and how anthropometric data should be applied within the design process.

2 BACKGROUND

2.1 ANTHROPOMETRY

The branch of science that deals with the measurement of the human body is Anthropometry, and anthropometrics is the term used for the application of such data.
This Anthropometry TG covers:

(a) The use of anthropometric data in contracting and requirements;
(b) The use of anthropometric data in design;
(c) 'Structural' and 'functional' anthropometrics and their relationship to the design of the workspace; and
(d) The important concept of body linkages and the use made, by designers, of two-dimensional manikins and computerised models of humans.

Anthropometric data are applied to ensure the appropriate fit of equipment, workstations and workplaces to accommodate the target population. Anthropometric data are gathered for a broad range of body dimensions; the most recent anthropometric survey of British forces (Pringle, 2011) gathered 120 individual body dimensions for each participant (over 2000 in total). Anthropometric data can be used to specify the size and shape that a workplace needs to be to accommodate a given target audience, as well as to tell you the proportion of a given target audience that can be accommodated by a workplace of a known size and shape.

Anthropometric data may be considered in terms of structural and functional anthropometry. **Structural** (or static) anthropometry concerns those dimensions taken with the body in rigid, standardised positions, and includes measures such as stature and sitting height; while **Functional** (or dynamic) anthropometry deals with the dimensions of the workspace envelope needed by persons as they perform their work. As functional measurements are made in working postures, they vary accordingly.

In requirements specification the acquirer will normally define the anthropometric properties of the User population using structural anthropometry. The Solution Provider will then apply the structural anthropometry in design to derive dynamic anthropometric requirements for the system together with associated design guidance. These derived requirements and guidance will then be used to inform the design of the system.

2.2 PEOPLE SIZE AND THEIR WORK ENVIRONMENT

People are not all the same size (whether you consider height, waist size or any other dimension) and it is rarely practicable to tailor, or customise, a piece of equipment to an individual operator. As a result, a designer is almost always required to create a workspace which is compatible with a range of individuals or population. Therefore, the first step in workspace design is always to define the 'target' population who will use the equipment. Summary statistical descriptions of the population are defined (usually expressed through "percentiles", discussed in section 2.5) which rigorously express what proportion of the possible range in values of dimensions are to be accommodated.

Adequate clearance must be provided for the tallest and the broadest individuals (remember breadth could be due to fatness or muscularity), particularly in military systems which operate in tough environments or have extreme performance requirements. At the same time, the smallest individual must be able to reach and operate all of the controls and be able to see all of the displays. On top of this, many personnel also wear protective clothing which may restrict their movements or reduce their visual field. Furthermore, in many roles, for example aircrew, the person wears a restraining harness that can restrict both reach and vision. These additional factors all need to be taken into consideration during system design.

Failure to account for the variability of the size of people in the work environment will inevitably result in poor working postures. This in turn will increase the risk of work related musculoskeletal disorders, having a direct impact on the availability and effectiveness of personnel, affecting the capability as a whole.

2.3 VARIATION IN HUMAN BODILY DIMENSIONS

Each body dimension varies between the individuals in a population and this variation often conforms quite closely to a statistical distribution (or model) known as the 'Normal' (or Gaussian or "Z") distribution. For any given dimension, values tend to cluster around an average (the mean), and extreme cases are relatively rare (see Figure 1 for a graphical introduction to this concept).

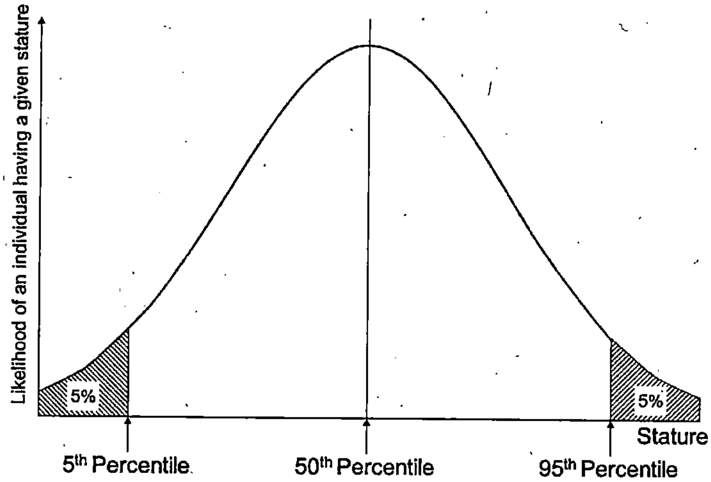


Figure 1 – Normal (Gaussian) Distribution Curve

Note: although the majority of body dimensions usually follow a normal distribution, some take other forms.

2.4 STATISTICAL ASPECTS OF ANTHROPOMETRY

The Normal distribution describing any variable may be characterised by two parameters; the mean and standard deviation. The mean locates the 'centre' of the Normal distribution, and the standard deviation summarises the extent to which values deviate from that mean. In statistics there are three common measures of "average": Mean, Median and Mode. In Normal distributions these averages are numerically equal.

It is particularly worth noting in the context of practical anthropometry that there is both a ***population*** mean and standard deviation (i.e. the values if "everybody" could be measured) and the ***sample*** mean and standard deviation which are those values obtained from any actual measurements made (usually more limited). See the side box for the potential implications of this.

Design Best Practice Note 01: The formula for calculating standard deviation may have a denominator N instead of N-1 only if the measurements represent the **whole** population, rather than a sample. Using the population formula in small sample sizes underestimates the standard deviation, although the difference may be small. For example, when 6 individuals or more are measured, the value calculated using N will be greater than 90% of the value obtained using 'N-1'. How the ratio of √(N-1)/N varies with N is illustrated in Figure 2.

The mean and standard deviation of a sample data set, in this case a particular bodily dimension x, are calculated as follows:

The arithmetic mean $(\bar{x}) = \frac{\sum_{i=1}^{i=N} x_i}{N}$

The standard deviation (SD) = $\sqrt{\frac{\sum_{i=1}^{i=N}(x_i - \bar{x})^2}{N-1}}$

Where:
x_i = the i^{th} person's value of the bodily dimension.
N = number of people upon whom measurements were made.

Roughly 68% of all values in a normal distribution are contained in the range of +/- 1 SD of the mean value (see Table 1 for more detailed descriptions).

The variation in the ratio of estimates of population standard deviation to estimates of sample standard deviation for the same data-set, expressed as a percentage, is presented in Figure 2.

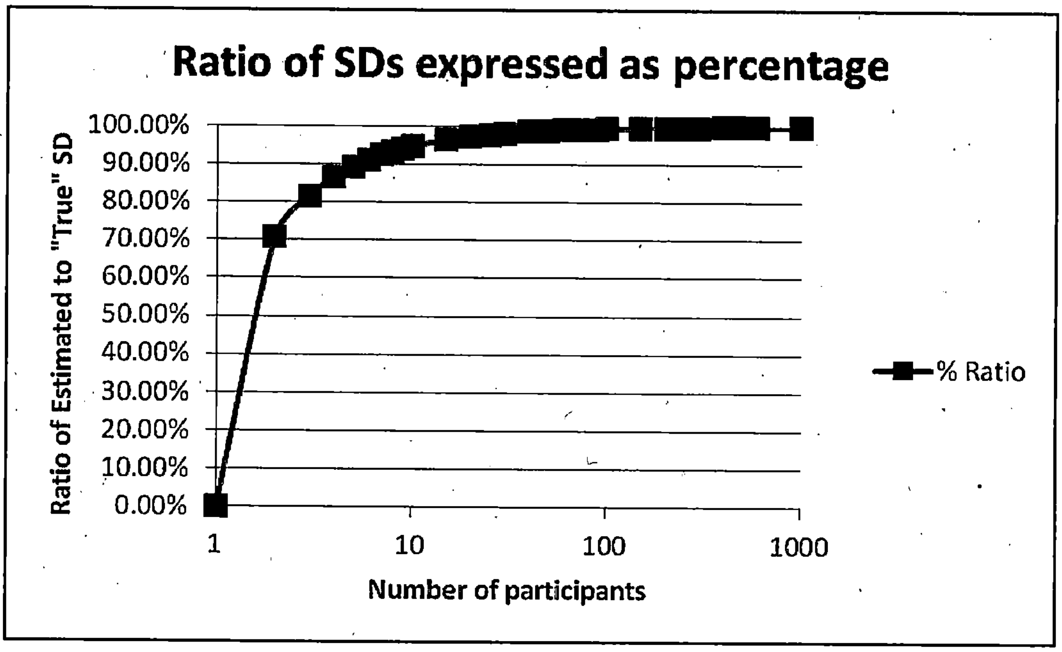


Figure 2 – Population and Sample Standard Deviations Compared

Note: Further detail concerning the statistical aspects of anthropometry is available through reference sources such as, "Bodyspace", (Pheasant & Haslegrave, 2005).

2.5 PERCENTILES

Anthropometric data are typically presented as tables of percentiles for given body dimensions. A percentile (%ile) is that proportion of a population which exhibits a measurement less than a particular value for that dimension. It is important to appreciate that a single individual who exhibits a particular percentile for a specific dimension, for example 97th percentile for stature, will not necessarily match that percentile for other body dimensions.

For any dimension in any population of individuals, 'n' percent of people are smaller than the 'nth' percentile. Hence, 5% are shorter in stature than the 5th percentile, 95% are shorter than the 95th percentile, and so on. For most practical purposes, we may consider the 50th percentile and the 'average' or 'mean' to be one and the same.

Two important points should be reinforced at this stage:

(a) A percentile value refers to one dimension only, hence a man of average (50th percentile) height may well have an above average waist depth (e.g. 80th percentile).
(b) A percentile value refers to a specific population and not all populations, for example the 50th percentile stature for UK aircrew (1783 mm) is the 63rd percentile for UK non-aircrew.

MOD has invested in the production of anthropometric data (Pringle, et al., 2011) that describe the UK military user population in terms of many of the most useful bodily dimensions. It provides the

actual percentile values in millimetres and kilograms for the most significant percentiles and contains a tool for calculating intermediate values.

The UK military anthropometric dataset is a valuable resource that projects can use to inform the design of products and workplaces. However, there may well be occasions when these data do not go far enough. For example:

(a) A bodily dimension critical to the usability of your design is not one of those in the UK military anthropometric dataset.
(b) You want to design to accommodate a target audience beyond the UK military population – UK civilians or personnel (military or civilian) from outside the UK.

It may be possible to find an applicable anthropometric dataset that gives you percentile values in either of these cases. However, many datasets are not as thorough or explicit as the UK military set and additional work may be required to generate percentile data. The sections that follow describe the techniques that can be used to generate percentile data from less-complete datasets.

2.6 CALCULATING PERCENTILES

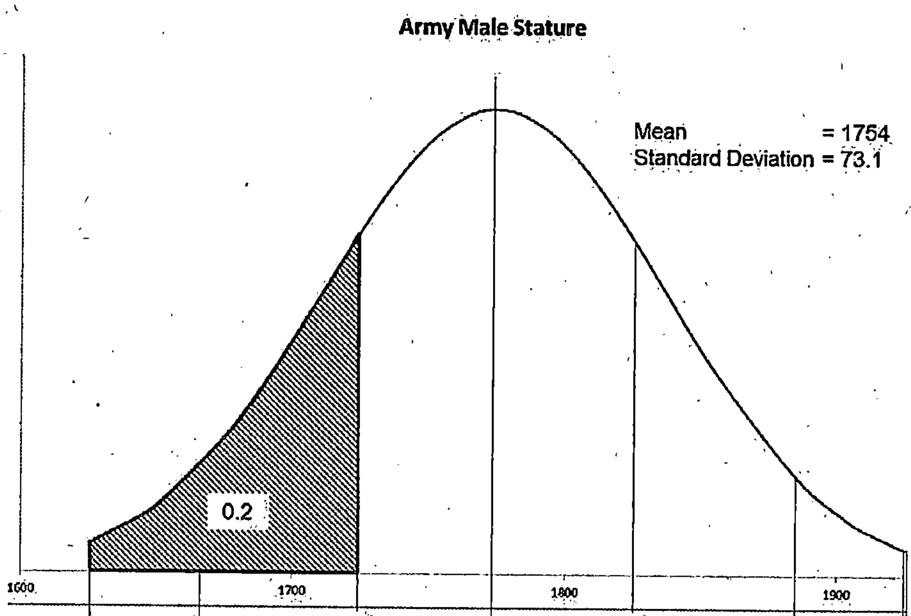
If the mean and standard deviation of any variable following a normal distribution are known, then any percentile of interest may be calculated using a statistic known as Z. The Z score determines the number of standard deviations that a value sits from the mean in a normal distribution. Values of Z are recorded in a table in Appendix E. Technically, the Z statistic provides a means of calculating the area under the normal distribution curve. The total area underneath the normal distribution curve is equal to 1 (100% of the data). The Z score of a particular value can be calculated using the following equation:

$$\text{Z score } (z) = \frac{x - \bar{x}}{SD}$$

Where:

x = the selected value
$\bar{x}$ = Mean of the population data
SD = standard deviation of the population data

Alternatively, using the look-up table, the Z score can be determined for a particular percentile, by using the probability matrix in the Z score tables in Appendix E. To look up the 20th percentile Z score, for example, search the table for the value that is equal to or greater than 0.2 (in this case 0.2005), giving a Z score of -0.84. Note: when using the tables to determine values greater than the 50th percentile the tables should return a positive Z score (as the value is greater than the mean, which carries a Z score of zero). Figure 3 illustrates the relationship between percentiles, probabilities and Z scores, using the Army male nude stature as an example.



Percentile	5th	20th	50th	80th	95th
Probability	0.05	0.2	0.5	0.8	0.95
z	-1.65	-0.84	0	0.84	1.65

Figure 3 – Calculating Percentile Values From the Mean and Standard Deviation

A "ready-reckoner" for calculating a selection of percentiles is given in Table 1. The accuracy of such calculations depends on the accuracy with which the parameters are known and on the extent to which the distribution is truly normal.

Table 1 – Percentile Values Calculated from the Mean and Standard Deviation

Mean is represented by $\bar{x}$, standard deviation by SD.

0.5 %ile = $\bar{x}$ – 2.58 SD	75th %ile = $\bar{x}$ + 0.67 SD
1st %ile = $\bar{x}$ – 2.33 SD	80th %ile = $\bar{x}$ + 0.84 SD
2.5 %ile = $\bar{x}$ – 1.96 SD	85th %ile = $\bar{x}$ + 1.04 SD
3rd %ile = $\bar{x}$ – 1.88 SD	90th %ile = $\bar{x}$ + 1.28 SD
5th %ile = $\bar{x}$ – 1.65 SD	95th %ile = $\bar{x}$ + 1.65 SD
10th %ile = $\bar{x}$ – 1.28 SD	97th %ile = $\bar{x}$ + 1.88 SD
15th %ile = $\bar{x}$ – 1.04 SD	97.5 %ile = $\bar{x}$ + 1.96 SD
20th %ile = $\bar{x}$ – 0.84 SD	99th %ile = $\bar{x}$ + 2.33 SD
25th %ile = $\bar{x}$ – 0.67 SD	99.5 %ile = $\bar{x}$ + 2.58 SD

Calculations of this kind enable determination of the percentage of a population that would be accommodated by a particular workspace dimension or range of adjustability on a univariate (or single measure) basis.

2.7 USING PERCENTILES

It is rare for designs to accommodate 100% of the population as expanding design limits to include further percentiles is an increasingly costly endeavour. Common practice is to design for the 5th to the 95th percentile, trusting human adaptability to cope with residual mismatches which might arise unless specified otherwise by the Acquirer in contractual documentation.

Consider the case of a doorway or passage designed, both in height and width, to average (50th %ile) dimensions. Such a door would greatly inconvenience those of the population who were taller or wider than average. The 50% of people taller than average would have to stoop. Since there are some people who are not only shorter than average but **also** wider than average, a certain additional number of individuals would have to squeeze through, or pass throughout sideways. Hence, the door or passage 'designed for the average person' would be suitable for less than half the people who used it!

The most difficult problems arise in those workplaces where several dimensions are all critical for various reasons, e.g. a cockpit or a driving position. Although the designer should as a minimum accommodate a population range of 5th to 95th percentile, and 3rd to 97th where possible, it must be remembered that a person who is 3rd percentile in stature, certainly is not 3rd percentile in all other dimensions. For example, if all personnel who are 3rd percentile and less or 97th percentile and more are excluded, when six critical design dimensions are used, it is not 94% of the population but only 78.6% who are accommodated.

The statistical calculations that would highlight just how many more individuals are excluded are complicated. It depends on the degree to which the bodily dimensions concerned are correlated with each other. Refer to Pheasant (2005) for more detail. The correlation of body dimensions and the impact on the actual level of accommodation achieved by a design is illustrated below in Table 2.

Table 2 – Impact of 3rd – 97th Percentile Limits on the Percentage of the Total Population Accommodated

Serial	Dimension	Range limitation	% of total population accommodated					
1	Sitting height	3 to 97% ile	94					
2	Buttock-knee length	3 to 97% ile		89				
3	Buttock-heel length	3 to 97% ile			87			
4	Functional reach	3 to 97% ile				84		
5	Sitting knee height	3 to 97% ile					83	
6	Bideltoid breadth	3 to 97% ile						78.6

Note: updates to Version 2 of the Tri-service Anthropometric database (Pringle, et al., 2013) mean that it is now possible to calculate the percentage of the population accommodated by a given design (where limiting selection criteria for particular anthropometric dimensions can be identified). This is illustrated below in Figure 4 using six body dimensions.

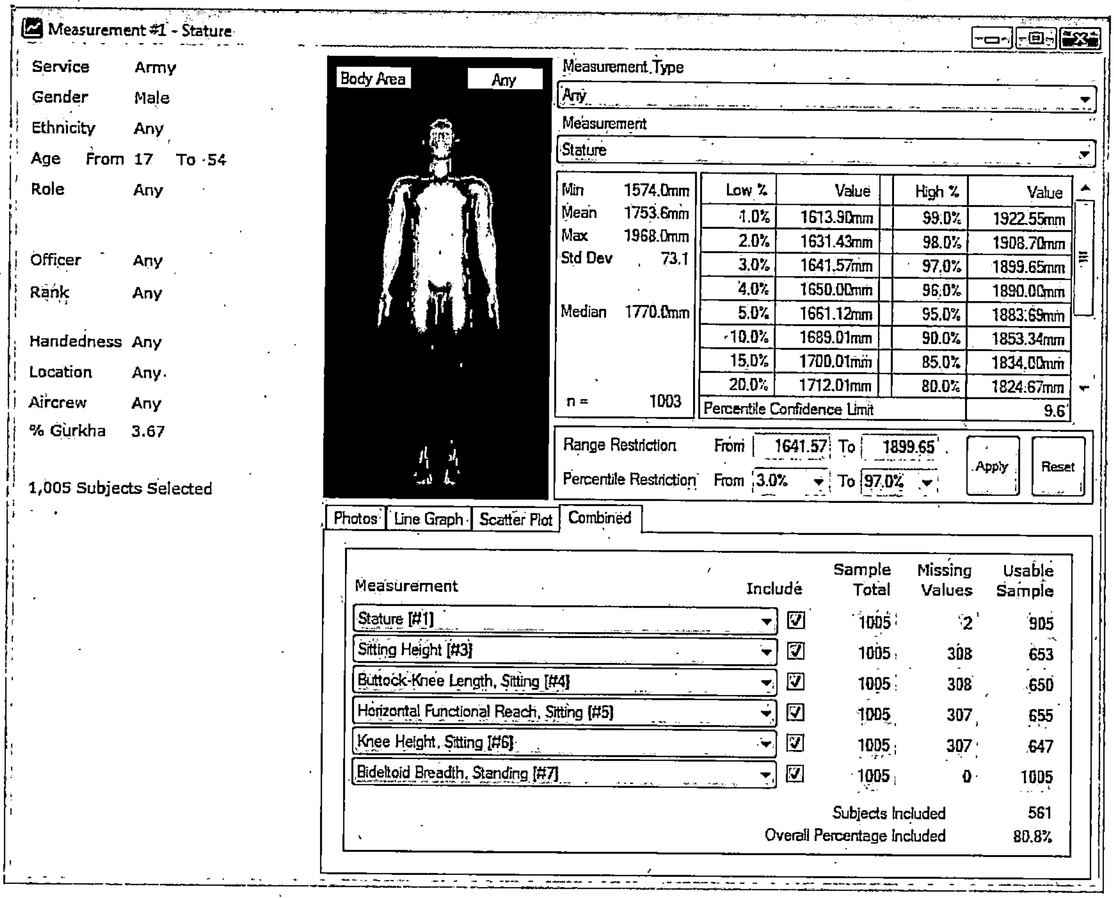


Figure 4 – Calculating the Overall Percentage of Users Included Using Six Body Dimensions

2.8 ISSUES AND DIFFERENCES IN MALE AND FEMALE POPULATIONS

Currently, few military roles are the sole remit of either the male or female population. Although historically the female population was excluded from many frontline military roles, more roles are now open to both sexes. Therefore the designer must take account of both male and female sizes when designing equipment.

When considering differences between the sexes, the designer should take into account issues such as body size, body weight and strength differences. In these instances, designing for the 'limiting user' may increase the likelihood that most or all users can perform the task. In addition, it may improve performance generally and/or decrease risks to health and safety.

There is a considerable overlap between the sexes, for example the strongest woman may have greater capability than many of her male counterparts. In addition, the smallest male may be far smaller than many of his female counterparts.

The summary statistical tables in Appendix H in this design guide (and the more detailed anthropometric database tool described in Appendix G) provide anthropometric data for male and female populations. For most dimensions, men are larger and heavier than women in any given racial group.

The twin population distributions shown in Figure 5, illustrate an example requirement and the consequent difficulty that an equipment designer has in accommodating all potential users. Note: The height differential between the male and female populations is caused by the smaller standard deviation of stature in the female population.

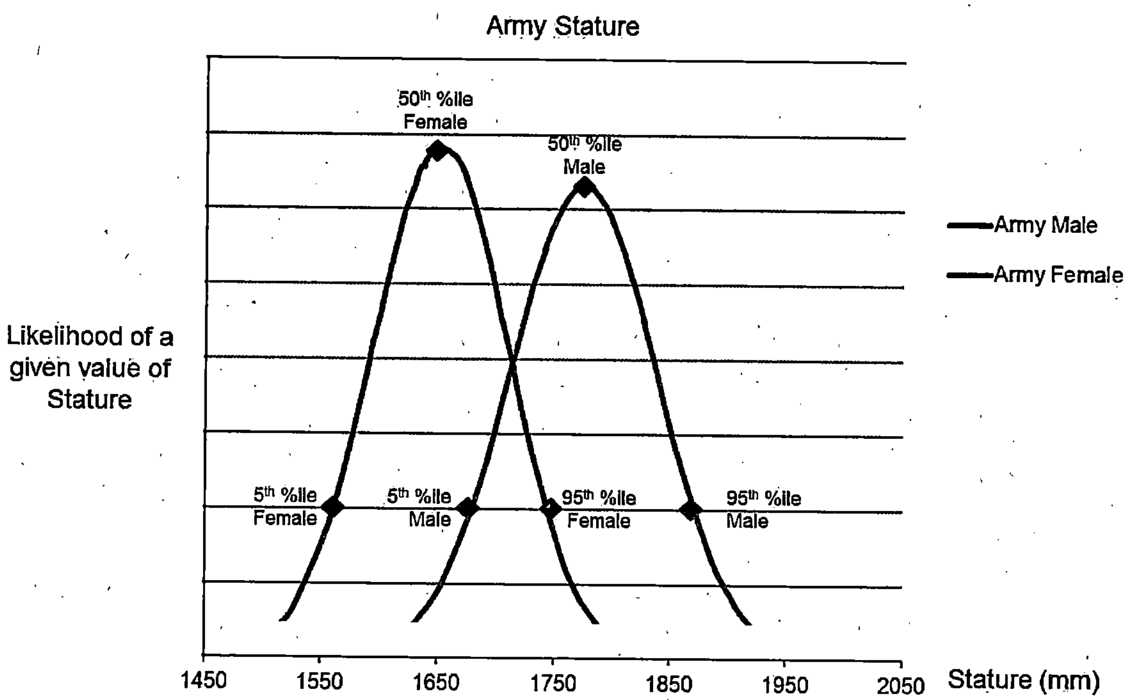


Figure 5 – Illustrative Differences in Female and Male Army Population Distribution of Stature

3 KEY PRINCIPLES COVERED BY THIS GUIDE

Anthropometrics need to be considered early and throughout the system lifecycle. The anthropometric design process should start in the Early Human Factors Analysis (EHFA) process conducted by the Front-Line Commands (FLCs). The basis of the anthropometric requirement set will be established through the development of Context of Use information in the EHFA process. The Context of Use (not to be confused with the Concept of Use (CONUSE)) is a term used in usability and Human Centred Design (HCD) to capture key contextual information that influences the ease of use of the System. The Context of Use should include information regarding:

- The Target Population;
- The Tasks / Functions that the users will perform;
- The Equipment that Users will interact with; and
- The Environments in which the Users will have to operate.

These aspects of the Context of Use should be used in the development of HF System Requirements and HF Process Requirements, as well as supporting information for the contractual documentation set, such as the Target Audience Description (TAD). The detail available in the Context of Use will vary between acquisition programmes and will develop through the Concept and Assessment phases in support of the SRD and supporting annexes / design guides.

This TG is therefore structured to reflect the following high-level principles:

- Define the target population;
- Generate anthropometric requirements;
- Account for structural anthropometry;
- Account for clothing; and
- Account for movement.

3.1 DEFINE THE TARGET POPULATION

Anthropometric data are a key input into the design process and should represent the user population for which the product is being designed. That is, for a military product, a military dataset should be applied and, where appropriate, a dataset should be specific to the Service (i.e. Army, Navy, or RAF) and sub-group (e.g. Royal Armoured Corps, Gurkha, Royal Marines, etc.) for which the capability is being procured.

3.2 GENERATE ANTHROPOMETRIC REQUIREMENTS

The specification of anthropometric requirements is fundamental to the subsequent application of anthropometrics in design. Specific Measurable Achievable Realistic Time-Related (SMART) System Requirements for anthropometrics should be included in the SRD and associated Statement of Requirement (SoR) to instigate the HCD Process and ensure that compliance can be monitored, tested and assured.

3.3 ACCOUNT FOR STRUCTURAL ANTHROPOMETRY

Structural Anthropometry defines the baseline nude anthropometric dimensions of the User population. The design activities must identify the key structural dimensions that characterise human accommodation in the design solution and apply them with appropriate limits as defined by the acquirer.

3.4 ACCOUNT FOR CLOTHING

Clothing and personal equipment will have a significant effect on the size, shape and movement of the user. The design must take account of the clothing and equipment ensembles worn in the full range of environmental conditions in which the system will have to operate, to ensure that the System remains operable and maintainable under all envisaged operational conditions.

3.5 ACCOUNT FOR MOVEMENT

To plan positioning and operability of controls, as well as the layout of spaces occupied by personnel, the designer must take into account the range of movement of the torso, arms and legs, in order to establish the comfortable limits for optimisation of the design solution.

3.6 RELATIONSHIP WITH CIVIL STANDARDS

This document contains technical guidance for HFI during defence acquisition. The Health and Safety at Work Act (1974) (also referred to as HSWA), and the Environmental Protection Act 1990 (EPA), are primary pieces of relevant UK legislation. Nothing contained in this HFI TG removes the responsibility of any Duty Holder to comply with the applicable legislation, Defence regulations and H&S policy, as stated in DSA01.1: Defence Policy for Health, Safety and Environmental Protection.

4 DEFINE THE TARGET POPULATION

The first step in workspace design is always to define the 'target' population that will use the system. Definition of the target population is the responsibility of the FLCs during the production of the User Requirements Document (URD). However, in some contracts this may be delegated to another organisation, such as the DE&S project team, the Dstl Human Systems Group or a Defence contractor operating as a 'Customer Friend'. The contractual document that defines the target population is known as the Target Audience Description or TAD. The TAD provides a detailed description of the physical, psychological and sociological characteristics and organisation of the types and groups of people that will operate, support, sustain and maintain the solution, together with supporting data. The FLCs are responsible for ensuring that the TAD is produced during the Concept Phase to support the development of the URD, SRD and Concept of Employment (CONEMP). One aspect of the physiological characteristics in the TAD will be the definition of the anthropometric attributes of the target population and the appropriate clothing modifiers for application in the design. A product description for the TAD is provided in HuFIMS.

> **Design Best Practice Note 02:** The first step in design of a workspace shall be to define the "target" population who will use the equipment being designed.

> **Design Best Practice Note 03:** The TAD provides the definition of the anthropometric attributes of the target population, and is therefore one of the key contractual documents concerning anthropometrics.

4.1 SELECT POPULATION DATASET

Anthropometric data are a key input into the design process and should describe the user population for which the product is being designed. That is, for a military product, a military dataset should be applied and, where appropriate, a dataset should be specific to the Service (i.e. Army, Navy, or RAF) and sub-group (e.g. Royal Armoured Corps, Gurkha, Royal Marines, etc.) for which the capability is being procured. Users may be sourced from a variety of organisations that will operate, support, and maintain the System being acquired. This should be considered and identified in the production of the TAD. If, for example, maintainers may be sourced from civilian organisations, it may be necessary to identify this as a particular group in the TAD. Furthermore, anthropometric data also vary considerably between populations. For example, Dutch populations tend to be taller; the American population tends to be broader, while Asian and Italian populations tend to be shorter. Therefore, if a System is being procured for a multinational population, consideration should be given to the inclusion of data from all nations for which the System is being procured.

A decision must also be made concerning whether the system being procured should accommodate both male and female users. Traditionally the female population was barred from serving in a large number of front line roles, including working in submarines, armoured vehicles and infantry units, as well as fast jets and attack helicopters. However, over time many of these roles have become open to both sexes. Although the system being procured may not currently be operated by females, consideration must be given to whether there is any chance of both sexes having to operate or maintain the system through the course of its service life. By default, systems will be required to accommodate both sexes equally. Anthropometric differences between the sexes are discussed further in section 2.8. If the female population is excluded at any stage of the acquisition, this must be recorded and justified, through the programme Risks, Assumptions, Issues, Dependencies, and Opportunities (RAIDO) and / or HFI Assumptions Register.

The most recent anthropometric survey of UK armed forces was conducted in 2007 using a cloud-point laser scanning technique. In total, 2470 subjects were measured (Pringle, 2011), representing 820 different roles & trades, and 67 ranks or rates. The survey measured 120 individual, static dimensions (18 manual, 13 sitting scan, 83 standing scan and 6 deduced measurements were recorded). Data were gathered for each of the armed services. Three additional groups were surveyed separately, as they might present

> **Design Best Practice Note 04:** There are some significant differences between UK data and other nations, as well as between Services. Care must therefore be taken to ensure that the correct data set is used in the production of the TAD.

different anthropometric data from the remainder of the armed forces. These were aircrew (as aircrew selection includes anthropometric limitations); the Gurkhas (due to anthropological differences); and the Royal Marines (due to stringent training regimes). The Anthropometric data in the database have been divided into groups as detailed below in Table 3.

At the time of writing, an additional study is being conducted into the anthropometry of Royal Armoured Corps (RAC) users, which will be added as an additional group in a future iteration of the database tool.

Table 3 – Anthropometric Database Version 2 Groups

Serial	Group	Male	Female	All (Total)
1	All	✓*	✓	✓**
2	Army	✓***	✓	✗
3	Royal Air Force	✓	✓	✗
4	Royal Navy	✓****	✓	✗
5	Gurkha	✓	✗	✗
6	Royal Marines	✓	✗	✗
7	Aircrew	✗	✗	✓
8	* Including Gurkhas & Royal Marines ** All Survey *** Including Gurkhas (Default 3.67%) **** Not Including Royal Marines			

Further details concerning the functionality of the anthropometric database tool can be found in Appendix F. Summary anthropometric data tables for the groups detailed above in Table 3 are provided in Appendix H.

4.1.1 Secular Change

> **Design Best Practice Note 05:**
> Fitting people into systems is complicated by the length of service of equipment, which may be 50 years, or more.
> For example, the Fighting Vehicle (FV)432 Bulldog Armoured Personnel Carrier (APC) first entered service in 1963 and in 2014 is still in use. During this time the general population has changed in both size and shape.

The characteristics of a population change over time. Changes in diet and nutrition as well as immigration will all have an effect. These changes are known as secular changes. The extended life of military systems means that it may be necessary to forecast the data in the TAD to take account of these secular changes in the population. Secular trends in anthropometry are influenced by many factors, most of which are very difficult to predict. In several countries, there has been a relatively constant rate of increase in average stature and body weight since the Second World War, suggesting that those body dimensions can be predicted. However, the rise in average stature has stopped in some countries, and this has made earlier predictions inaccurate. Predictions based on extrapolating historical, secular growth trends are highly unreliable (a) because the underlying causative factors cannot be assumed to remain constant, and (b) because of the inevitably large errors in the definition of the trend line (Usher, et al., 2014). The period over which extrapolation can be used is considerably shorter than that needed for many Defence System design purposes.

While the recent increase in the stature of the UK population has been modest, waist circumference, chest circumference, buttock circumference, hip breadth, bideltoid breadth and weight have

increased dramatically over the past 40 years. The prevalence of overweight and obesity in the military is somewhat below that of the general population, but it is of concern that a minority of Service personnel are at risk of ill health for this reason (Usher, et al., 2014). While predictions based on extrapolations of historical data have proved to be highly unreliable, and trends in the civilian population cannot be directly transferred to military applications (because of differences in composition), it is likely that future Defence Systems will need to accommodate crew and passengers with a more variable stature than at present.

4.1.2 SUPPLEMENTARY ANTHROPOMETRIC DATA SOURCES

Most Defence systems will be able to use the anthropometric data in the Tri-Service Anthropometric Database and summary tables contained in Appendix H. However, in some instances it may be necessary to seek additional data, due to the specific population that the System is being procured for. A number of additional sources are detailed below:

Hand and Foot Anthropometry
British Armed Forces – hand and foot anthropometry 2001: Targeted sample of 2056 personnel. (Bradley, et al., 2002)
This tri-service anthropometric survey collected 80 measurements of the right hand and arm and 33 measurements of the left foot and lower leg.

RAF Aircrew:
Defence Standard 00-970 Part 1, section 4, leaflet 63 "Crew stations – general requirements aircrew anthropometry".
This standard draws on the anthropometric surveys of 1970/71 (DRA, 1970,1971) and a subset of (Pringle, 2011) which is represented in (Connett & Marston, 2009).

UK Military Females:
Survey of UK Military Females (J E Aplin) 1995.

Design Best Practice Note 06:
It is not always possible to provide all the necessary anthropometric data (for example new clothing systems may change clothing additions, or additional dimensions may be required which are not included in the current anthropometric database). In these instances, the Solution Provider should identify and agree the proposed sources of data, or methods of obtaining such data with the Acquirer.

US Army:
1991 DOD-HDBK-743A Military Handbook Anthropometry of U.S. Military Personnel (Metric)
1989 Natick Report TR89/0441988 Anthropometric Survey of US Army Person Anthropometric
ANSUR II (Anthropometric Survey) (Paquette, et al., 2009).

Civilians:
ADULTDATA. The Handbook of Adult Anthropometric and Strength Measurements - Data for Design Safety (Peebles & Norris, 1998).
PeopleSize Software, 2008, Open Ergonomics Limited, Loughborough Technology Centre, Epinal Way, Loughborough, LE113GE, UK. (Open Ergonomics Limited, 2015)
Civilian American and European Surface Anthropometry Resource (CAESAR) (Robinette, et al., 2002).

Other:
ISO/DIS 7250 Basic List of Anthropometric Measurements. International Standards Organisation. Geneva, Switzerland. 1996.

Design Best Practice Note 07:
In selecting sources of operator population characteristics data, the following order of precedence shall be followed unless the Solution Provider or the Acquirer can demonstrate that more relevant data exist:

- Operator characteristics data contained in any target audience description issued by the Acquirer.
- Operator characteristics data contained in this technical guide.
- Operator characteristics data that can be shown to relate specifically to the expected User population or the population from which UK Defence operator populations are drawn.
- Operator characteristics data that relate to a more general population.

4.2 DETERMINE THE PROPORTION OF THE POPULATION TO BE ACCOMMODATED

Once the population group and sex mix have been identified, a policy decision is required concerning the percentage of the population that should be accommodated by the design. Summary statistical descriptions of the population are usually expressed through "percentiles", (discussed in more detail in section 2.5). Percentiles are used as a means of expressing what fractions of the possible range in values of dimensions are to be accommodated.

As mentioned above, expanding design limits to include further percentiles is an increasingly costly endeavour. The percentile at which to stop is a question that has no hard and fast answer. Good HF guidance would suggest designing to the 3rd to 97th percentile; however, this is frequently traded down to the 5th - 95th percentile. Common practice is to design for the central 90% of the anticipated user population using the 5th and 95th percentiles as bounding measures, trusting human adaptability to cope with residual mismatches which might arise.

***Candidate HF System Requirement 01*:**

The System shall accommodate the central 90[1] percent of the anticipated user population in accordance with the TAD.

Clearly there are cases where such a procedure would be unacceptable. In the case, for example, of an escape hatch, maximal dimensions (99th percentile) should be used to ensure that all users can escape in case of emergency. Therefore, it is often necessary to ensure that the measure of performance (MoP) for emergency egress and casualty evacuation (CASEVAC) requirements is set as a larger 99th percentile requirement.

Candidate HF System Requirement 02:

Emergency egress routes (including hatch apertures) shall accommodate Crew and Passengers of body dimensions 1st percentile male to 99th percentile male as defined in the TAD dressed in all clothing assemblies.

Candidate HF System Requirement 03:

Emergency egress routes (including hatch apertures) shall accommodate Crew and Passengers of body dimensions 1st percentile female to 99th percentile female as defined in the TAD dressed in all clothing assemblies.

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[1] Normal anthropometric design practice is to design for 90% of the population; a policy decision is required to define the required level of accommodation specified. This should be recorded and justified in the RAIDO or HFI Assumptions Register.

Policy decisions concerning the accommodation of the user population vary between Defence acquisition programmes. These decisions may be shaped by the type of acquisition (e.g. legacy upgrade compared to Developed Item contracts) as well as by Service manning policy.

The type of acquisition programme may affect the ability of the Solution Provider to meet the anthropometric requirements or place conditions on the anthropometric requirements that it is reasonable to expect the Provider to satisfy. For example, in legacy upgrade programmes, limitations of the base platform may limit the size of the population that can be accommodated. Similarly, the space available in a fast-jet cockpit may constrain the buttock-to-knee length of the pilot (to maintain safety during ejection); the size of the turret ring in an armoured vehicle programme may place a limit on the maximum shoulder breadth of turret occupants; and the ceiling height in a passenger compartment may limit the sitting height of passengers.

Percentile limits for aircrew are normally defined as the 3rd to 99th percentile. Selection criteria for aircrew (for example sitting height, buttock to knee length and reach) are based around the limitations of aircraft cockpits, thereby limiting the number of potential recruits, and constraining the aircrew population at RAF selection. The use of selection criteria in the RAF means that a 99th percentile requirement should be specified.

Once the percentage of the population has been agreed, lessons identified from previous acquisitions suggest that it is worthwhile recording the bounding percentiles in the TAD along with the 50th and 99th percentile data where appropriate, i.e. provide data for the 5th, 50th, 95th and potentially 99th percentile in the TAD.

4.3 SELECT RELEVANT ANTHROPOMETRIC DIMENSIONS

Not all anthropometric dimensions are relevant to all acquisition programmes. The Anthropometric Survey measured 120 individual static dimensions (Pringle, 2011). It would be impractical to specify this many anthropometric dimensions in the TAD (likewise it would be impractical to test against this many dimensions later in the acquisition programme). Therefore, a subset of the critical dimensions are selected which are of specific relevance to the procurement programme. The number of dimensions required can vary significantly. Land Vehicle TADs, as a minimum, should include 16 critical dimensions (in accordance with TG10.2 (Land Vehicle TG)). Other Systems may require the specification of different anthropometric measures. A guide to the use of different anthropometric measures is provided in Table 4.

> **Design Best Practice Note 08:** Data recorded in the Summary tables in Appendix H are nude anthropometric data. Clothing and equipment corrections will need to be applied as appropriate for the capability being procured.

The summary data tables in Appendix H may then be used, with the percentile limits identified in 4.2 to generate the nude anthropometric data for the TAD.

4.4 IDENTIFY CLOTHING ENSEMBLES

The TAD should record the Acquirer's assumptions concerning the clothing and equipment ensembles worn by the target audience. The TAD should provide:

> **Design Best Practice Note 09:** Changes to the TAD post contract award may be costly to both the Solution Provider and the Acquirer.

(a) Definition of clothing ensembles;
(b) Clothing context;
(c) Layering of clothing ensembles; and

(d) Clothing modifiers.

> **Design Best Practice Note 10:** Changes in clothing and equipment ensembles through life can have a significant impact on crew comfort and safety. The introduction of new body armour designs for example has had a significant effect on emergency egress and CASEVAC in a number of legacy land platforms.

The clothing and equipment ensembles should be defined taking account of the full range of environmental conditions in which the system will have to operate, including special environments such as the Chemical, Biological, Radiological & Nuclear (CBRN) and Extreme Cold Weather (ECW).

The TAD may also need to define the clothing context – the configuration required by individual crew roles and tasks. For example, it is likely that vehicle crews will be dressed differently from vehicle passengers, so TADs should clearly specify the clothing and equipment ensemble worn at each position in a vehicle (if there are differences). A number of different ensembles worn by crew role and environmental condition may be envisaged. Particular assumptions that are useful to record include personal load carriage configurations (such as webbing pouches), body armour configurations and personal weapon stowage (such as leg or chest pistol holsters). The clothing and equipment ensembles described in the TAD should, of course, be those used in development trials and environmental testing. Further detail concerning environmental requirements is provided in TG5.1 "The External Environment".

The layering of clothing ensembles is also an important factor that should be considered. Body armour in particular has a tendency to compress the clothing bulk underneath. Therefore, understanding the correct layering of clothing is fundamental to subsequent trials activities. Where possible, images of users dressed in the clothing bulk should be provided in the TAD to enable industry to visualise and model the clothing ensembles more easily.

Clothing modifiers should be included in the TAD in accordance with the specified clothing ensembles. Clothing modifiers provide the clothing additions to be applied to the nude anthropometric dimensions. Further information is provided on available clothing modifiers in section 7.

4.5 DEFINE THE TASKS / FUNCTIONS THAT USERS WILL PERFORM

During the EHFA process, practitioners should seek to understand the Human role in the system, and the high-level tasks and functions that the user will have to perform. This may be achieved through Task Analysis activities such as Hierarchical Task Analysis (HTA) or through other Systems Engineering activities such as Use Case Modelling / MOD Architectural Framework. Lessons identified from previous acquisition programmes suggest that task analysis data should be considered at three levels:

- Human functions;
- Human tasks; and
- Human actions.

> **Design Best Practice Note 11:**
>
> A high-level list of human functions and tasks makes a useful checklist for assessing anthropometric compliance through the course of a development contract.

At the requirements level, the authority (MOD and FLCs) should focus on specifying the human functions and high-level tasks in the system. Less emphasis should be placed on the analysis of human actions as this will fall much more into the solution space and therefore become the responsibility of the Solution Provider. HFI Process requirements should be placed on the Solution Provider to generate the Task Analysis following contract award, with particular focus on the development of solution-specific elements of the Task Analysis, including the Human Actions. The human functions and tasks provide the task context against which the anthropometric requirements set should be assessed, shaping trials activities and identifying potential anthropometric issues and risks in the System.

5 GENERATE ANTHROPOMETRICS SYSTEM REQUIREMENTS

The development of clear anthropometrics requirements is fundamental to the subsequent application of anthropometrics in design. In the first instance, the URD must provide adequate linkage for the development of HF and anthropometric requirements in the SRD.

The SRD must contain anthropometrics requirements. There does not need to be a huge number of anthropometric requirements in an SRD; however, it is advantageous to provide as much supporting information as is available, as well as a number of HFI Process requirements for anthropometrics in the SoR.

Candidate anthropometry technical requirements for inclusion in an SRD are collated in Appendix C (they have been highlighted in blue boxes throughout the main body of this TG). These HF requirements are also linked (for traceability purposes) to the relevant generic HFSRs given in Defence Standard 00-251 (i.e. HFSR-1.1: "The system shall accommodate the anthropometric and physical characteristics of the specified User population (including the relevant clothing corrections"). Thus, the candidate requirements contained in this TG form the lower level of a hierarchical set derived from Defence Standard 00-251.

The effectiveness of the requirements will be dependent on each of the requirement's attributes. The attributes that must be defined for each anthropometric requirement in the SRD are as follows:

- Requirement text;
- MoP;
- Requirement priority; and
- Verification criteria.

Anthropometric requirements in the SRD may also have to be supplemented with supporting information such as the TAD and other related requirements.

5.1 REQUIREMENT TEXT

The Requirement text identifies the key principles that must be applied in the design of the System as a whole. The requirement text must abide by the SMART principles in order to ensure that the Solution Provider can deliver to the requirement. But to understand what a SMART anthropometric requirement is, it must be broken down into its component parts:

- **S** The requirement must be Specific – it must identify the intended user population (normally this will be UK-only data, although some multinational programmes may have to consider other user populations);
- **M** The requirement must be Measurable – it must include or reference the anthropometric measures, percentile ranges or boundary cases in the population against which the design will be assessed and verified;
- **A** The requirement must be Achievable – it must comply with the constraints of the system (this may be particularly important in Commercial Off The Shelf (COTS) acquisitions and legacy system upgrades, where features of the base platform such as the size of the turret ring (in an armoured vehicle) may limit accommodation of the user population);
- **R** The requirement must be Realistic – it must identify the context in which the requirement applies, details of tasks and functions performed, and reference to environmental conditions (normally this will be UK-only data, although some multinational programmes may have to consider other user populations);
- **T** The requirement must be Time-related – Timescales for proving must be clearly defined.

The link between anthropometric requirements and task performance can be maintained by linking the requirement to a task analysis, or a set of use cases. This can be achieved through the requirement text and through the requirement MoP. A high-level task analysis, functional analysis or set of use cases should have been generated as part of the EHFA process. Linking these analyses to the anthropometric requirements provides context to the anthropometric fit requirement, maintains a link to task performance, and can provide a checklist for anthropometric requirement assurance

and acceptance throughout the acquisition process. Linking the requirement to task performance has been seen to improve physical assessments conducted during assurance activities by preventing contractors from cherry picking people of the right size who can complete the tasks. Assuming that the policy decision has been made to accommodate the 5th to 95th percentile the overarching anthropometric fit requirements may become:

> ***Candidate HF System Requirement 04:***
>
> *"The System shall accommodate Crew and Passengers of body dimensions 5th percentile male to 95th percentile male as defined in a TAD, dressed in all clothing assemblies whilst performing all tasks (as defined in the Task Analysis)"*
>
> ***Candidate HF System Requirement 05:***
>
> *"The System shall accommodate Crew and Passengers of body dimensions 5th percentile female to 95th percentile female as defined in a TAD, dressed in all clothing assemblies whilst performing all tasks (as defined in the Task Analysis)"*

In this instance the male and female requirements have been split. The authority may wish to split male and female anthropometric requirements in order to atomise the requirements and ensure that the nuances between the populations are adequately accounted for in the design. Splitting the requirements may also be beneficial to maintain transparency during any requirement trading that may have to occur during the acquisition process. Postural clearances should also be included in the requirement MoP, or potentially raised as separate requirements, if not included in the MoP or a Design Guide. Postural clearances are required to ensure that the personnel have sufficient space to adjust their posture and prevent contact injuries from impacts with workspace equipment.

Anthropometrics can provide a significant differentiator between Solution Providers' designs; as such the authority may wish to specify "Threshold" and "Objective" levels of performance for the anthropometric requirements. The Threshold level defines the minimum required level of performance, while the Objective level is defined as the maximum performance expected in System acceptance (Ministry of Defence, 2018). Although objective requirements are frequently removed during contractual negotiations, they can provide a useful differentiator in the assessment of different Solution Providers' bids and set an expectation in the Solution Provider organisation for anthropometrics. For example, an objective requirement may encompass a greater percentile range such as 3rd – 97th, while the threshold requirement is specified as 5th-95th percentile.

The provision of the TAD forms a critical part of the SRD, as may the Task Analysis or System Use Cases if used as a means of acceptance. As such, the TAD and Task analysis should be referenced in the requirements text or MoP.

During requirements development it can be useful to employ Computer Aided Design (CAD) reference concepts or basic mock-ups to de-risk the anthropometric requirements set. A reference concept enables the Project Team (PT) to visualise the problem space and understand the feasibility of the requirements set, particularly when considering the design of confined spaces such as vehicle interiors. The use of reference concepts also enables derivation of particular anthropometric requirements for the system being procured. For example, reference concepts may be used to derive anthropometric requirements and design guidance for the minimum internal roof height in platforms.

> **Design Best Practice Note 12:** A Reference Concept is a conceptual representation of the solution (normally a CAD model or physical mock up) developed to understand the feasibility of the requirements set.

Case Study:

The use of Reference Concepts and Technology Demonstrator Programmes (TDPs) in the MOD proved useful during requirements development for the Future Rapid Effect System, Utility Vehicle (FRES UV) and the Medium Armour Tracks Team, Specialist Vehicle (MATT SV). It enabled the PT to determine what was possible when developing the requirements for FRES UV and SV Scout, both of which relied on the use of Modified Off The Shelf (MOTS) vehicle hulls. Reference Concepts can be particularly important when considering the full requirements set, and for identifying areas where trades may be required between requirements.

The use of reference concepts enabled the identification of minimum roof height requirements for the ambulance and personnel carrying variants, using crew and passenger task-based assessments in a Digital Human Modelling tool and subsequent mock-up trials to further develop the requirements for internal roof height.

Lessons Learned

1. *Where an acquisition is based on the constraints of a legacy or Off The Shelf (OTS) platform, the generation of reference concepts provides a useful means of understanding the feasibility of meeting the requirements and identifying areas where requirements trades may need to be considered later in the acquisition process.*

Related requirements should also be raised for posture and postural support to provide further context to the accommodation requirement. For example, it is immediately evident that the driver illustrated in Figure 6 will not be comfortable and will have difficulties operating the pedals and completing other key activities. However, some engineers may argue that in this instance the Driver has been accommodated as he can be physically squeezed into the space available. Providing linkage to a task set through the requirement and related postural and clearance requirements should reduce the likelihood of this type of debate arising.

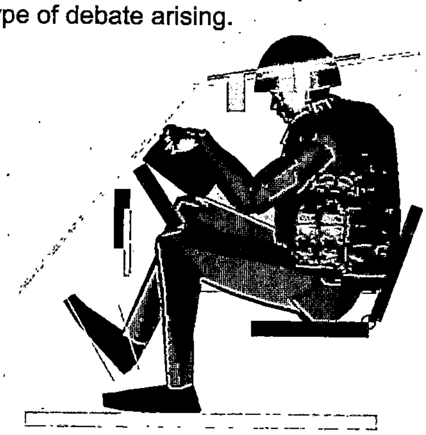


Figure 6 – Cramped Driver's Posture in an Armoured Vehicle

The postural angles required for a Driver are illustrated below in Figure 7.

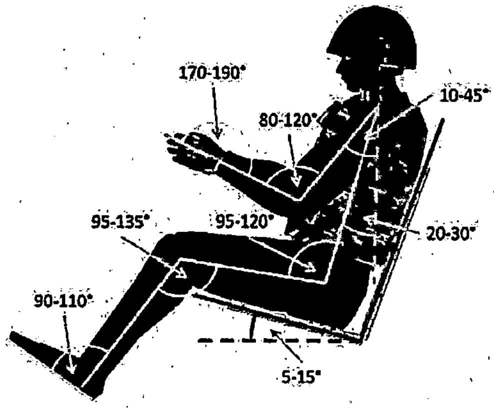


Figure 7 – Driver Postural Requirements

Postural support should also be considered in the requirements set. Requirements for postural support include the provision of headrests, armrests, footrests or features in the seat back to accommodate body armour plates. Failure to include posture in accommodation requirements makes it difficult for the HF practitioner to justify the physical volume required for the user to maintain comfort. An example of a postural requirement for a Driver's crewstation might be as follows:

Candidate HF System Requirement 06:

The System shall provide the Driver with a crewstation which provides a supported seated posture in accordance with TG1.1 Anthropometry Technical Guide Figure 7.

Postural requirements will vary depending on whether the occupant is seated or standing and the tasks which he/she is performing. Further guidance concerning posture is provided in TG4.1 Working and Living Spaces.

Postural requirements should be validated against any known constraints in the design. In a legacy platform upgrade these may be the size of the turret ring or the height of the roof. Issues such as these should be identified during the EHFA and accommodated in the requirements set and PT RAIDO, if necessary. Checking the feasibility of design constraints using reference concepts or TDPs can prove a useful activity in the requirements development process to prevent contractual negotiations later in the acquisition process.

Comfort requirements are difficult to include in SRDs due to their inherently subjective nature (therefore falling outside of the SMART requirement criteria). Consequently, comfort is often equated to the provision of good posture and prevention of postural stress, thereby providing further support for the need to provide postural requirements in the SRD. While short term discomfort may be acceptable in difficult circumstances, longer term discomfort is not sustainable and can lead to health problems. Therefore, comfort may still need to be addressed through HF process requirements in the statement of requirement.

Design Best Practice Note 13: The Solution Provider should demonstrate how comfort has been assured in the development of the design solution.

Postural clearances should be included in the accommodation requirement MoP.

5.2 REQUIREMENT MEASURE OF PERFORMANCE

The MoP provides the criteria against which a requirement will be assessed in subsequent assessment, development, and acceptance activities. Therefore, the MoP for the requirement must be measurable. For example, if the requirement specifies the 5th – 95th percentile, the MoP must define the population data from which this range is extracted, the clothing that the user will be wearing and the tasks they will be performing. Thus, the TAD and some form of task analysis or use case analysis must be referenced in the requirement MoP.

The TAD may be supplemented with CAD manikins representing the extreme cases of users to be accommodated. These "boundary manikins" may be used in the development and assessment of developing CAD designs and may be particularly useful in overcoming contractual negotiations concerning manikin size.

It is also useful to provide the Solution Provider with a task analysis against which the anthropometric requirements will be tested. This helps set the expectation and the planning of Validation and Verification (V&V) activities through the programme, as well as providing a means of tracking progress against the assessment of the anthropometric requirements set.

5.3 REQUIREMENT PRIORITY

The requirement priority provides an indication of the potential for trading relative to:

- Other requirements in the same SRD;
- The impact on satisfying User requirements (Ministry of Defence, 2018).

Each requirement may be prioritised in the SRD as follows:

- Mandatory (M) – A requirement that cannot be traded (e.g. legislative requirements);
- Key System Requirement (KSR) - key to the achievement of the mission, or capability;
- Priority 1 - A high priority requirement, with low potential for trading. Typically, permission would be required to deviate from MOD policy, or the satisfaction of a Key User Requirement (KUR) would be prejudiced;
- Priority 2 - A medium priority requirement – tradable with care. Satisfaction of a high priority UR might be prejudiced; and
- Priority 3 - A low priority requirement – the first choice for trading (Ministry of Defence, 2018).

Generally, the lower the priority of the requirement, the lower the chance of the requirement surviving the development process as it is more likely to be traded for higher priority requirements during design optimisation. Therefore, anthropometric requirements should be considered as KSRs in most acquisitions. Some anthropometric requirements, such as those for emergency egress and CASEVAC may even have to hold a Mandatory level of priority on grounds of their safety critical nature.

5.4 VERIFICATION CRITERIA

The acceptance and assurance of anthropometric requirements must also be considered and defined at the requirements definition stage. The verification criteria define the testing that the Solution Provider must perform to prove the acceptability of the solution. The type of acquisition – Development Item or Urgent Operational Requirement (UOR) – will drive the timescales and the type of acceptance and assurance activities expected. However, irrespective of acquisition type, these activities need to be defined and agreed between the Acquirer and Solution Provider. Progressive assurance should be considered in the requirements set and defined in order to enable the Solution Provider to generate acceptance plans which meet the Acquirer's expectations.

Assurance and Acceptance are likely to require a combination of two or more different V&V activities. Typical final acceptance will normally be based on a full User trial as part of standard acceptance. However, it is advisable to specify additional progressive assurance activities, to monitor design progress at key design reviews. Progressive assurance activities may include the following:

- Design Inspection;
- Modelling & Simulation;
- Development Test; and
- User Trial.

5.4.1 DESIGN INSPECTION

Design inspections may be used, particularly during the Concept phase, to assess the design against anthropometric data tables. These may include, for example, sitting height and basic accommodation measures such as hip breadth and shoulder breadth. Design inspections are usually conducted using 2D drawings, therefore limited analysis can be performed at this stage.

5.4.2 MODELLING AND SIMULATION

Modelling and simulation includes the use of Digital Human Modelling (DHM) to assess anthropometric fit (DHM is discussed further in section 10). This type of analysis can be particularly useful in a development contract to assess different design options and in instances where building a full-scale mock-up may be impractical (such as for many naval ships). Modelling and simulation are useful tools but have some limitations when gaining user buy-in and when assessing some activities, such as CASEVAC, for which the effect of a cramped space on human performance is hard to accurately simulate.

Case Study: Digital Human Modelling

During the development of Scout SV Digital Human Modelling was used extensively to de-risk elements of the system design. Anthropometric fit, crew posture and emergency egress were all identified as programme risks during the EHFA. Therefore, DHM was used extensively to de-risk the developing design solution, prior to a vehicle mock-up being available for testing. DHM proved useful in identifying issues and optimising design solutions but could not fully replace the need for development tests using mock-ups.

Lessons Learned:

1. *DHM enabled design solutions that would definitely not meet the requirements set to be rapidly dismissed prior to committing to building mock-ups.*

2. *Although modern DHM tools are very powerful, they do not currently do away with the need for mock up testing, particularly for time-based requirements such as emergency egress.*

   Mock-ups provided a useful means of validating the DHM modelling, particularly when considering the postures adopted by vehicle crewman.

5.4.3 DEVELOPMENT TEST

Development tests tend to use mock-ups, simulators and prototype equipment to test the performance of the system. Development tests are particularly useful for assessing the more dynamic aspects of operator tasks. These may include subjective aspects such as comfort, as well as time-bound requirements, such as emergency egress, that are very difficult to model effectively.

Case Study: Testing Using Representative Clothing and Equipment

During the early development of the Hawk Aircraft, mock up testing was used extensively to de-risk the cockpit layout design and ensure that the pilot could perform their tasks within the physical confines of the cockpit. However, early in the mock-up testing phase it became apparent that there were significant differences between trial results concerning the achievable level of stick travel. Fortunately, the design team identified that initial testing had been conducted without inflating the G-suit trousers worn by pilots to prevent blood pooling in the legs during high g manoeuvres. Once the G-suit trousers were inflated the level of achievable stick travel reduced significantly, highlighting an additional constraining factor that initial test had overlooked.

Lessons Learned:

1. *Development testing must be conducted with personnel dressed in appropriate clothing and equipment in order to obtain accurate results.*

2. *All settings and constraining factors must be identified and recorded within Detailed Test Schedules for requirements testing. Test Schedules must accurately describe all parameters and equipment states for testing to ensure repeatability of testing and results.*

5.4.4 USER TRIALS

Final acceptance is normally based on the results of User Trials. These trials may be split into static and dynamic trials to test system performance on the actual equipment. The nature of User trials may vary significantly between acquisitions. For example, it is unlikely that a prototype aircraft carrier would ever be built and therefore testing has to be conducted on system component prototypes and the first of class. However, in land systems it is wholly likely that a prototype land vehicle would be built and tested (possibly to destruction). Static trials are generally conducted with the equipment in a controlled environment, using a combination of real and virtual inputs to stimulate platform systems. Testing anthropometric requirements will require a combination of static and dynamic trials. While static trials may be required to assess basic anthropometric fit and postural angles, dynamic trials are also required to ensure that suitable clearances have been provided to maintain comfort whilst completing the battlefield mission (BFM).

Dynamic trials are conducted with a full system prototype and undertaking BFMs in representative environments. Final acceptance will normally be based on the results of dynamic trials and used to verify progressive assurance activities conducted in the development of the solution. Dynamic trials are particularly important in testing anthropometric fit and the effect of platform motion and restraint systems in different operational environments.

5.5 SUPPORTING INFORMATION

A range of supporting information may be provided with the anthropometric requirements in the SRD to capture the richness of information generated in the EHFA and de-risking activities conducted during the Concept and Assessment Phases. Supporting information provided in support of the SRD might include:

- TAD (should be provided in all procurements);
- Task Analysis;
- Use Cases;
- Design Guides (capturing lessons from studies in the Concept and Assessment Phases); and
- Anthropometric Issues and Risks (particular issues and risks from the programme risk register / RAIDO).

5.6 GENERATION OF HF PROCESS REQUIREMENTS FOR ANTHROPOMETRY

In general, the requirements in the SRD and associated verification criteria will define the scope of much of the anthropometric design effort employed in the generation of the design solution. Some process requirements may also be required in the SoR for HFI in general, and anthropometrics specifically. HF process requirements should ensure that the Solution Provider adopts a HCD process to ensure that the design approach places the user (including operators and maintainers) at the central focus for design decision-making. Every design decision should be reviewed in terms of its impact on the users, undertaking tasks in the context of use. HCD will require such reviews to examine engineering detail, but also to consider the wider impact at whole-system level and at capability level. This section contains guidance that could be used as the basis for generating design process requirements. Design best practice notes are presented in full under Appendix E.

Design Best Practice Note 14:
The Solution Provider should adopt an iterative Human Centred Design process to ensure that operators and maintainers can complete their tasks in accordance with the context of use.
Design Best Practice Process Recommendation 3
The Solution Provider should demonstrate that all physical components that constitute workplaces, including platforms, workspaces, work rooms, and workstations, that comprise or are modified by the Solution, have been based on a systematic analysis of:

a) Functional needs;
b) Context of use;
c) Operational conditions of use;
d) User clothing and PPE considerations;
e) The physiological, psychological and sociological characteristics of the Operator Population, including human error characteristics;
f) Human performance shaping factors
g) Human needs.

Lessons from past acquisitions suggest that building an anthropometric audit process is valuable as a means of tracking anthropometric compliance and design maturity through programme design reviews as the system solution develops. The nature of the audit may vary with the system being procured but building anthropometric audits into the entry criteria for design reviews has proved useful in the past. These should be aligned with the agreed maturity schedule defined in the System Readiness Levels (SRLs).

Design Best Practice Note 15:
The Solution Provider should conduct an anthropometric design audit as part of each major programme design review.

HF process requirements concerning anthropometry may be required where particular risks are present in the system that must be de-risked through the course of the demonstration phase. Particular requirements may concern the provision of CAD data, provision of particular mock-ups and mock-up testing. Overall, the HF process requirements for anthropometric design should ensure that the Solution Provider manages anthropometric issues and risks through the design process.

Design Best Practice Note 16:
Solution Provider should adopt a systematic and iterative approach to the identification and resolution of all anthropometric issues and risks throughout the contract.

Although the Acquirer will specify a proposed set of verification criteria against each system requirement, these will need to be agreed with the Solution Provider. The Solution Provider should propose and agree the exact methods of verification to be applied against each anthropometric requirement, including the agreement of the final verification method against which the design will be accepted.

Design Best Practice Note 17:
The Solution Provider should identify and propose means of demonstrating compliance with each requirement. The Solution Provider shall submit their proposals to the Acquirer for agreement.

Through the course of design, some trade-off between requirements may be required. The Solution Provider must maintain records to show the traceability between each requirement in the SRD and the Solution. Such records should be maintained as Living Documents throughout the life of the contract, forming part of the contract deliverables. The deliverable set may vary between contracts, but generally key decisions should be recorded through the RAIDO, HFI Case or HFI Log. The Solution Provider must make arrangements to enable stakeholders, SMEs, user representatives and operators to take part in anthropometric requirements trade-off decision-making. Trade decisions concerning anthropometrics should be identified at the HFI Working Group and flowed up through the Requirements Working Group and Capability Integration Working Groups for final decision-making. Key trade decisions should then be recorded through project documentation such as the RAIDO and HFI Case.

Design Best Practice Note 18:
The Solution Provider shall create and maintain records of requirement trade-off decisions.

Guidance concerning the precedence of anthropometric information sources should be agreed between the Authority and the Solution Provider. This information may be recorded in the RAIDO, HFI Assumptions Register or as part of the SoR for Anthropometrics.

Design Best Practice Note 19:
In selecting sources of operator population characteristics data, the following order of precedence shall be followed unless the Solution Provider or the Acquirer can demonstrate that more relevant data exist:

a) Operator characteristics data contained in any target audience description issued by the Acquirer;
b) Operator characteristics data contained in TG1.1 "The Anthropometry Technical Guide";
c) Operator characteristics data that can be shown to relate specifically to the expected User population or the population from which UK Defence operator populations are drawn;
d) Operator characteristics data that relate to a more general population.

Finally, detail should be provided in the SoR for the documentation of the results of anthropometric studies. Anthropometric studies will normally be documented as part of the HFI Case; example wording for the anthropometric section of this document is provided below (note this will need to be edited in accordance with the type of acquisition programme):

Design Best Practice Note 20:
The Solution Provider should provide details of the activities undertaken to investigate the design of the system and the accommodation of the user / maintainer:

a) Details of the activities undertaken to investigate the accommodation of the crew, passengers, and maintainer and in identifying key constraints to operator accommodation;
b) Details of the activities undertaken to investigate crewstation and workstation physical design and integration and the outcomes of these activities;
c) Details of activities undertaken to investigate crewstation adjustability and the accommodation of the user population;
d) Details of the activities undertaken to investigate access and egress as well as emergency evacuation;
e) Details of the activities undertaken to investigate hatch aperture sizes employed in the final design;
f) Details of the activities undertaken to ensure crew seating supports the accommodation of the user population, as defined in the Target Audience Description, and as appropriate to user and platform role;
g) Details of CAD model reviews held with the Users and the outcomes;
h) Details of physical mock-up trials held with Subject Matter Expert and User representatives for the different vehicle types and the outcomes of the trials.

6 STRUCTURAL ANTHROPOMETRIC DATA

It is not possible to include here every dimension a designer may require. Therefore, a list of those dimensions considered to be the most representative in the field of equipment design and workspace layout has been compiled. This list comprises the 37 most-often applicable distances (and one weight) from the 120 measurements that make up the UK Tri-Service Database (Pringle, et al., 2013).

Design Best Practice Note 21: Further information concerning anthropometric body landmarks can be found in The ANSUR II Pilot Study: Methods and Summary Statistics Report (Paquette, et al., 2009).

Equipment should be designed around the operators who have to interact with it, both now and in the future. During the time in service, changes to equipment in the platform, the sex mix of users, changes in the general population (see section 4.1.1) and changes in the clothing and equipment ensembles worn, all have an effect on the suitability of the crew-space. While this makes the problem complex, it is possible to address it satisfactorily. Figure 8 and Table 4 list all anthropometric variables in common use with examples of how they should be used when applying anthropometry in design.

Table 4 – Anthropometric data measurement descriptions and uses

	Definition	Description	How to Use It	Figure 8 Ref #
1	Stature	The vertical distance between a standing surface and the top of the head (vertex).	Used to determine minimum vertical clearance in standing workplace. Use 95th %ile male for clearance above head.	A
2	Eye height, standing	Height of the eyes above the standing surface (floor).	Can be used to locate visual displays for standing operators. The displays should be positioned to accommodate the specified anthropometric range without the need for excessive flexion or extension of the neck.	A
3	Acromial height	The vertical distance between a standing surface and the acromion bodymark on the tip of the left shoulder.	Used to specify the maximum allowable height for controls so that 5th %ile females need not elevate the arms above shoulder height to operate controls and may be used as a measure of maximum lift height (does not remove the need for a manual handling risk assessment though).	A
4	Elbow rest height, standing	Vertical distance from the standing surface to the lower edge of the olecranon process (bony tip of the flexed elbow) with the elbow flexed at 90°.	Used to design the maximum allowable desk height for standing workers.	A
5	Foot Length	Distance from heel to the longest toe.	Used to determine clearance for foot spacing of pedal, etc.	F

	Definition	Description	How to Use It	Figure 8 Ref #
6	Bideltoid breadth	Width of the shoulders at the widest point. (The horizontal distance between the maximum prominences of the left and right deltoid muscles.)	Use for clearance at shoulder level, to determine the minimum width of narrow doorways, corridors, etc., to provide clearance for those with wide shoulders. Generally, use 95th %ile male to specify minimum aperture widths (in cases where a hatch aperture is used for emergency egress use 99th %ile dimensions).	B
7	Biacromial breadth	The horizontal distance between the left & right acromial bodymarks.	Used to determine the centres of rotation of the shoulder. for clothing sizing and multi-variate reach analysis.	B
8	Crotch height	The vertical distance between the standing surface and the crotch with feet apart (height of the perineum from the standing surface).	Used for clearance of obstacles, for example guard rails that may need to be crossed. Use 5th %ile female.	B
9	Shoulder height, standing (90mm from mid-line body)	The vertical distance between a standing surface and the shoulder – 90mm from the mid-line body.	Can be used as a reference height for functional reach and for finding the zone of convenient reach at shoulder level for standing users. Use 5th %ile female for maximum reach distance.	C
10	Hip breadth, standing	Width of the buttocks at widest point.	Used to determine the space requirements necessary for clearance, Use 95th %ile female.	D
11	Waist (natural) circumference	The horizontal circumference of the waist at the level of the natural indent.	Use for belt circumference. Use range from 5th %ile female to 95th %ile male.	D
12	Inter-elbow span	The horizontal distance between the right and left elbows stretched laterally at 90 degrees.	Used to determine approximate centre of rotation of upper arm, determining zone of comfortable reach by providing reference for elbow functional reach; reference datum for location of fixtures, fittings and controls. Also used for clearance in passages for donning of clothing, PPE (personal protective equipment), etc.	E
13	Buttock - Popliteal length	The horizontal distance between the vertical surface at the rear of the buttocks and the popliteal point behind the left knee, while in the seated position.	Can be used to determine seat pan lengths; use 5th %ile female to determine the maximum seat pan length (unless an adjustable seat pan length is incorporated in the seat design).	F

	Definition	Description	How to Use It	Figure 8 Ref #
14	Buttock-knee length	The horizontal distance between the vertical surface at the rear of the buttocks and the front of the knee, while in the seated position.	Used to determine seated clearance requirements at the knee; use 95th %ile male dimensions (note allowance should also be made for comfortable knee angles and foot accommodation).	F
15	Stomach depth (to wall)	The horizontal distance between the vertical surface at the rear of the buttocks and the maximum protrusion of the stomach, while in the seated position.	Used to determine the minimum clearance required in confined spaces. Use the 95th %ile male value.	F
16	Elbow functional reach	The horizontal distance between the elbow and the thumb tip.	The dimension of the reach envelope for the upper arm around an operator. Arm movements should be kept in the normal work area to eliminate reach over 400 mm for repeated actions. These data are applicable to the design of all vehicle cockpits and cabins. 5th percentile female data should be used.	G
17	Elbow rest height, sitting	Height of elbow above the seat surface, joint flexed at 90 degrees.	Used to design the maximum allowable desk height for seated workers, height of armrests, reference point for heights of desktops, keyboards, etc.	G
18	Vertical functional reach, sitting	Vertical distance from seat surface to the tip of the left thumb.	The dimension of the reach envelope around an operator can be used to locate controls so that seated operators can operate them without having to lean forward away from the backrest or twisting the trunk. Arm movements should be kept in the normal work area to eliminate reach over 400 mm for repeated actions. These data are applicable to the design of all vehicle cockpits and cabins. 5th percentile female data should be used.	G

	Definition	Description	How to Use It	Figure 8 Ref #
19	Functional reach (horizontal thumb tip reach), sitting	The horizontal distance between the wall at the back of the shoulders to the tip of the thumb.	The dimension of the reach envelope around an operator can be used to locate controls so that seated operators can operate them without having to lean forward away from the backrest or twisting the trunk. Arm movements should be kept in the normal work area to eliminate reach over 40 mm for repeated actions. These data are applicable to the design of all vehicle cockpits and cabins. 5th percentile female data should be used.	H
20	Sitting height	The vertical distance from seat surface to top of head (vertex).	Used to determine clearance required between seat and overhead obstacles. Can be used to determine ceiling heights in vehicles to provide clearance for users with tall sitting heights. Use 95th %ile male for minimum overhead clearance.	H
21	Eye height, sitting	Height of eyes above the surface of the seat.	Can be used as a maximum allowable dimension to locate visual displays for sitting operators. The displays should not be higher than the eye height of a short operator, so that short operators do not need to extend the neck to look at displays.	H
22	Thigh clearance height	The vertical distance between the stool sitting surface and the highest point of the upper surface of the thigh.	Can be used to determine the vertical clearance required under a table.	H
23	Stool height	Distance from floor to seat surface floor to the seat surface when the operator sits in the anatomical neutral position for seated measures (on an adjustable seat).	The 5th %ile female stool height is used to determine the maximum allowable height of non-adjustable seats. The 95th %ile male stool height is used to set the highest level of adjustment of height-adjustable seats.	I
24	Popliteal height	Vertical distance from the floor to the back of the knee at the Popliteal Fossa (popliteal tendon which extends back from the knee along the lower outer part of the thigh).	The 5th %ile female popliteal height is used to determine the maximum allowable height of front of the seat pan. The 95th %ile male popliteal height is used to set the highest level of adjustment of the front edge of a height-adjustable seat pan.	I

	Definition	Description	How to Use It	Figure 8 Ref #
25	Knee height, sitting	Vertical height of the top of the knee above the floor in sitting posture, with thigh parallel to the floor and the lower leg perpendicular to the floor.	Can be used to determine the thigh clearance required under a table.	I
26	Head length	Length of the head at the longest point.	Design of helmets, headphones, etc. Use 5th %ile female – 95th %ile male range to specify the amount of adjustability needed.	I
27	Pupil to vertex	The vertical distance between the pupil and the top of the head (vertex).	Reference point for eye height, used for optimal visual zones.	I
28	Head breadth	Maximum breadth of the head at the widest point (above the level of the ears).	Design of helmets, headphones, etc. Use 5th %ile female – 95th %ile male range to specify the amount of adjustability needed.	J
29	Hip breadth, sitting	The horizontal distance between the widest part of the hips in a seated position.	Used to determine the width of seats and lateral clearance at the hip for those with wide hips. Use 95th %ile female.	J
30	Head circumference	The circumference of the head just above the brow ridges and over the occiput.	Design of helmets, headphones, etc. Use 5th – 95th %ile range to specify the adjustability needed.	J
31	Foot Breadth	Maximum horizontal breadth, wherever found, across the foot, perpendicular to the long axis.	Used to determine clearance for foot spacing of pedal, etc.	J
32	Hand breadth	Breadth of the widest part of the hand (between 2nd and 5th metacarpals).	Breadth of the widest part of the hand. Used for clearance required for hand access, tool design, grips and handles, etc. Use 95th %ile male for minimum dimensions of handles.	K
33	Hand length	The length of the left hand between the stylion bodymark on the wrist and tip of the middle finger.	Used for clearance required for hand access, tool design, grips and handles, etc. Use 95th %ile male for minimum dimensions of handles.	L
34	Wrist circumference	The circumference of the wrist immediately proximal to the styloid process of the ulna.	Used for clearance required for hand access, tool design, grips and handles, etc. Use 95th %ile male for minimum dimensions of handles.	L

	Definition	Description	How to Use It	Figure 8 Ref #
35	Shoulder (Mid) height, Sitting	Distance from seat surface to the highest point on the left shoulder 90mm from the midline of the body.	Used to determine height above the seat of the upper arm. Can also be used as a reference height for functional reach and for finding the zone of convenient reach at shoulder level. Use 5th %ile female for maximum reach distance.	J
36	Chest Depth	Maximum horizontal distance from a reference plane to the front of the chest in men (front of the breast in women).	Generally, use 95th %ile female to specify minimum aperture depths (in cases where a hatch aperture is used for emergency egress, use 99th %ile dimensions).	I
37	Inter-pupillary Distance	The horizontal distance between the centres of the pupils when the subject looks straight ahead.	Used, for example, in the design of binocular devices.	D
	Weight	The weight of the individual is measured using a set of scales.	Used, for example, in the design of seating to determine the maximum loading under blast.	N/A

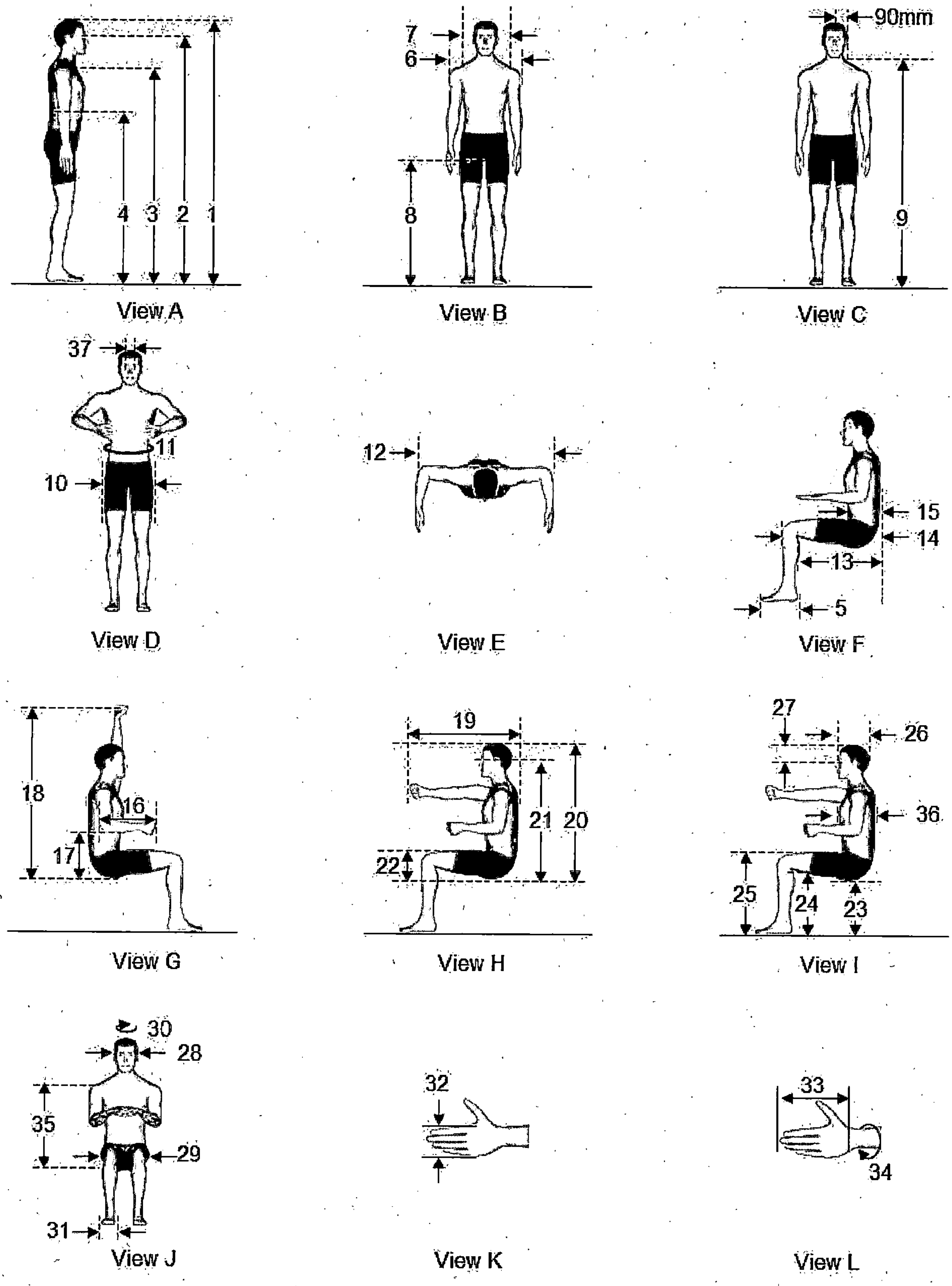


Figure 8 – Anthropometric Measurement Locations

7 CLOTHING AND EQUIPMENT

7.1 CLOTHING INCREMENTS

Clothing regimes worn by users add bulk to nude body dimensions. These can be broadly summarised as size increments expressed as linear measurements. Surveys are generally conducted on near-nude subjects. Clothing corrections must therefore be considered by designers when planning workspace layout and control positioning, etc.

The latest military anthropometric survey on Land forces (Pringle, et al., 2013) contains measurements on clothed individuals to estimate the required corrections for various clothing ensembles, including those for Operation Herrick (Summer), Operation Herrick (Winter), CBRN and Winter (ECW). The measurements were made with participants sitting on an adjustable, reclining seat and relevant measures with the seat at 0° and 20° of recline are available. The full set of clothing corrections can be obtained by running the database tool. The derived set of corrections for twenty key anthropometric measures is given in Table 6.

An important factor that determines the clothing correction to be applied is the operational (e.g. CBRN) and/or environmental conditions in which the equipment is to be used, ranging from perhaps arctic to tropical environments. For example, a 60 x 110 mm aperture handgrip which will comfortably admit the largest un-gloved hand needs to be increased to 100 x 200 mm for a man wearing arctic mittens (refer to Figure 9).

Design Best Practice Note 22: Substantial differences can occur in anthropometric data with the addition of clothes, tools and equipment.
An increase in the overall space occupied by a person due to bulky clothing is intuitive, but for overhead reach, for example, there is a **decrement** in limb movement due to clothing restrictions.

Design Best Practice Note 23: Allowance must be made for the clearance of the operator's gloved or mittened hand if the access is located externally and may require servicing in cold weather conditions.

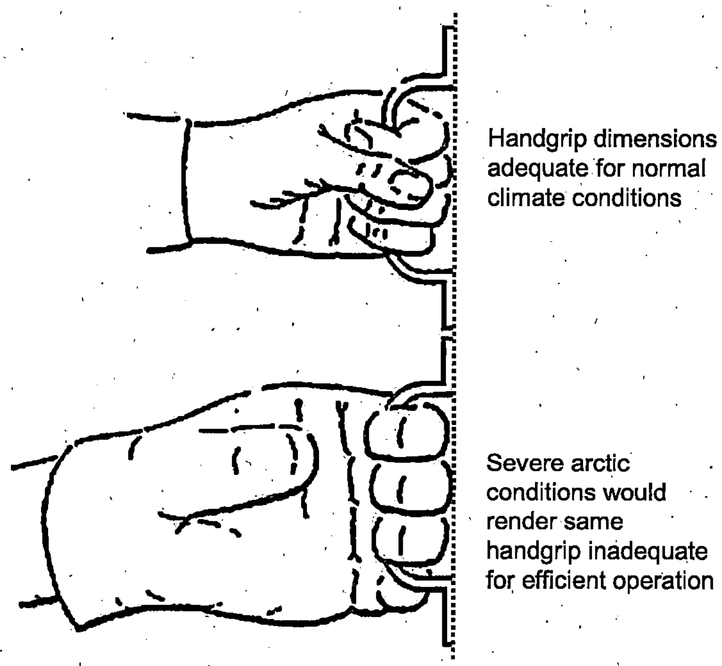


Figure 9 – Illustration of the importance of clothing correction

For further advice on usability testing whilst wearing PPE refer to sections 2.2 and 3 of "Usability of Interaction Devices Whilst Wearing PPE" (Pelly, et al., 2007). For example, the presence or threat of chemical and biological contaminants requires the human operator to use defensive measures which can impair efficiency and hence performance. Physical defence is provided by Individual Protective Equipment (IPE) comprising a smock with hood, trousers, plastic overboots, inner cotton and outer synthetic rubber gloves and a respirator (currently General Service Respirator). Physically, IPE is bulky; it restricts movement and increases the effective size of the body, hands, feet and head by as much as 50%. The respirator restricts peripheral vision and the wearer needs to turn his/her head more than normal. Equipment should allow adequate access room for hands, fingers and feet and extra room for the head to allow for both access and movement. Refer to TG4.1 "Working and Living Spaces", for further information.

Civilian footwear, with extremes of personal taste, can add substantially to the variability of stature as well as the mean. Clearance dimensions in workspace and passageways may require taking account of a variety of personal equipment and luggage (headsets, rescue gear, tool bags, etc.). Additions for clothing and footwear are absolutely vital for damage control, fire-fighting and emergency escape. In these circumstances, dimensions must be chosen which will allow 100% of the population to pass without impediment.

7.2 PERSONAL EQUIPMENT ENVELOPE

Equipment carried or operated by users and maintainers, may provide additional bulk to that of clothing regimes; this may markedly increase the volume or 'envelope' within which the users or maintainers work and must be taken into account when designing the areas/spaces within which tasks will be performed.

Military headgear may add over 50 mm stature and boots up to 30 mm. An example of a person wearing bulky equipment, such as a parachute, is shown in Figure 10, showing the dimensions of an aircraft escape hatch (note: these dimensions have been provided as a guide and will not be appropriate in all cases; for example if passengers are wearing body armour, webbing or other bulky equipment during ingress and egress the dimensions provided will have to be modified accordingly).

Design Best Practice Note 24: The dimensions in escape hatch design should be chosen to allow 100% of the population to pass through without impediment.

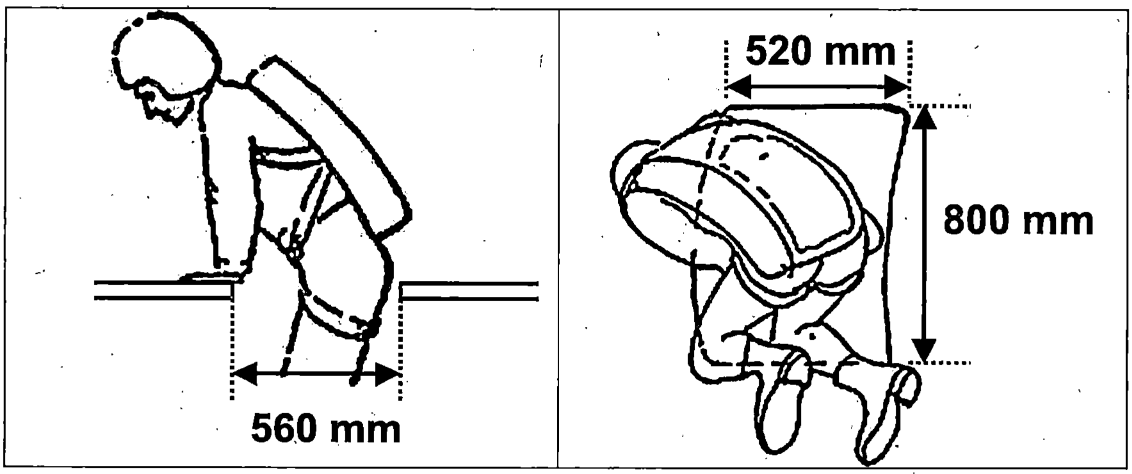


Figure 10 – Escape Hatch Illustrative Dimensions

Naturally, there are other types of equipment to be considered. For example, the infantry soldier may be carrying a significantly sized backpack and weapons, as well as wearing protective clothing.

7.2.1 LAND ENVIRONMENT

Since the introduction of the Combat Soldier 95 (CS95) and subsequent clothing, body armour and personal load carriage equipment systems, there has been an emphasis on re-configurability of load carriage to meet personal preference and mission requirements. This makes it impossible to identify a single, definitive clothing ensemble and so define a standard land environment set of clothing corrections for anthropometric measurements.

At the time of writing, the most recent study conducted is the Vehicle Anthropometry Study, performed in 2013 (Pringle, *et al.*, 2013). The study characterised land environment clothing and equipment corrections for two groups of vehicle users as follows:

- Vehicle Driver; and
- Vehicle Dismount.

> **Design Best Practice Note 25:** The VIRTUS programme, formerly PECOC (Personal Equipment and Common Operational Clothing), is intending to deliver an integrated head, torso and load carriage system which should replace Osprey body armour and associated load carriage systems. Once this has been delivered, the details in
>
> Table 5 should be updated to reflect the new clothing and equipment ensembles.

Clothing ensembles comprised the items in Table 5, which could be used as the basis of assumptions for the definition of clothing ensembles for future programmes in the land environment. The study quantified the anthropometric impact of the clothing and equipment ensemble based on the clothing ensembles employed from Operation Herrick 15 onwards. The clothing ensemble varies significantly depending on the time of year, and therefore the study quantified the impact of the following clothing configurations:

- Operation Herrick (Summer);
- Operation Herrick (Winter); and
- Winter ECW.

Table 5 – Vehicle Anthropometry Survey Clothing Ensembles (Pringle, *et al.*, 2013)

Serial	Item	Herrick Summer	Herrick Winter	Winter (ECW)
1	Own underwear and socks	Yes	Yes	Yes
2	Lightweight Shorts	Yes	Yes	Yes
3	Lightweight T-Shirt	Yes	Yes	Yes
4	Long-sleeved T-Shirt			Yes
5	Long johns			Yes
6	UBACS (with pads) (Tourniquets in each arm pocket)	Yes	Yes	
7	Smock combat, windproof temperate Multi Terrain Pattern (MTP) (Tourniquets in each arm pocket)		Yes	Yes
8	Combat thermal undershirt			Yes
9	Fleece (represents future Buffalo shirt)			Yes
10	Softie top		Yes	Dismount Only
11	Trouser combat, warm weather MTP (Personal Clothing System (PCS))	Yes	Yes	
12	Trouser combat, temperate MTP (PCS)			Yes
13	Softie trousers			Dismount Only
14	Belt General Purpose	Yes	Yes	Yes
15	Mk7 helmet	Yes	Yes	Yes
16	Gloves warm weather MTP	Yes	Yes	
17	Mittens inner, mittens outer and wristlets			Yes
18	Boots	Yes	Yes	Yes
19	Osprey body armour vest with front, back and side plates. (No collars/brassards)	Yes	Yes	Yes
20	Pouches on Osprey vest. Right: 1x first aid; Left: 2x ammo. Fixed on third MOLLE from BA front.	Driver Only	Driver Only	Driver Only
21	Osprey hip belt and yoke	Dismount Only	Dismount Only	Dismount Only
22	Pouches on Osprey hip belt (Left to right: 2x ammo, 1x water, 1x UGL 2x utility, 1x first aid, 1x Light Machine Gun)	Dismount Only	Dismount Only	Dismount Only
23	Tier 2 (Pelvic protection)	Dismount Only	Dismount Only	Dismount Only
24	Personal Role Radio (PRR) (on BA left shoulder) and PIHP (fixed below, 2 MOLLE loops in from left side)	Yes	Yes	Yes
25	Personal Hydration System (Camelbak®) (with 3 litres water)	Dismount Only		
26	Representative SIG Pistol & Blackhawk holster (on front of right thigh)	Driver Only	Driver Only	Driver Only
27	Knee pad (Left only)	Dismount Only	Dismount Only	Dismount Only

Data were also gathered concerning the impact of the CBRN equipment on the size of the head.

The Vehicle Anthropometry Study identified a broad range of clothing and equipment additions; for the convenience of users of this anthropometric guide, certain data have been extracted from the

Vehicle Anthropometry Study, in line with the anthropometric dimensions identified above in Table 4. These data are presented here in Table 6 (all spatial dimensions listed are provided in mm). These data may also be extracted from the anthropometric database.

Table 6 – Operation Herrick 15 Clothing Additions (Pringle, *et al.*, 2013).

Serial	Dimension	Driver			Dismount			Figure 8 Ref #
		Summer	Winter	Winter (ECW)	Summer	Winter	Winter (ECW)	
1	Stature	73.0	73.0	73.0	73.0	73.0	73.0	1
2	Foot Length	35.3	35.3	35.3	35.3	35.3	35.3	5
3	Bideltoid Breadth	118.5	164.1	175.6	118	150.5	166.6	6
4	Inter-Elbow Span	16.3	16.1	16.9	19.5	18.9	21.8	12
5	Buttock - Popliteal Length (Dismount With Knee-Pad)	5.4	10.1	10.9	147	144.5	155.6	13
6	Buttock-Knee Length (Dismount Includes Knee Pad)	13.4	16.8	23.5	131.3	129	126.7	14
7	Stomach Depth (To Wall)	185.6	187.7	189.9	164.2	182.5	192.5	15
8	Elbow Functional Reach	7.5	16	22.2	14.3	23.3	25.1	16
9	Elbow Rest Height, Sitting	5.8	5.8	16.6	5.8	5.8	21.7	17
10	Vertical Functional Reach, Sitting	-145.1	-159	-200.4	-121.9	-172.8	-200.6	18
11	Functional Reach (Horizontal Thumb Tip Reach), Sitting	32.8	27.4	28.7	46.4	30.8	41.8	19
12	Sitting Height	46.1	46.1	45.1	46.1	46.1	47.4	20
13	Eye Height, Sitting	-4.1	-4.1	-2.8	-4.1	-4.1	-0.8	21
14	Thigh Clearance Height (Driver Measures With Holstered Pistol)	80.7	77.4	76.9	4.8	2.5	7	22
15	Stool Height (Popliteal Height)	20.6	21.6	21.4	18.2	20.1	20.3	23
16	Knee Height, Sitting (Dismount Includes Knee Pad)	39.3	37.0	38.6	65.7	67.2	66	24
17	Hip Breadth, Sitting	31.3	39.4	50	247.4	245.2	253.6	28
18	Foot Breadth	13.1	13.1	13.1	13.1	13.1	13.1	30
19	Hand Breadth	-	-	7.4	4.6	-	7.4	31
20	Sitting Shoulder Height	-1.4	-2.6	8.1	0.9	3.7	14.6	34
21	Chest Depth	93.7	107.1	114.4	107.9	119	133.5	35
22	Weight (Kg)	23.27	25.32	26.26	29.31	31.39	34.4	

7.2.2 AIR ENVIRONMENT

As for Land systems, consideration is given to summer and winter clothing schedules, CBRN systems, contents of pockets, g-trousers and survival vest. A worst case would be taken (maximum volume occupied) and both digital manikin modelling and high fidelity, physical mock-ups trialled to look for clashes, snags and effects on mobility etc.

Guidance for aircrew clothing corrections is available from DEF-STAN 00-970 Part 1, Section 4 (MOD Military Aviation Authority, 2015). In summary, it advises:

(a) Eye position – the relationship between the Seat Reference Point (SRP) and eyeball position of subjects strapped into aircraft seats is complex. Detailed information has been published (Beeton, 1975).
(b) Shoulder breadth – the clothing assemblies will add 10-20 mm to the nude Bideltoid breadth (minimum and maximum respectively).
(c) Buttock-knee length - the clothing assemblies will add 10-20 mm to the nude buttock-knee length (minimum and maximum respectively).
(d) It is recommended that specialist advice is sought in the definition of appropriate clothing assemblies and additional aircrew equipment such as maps, CBRN protection, personal weapons, body armour, survival equipment and night vision goggles (NVGs).

7.2.3 MARITIME ENVIRONMENT

There are no specific clothing corrections available for the Maritime environment. To date, the data used have been taken from the civilian ADULTDATA document (Peebles, et al., 1998) (Table 7) and the Combat Service 95 (CS95) clothing ensemble formerly defined in Defence Standard 00-250, Part 3 Section 9 (Table 8) (Note: these data do not include allowances for Body Armour). These data are summarised below:

Table 7 – Clothing Corrections (from ADULTDATA (Peebles & Norris, 1998))

Serial	ADULTDATA Clothing Correction	Guidance
1	Shoes	add 25 mm to all relevant dimensions
2	Hats and Helmets	add 90 mm to all relevant dimensions
3	Protective Clothing	add 40mm to all relevant dimensions
4	Protective Gloves	Add 25mm to all relevant dimensions

Table 8 – CS95 Clothing Corrections (from Defence Standard 00-250, Part 3, Section 9)

Serial	Description	Combat	Cold Weather	Figure 8 Ref #
1	Stature	64	76	1
2	Eye height standing	27	36	2
3	Sitting height	38	51	20
4	Eye height sitting	1	10	21
5	Thigh clearance	4	23	22
6	Knee height	33	56	25
7	Buttock to knee length	5	51	14
8	Shoulder breadth (Bideltoid)	6	152	6
9	Hip breadth	13	152	29

Serial	Description	Combat	Cold Weather	Figure 8 Ref #
10	Abdominal depth	13	51	15
11	Foot length	41	68	5
12	Foot breadth	5	46	31
13	Hand breadth	N/A	43	32
14	Hand thickness	N/A	84	
15	Note 1: N /A = data not available			

The Naval acquisition standard, MAP 01/107, contains exemplar methods for generating human centred requirements regarding occupancy. However, it is assumed that HF specialists will be employed to determine the correct spatial envelopes for the accommodation required.

Embarked Royal Marines, it is assumed, would use a very similar clothing ensemble to Army personnel but other RN would probably not. The clothing corrections contained in the anthropometric tool cited previously (Pringle, *et al.*, 2013) are not specific to the RN personnel. Changes to some dimensions due to body armour could be expected to be similar, but the effects of belt and chest mounted pouches, for example, will probably not be the same (or may not be worn as part of the RN ensemble).

Design Best Practice Note 26: Figures above are intended as a guide only. With the issue of the Combat Soldier 95 (CS95) clothing system, which includes the MK6/6A combat helmets and boots, it is no longer possible to define a single combat ensemble.

8 FUNCTIONAL ANTHROPOMETRY

Functional (or dynamic) anthropometry deals with the dimensions of the workspace envelope needed by persons as they perform their work. Unlike static body dimensions, which are measured with the subject in a rigid, standardised position, dynamic measurements are made in working positions and vary accordingly.

Design Best Practice Note 27: Static body dimensions are taken in rigid standardised postures and will not reflect the dynamic nature of many tasks the user will perform.

8.1 REACH DIMENSIONS

For many workspace design problems, it is important to know how far an operator is able to reach in a given direction from a specified reference point. All data in the tables and figures (e.g. Appendix G and Appendix H) refer to straightforward anatomical distances (or static body dimensions), although it should be appreciated that an individual is able to reach a good deal further forward than this distance, by thrusting forward or protracting their shoulders, and by flexing and inclining the trunk. However, even this increased reach may be severely limited if the person is constrained by a tight harness, protective clothing or seat geometry.

Case Study: Restraint Harnesses
A bulletin from the Air Accident Investigation Bureau describes an incident which illustrates the issue of multiple, interacting critical dimensions and the impact of the implementation of locking restraint harnesses on pilot reach within an aircraft cockpit (Air Accident Investigation Bureau, 1993).

An aircraft was indicating problems with hydraulics and landing gear, and emergency landing procedures were initiated. This required locking of seat harnesses. When the commander asked the first officer to select reverse thrust during the landing, "the first officer was unable to depress the reverse gate and retard the throttles with her left hand and with her seat harness locked; she was unable to use her right hand". In addition, the first officer was unable to reach the master electrical switch when harness was locked as these were placed some 60mm beyond the reach of the fingertips of a fully extended left arm. Fortunately, in this incident nobody died, and there were no injuries, however things could easily have been different.

An investigation into the incident identified that while a number of the controls were within reach of the first officer, they could not be operated as the user could not move their torso and therefore could not apply the necessary force within the posture to change the state of the switches, particularly those that had been positioned in an overhead panel.

Lessons Learned:
1. *Harnesses have a significant impact on the reach of a user.*
2. *The positioning of controls relative to a user will have a significant impact on their operability (particularly if positioned overhead).*
3. *Force cannot be applied equally through the full rotation of the shoulder; posture and freedom of movement both a significant effect on the user's ability to complete a task.*
4. *Just because a control is within reach, this does not mean that the user will be able to operate the switch within all operational conditions.*
5. *The context of use must account for all conditions of use, including emergency and reversionary modes.*
6. *Testing must utilise the full range of sizes of users under the conditions identified within the context of use.*

Reach measurements can be used to establish Zones of Convenient Reach (ZCR) (see Figure 11). ZCR is the concept of an area or zone in which an object is in normal reach, i.e. 'in arm's length'. The length of the arm (measured as functional reach) sweeps out a series of arcs centred on the joint and defines the ZCR for each hand. The zones for the two limbs intersect in the midline plane of the body, which creates two intersecting hemispheres of space which is the ZCR for both hands (see Figure 12). The radius of each hemisphere is the arm length and their centres are equal to biacromial breadth apart.

To calculate the radius of the Zone of Convenient Reach (ZCR) on a horizontal surface (see Figure 11 and Figure 12):

$$ZCR = \sqrt{(r^2 - d^2)}$$

where:

r = 5th percentile reach (use female data for mixed sex populations).

d (standing workers) = standing shoulder height (a) - height of top of horizontal surface above floor (c).

d (seated workers) = sitting shoulder height (a) - height of top of horizontal surface above seat (e)

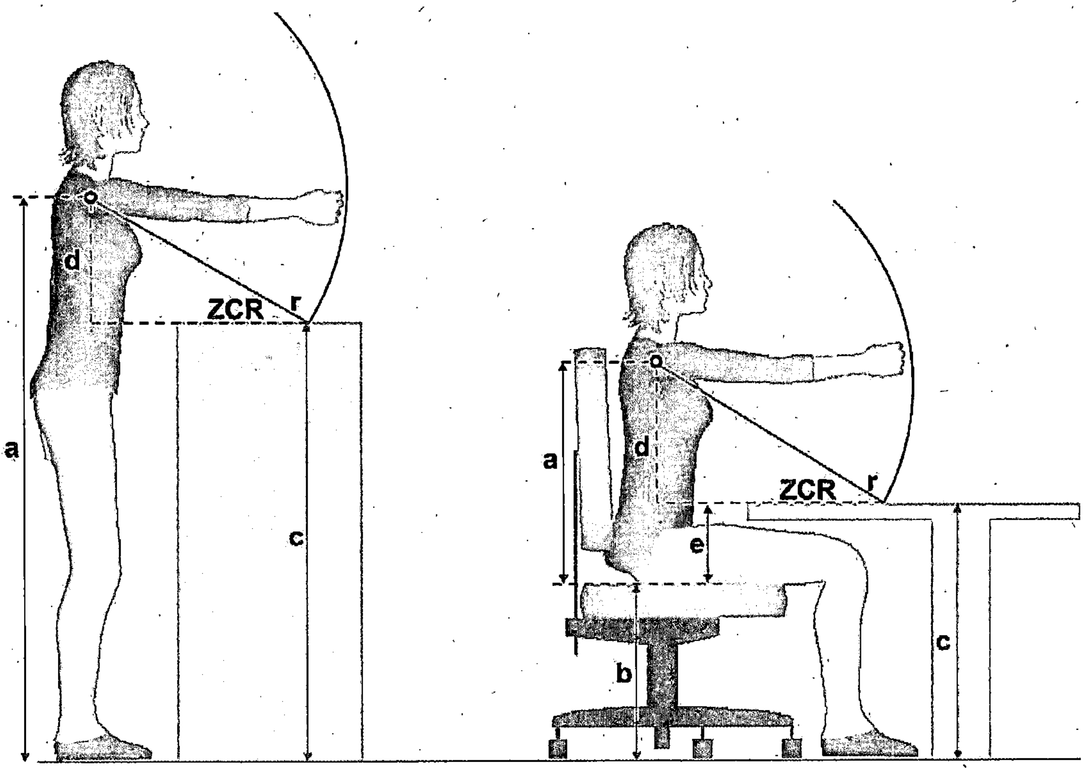


Figure 11 – Zone of Convenient Reach on a Horizontal Surface (Side View)

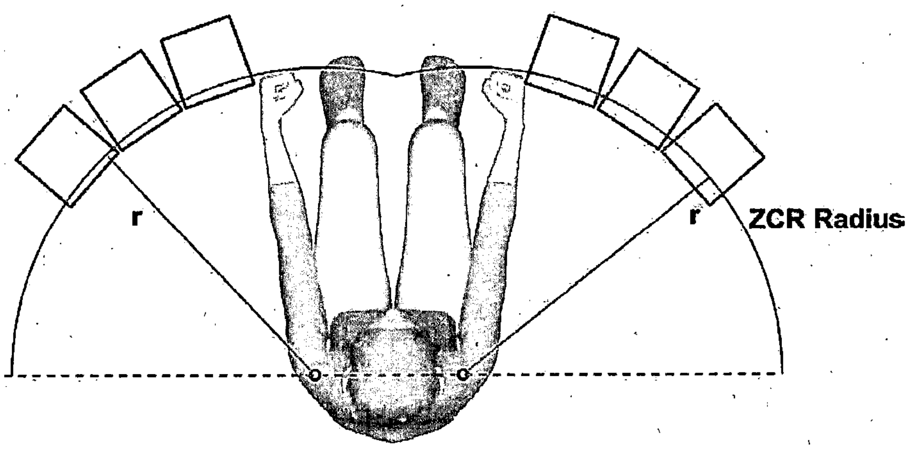


Figure 12 – Zone of Convenient Reach on a Horizontal Surface (Top View)

Note: r refers to functional reach; ZCR refers to the radius of the zone of convenient reach (projection of r onto a horizontal plane).

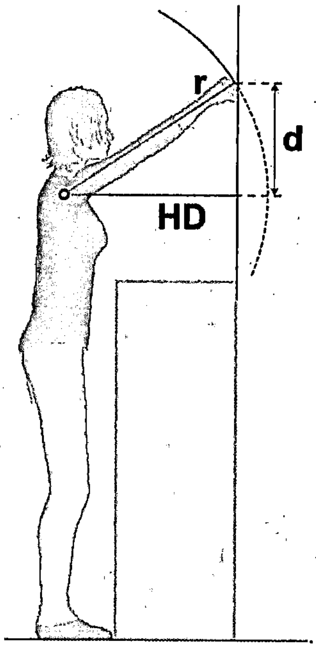
To calculate the maximum allowable horizontal distance (HD) of an object on a vertical surface (assuming operator foot position is constrained):

$$HD = \sqrt{(r^2 - d^2)}$$

Where:

r = 5th percentile reach (use female data for mixed sex populations)
d = the difference between the height of the object above the floor and the height of the shoulder above the floor, standing or sitting.

See Figure 13 for an illustration.



Design Best Practice Note 28:
For standing work, controls should be positioned at a height between the shoulder and the elbow, and should never be outside the arc described by the arm (upper limb) as it rotates about the shoulder.

Design Best Practice Note 29:
Work surface height for medium or light manipulative tasks should be 50-150 mm below elbow level.

Figure 13 – Zone of Convenient Reach on a Vertical Surface (Side View)

The anthropometry of reach can be viewed in terms of a relatively large volume which is 'possible', in which are successively smaller volumes which are 'acceptable', 'preferred' or 'optimal' for a particular activity (see section TG4.1 on "Working and Living Spaces" for further detail).

8.2 THE WORKSPACE ENVELOPE

The Seat Reference Point (SRP) shown in Figure 14 is commonly used as a standard starting point for the reach dimensions of seated operators, and is defined as the midpoint of the intersection of the plane of the seat surface with the plane of the backrest surface of the seat, and tangents of the mid-line contours of the seated person. The Seat Reference Line and the Seat Reference Vertical (SRV) illustrated in Figure 15 and Figure 16 are reference lines plotted from the seat reference point to the vertical axis to highlight reach boundaries when converted to horizontal contours. The examples are presented as a guide to the designer to introduce the workspace envelope pictorially. The examples given in Figure 15 and Figure 16 should not be used as the basis of design; rather these examples should be updated to take into account the specific attributes of the target audience being designed for. Body size data, clothing and equipment ensembles specific to the target audience will all affect the size and shape of the workspace envelope. At present, dimensional

Design Best Practice Note 30:
The Seat Reference Point should be used to determine the reach dimensions for seated operators when designing the workspace envelope.

Design Best Practice Note 31:
The range of adjustability of the crewstation must allow operators of all sizes (as defined in the TAD) to position themselves correctly with respect to crewstation displays and controls.

representations of the horizontal boundaries for British civilian and military personnel are not readily available. However, a fuller description can be found in Sanders, *et al.* (1992).

It should be emphasised that the dimensions tabulated in Figure 15, Figure 16, Figure 18 and Figure 19 should be treated with caution. Some of the data only apply to the populations that are similar in size and proportions to the US Air Force and cannot be used indiscriminately for all populations.

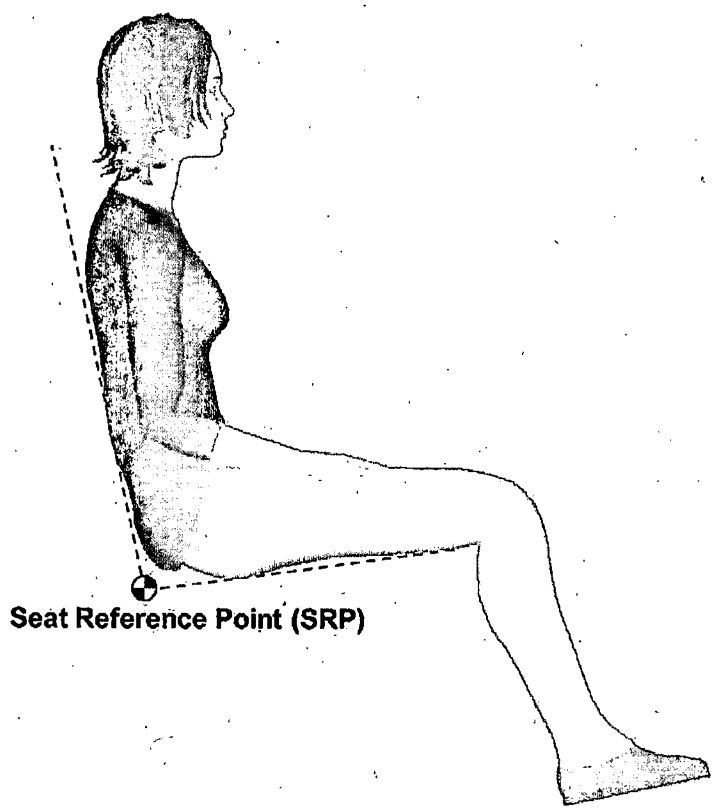


Figure 14 – Seat Reference Point

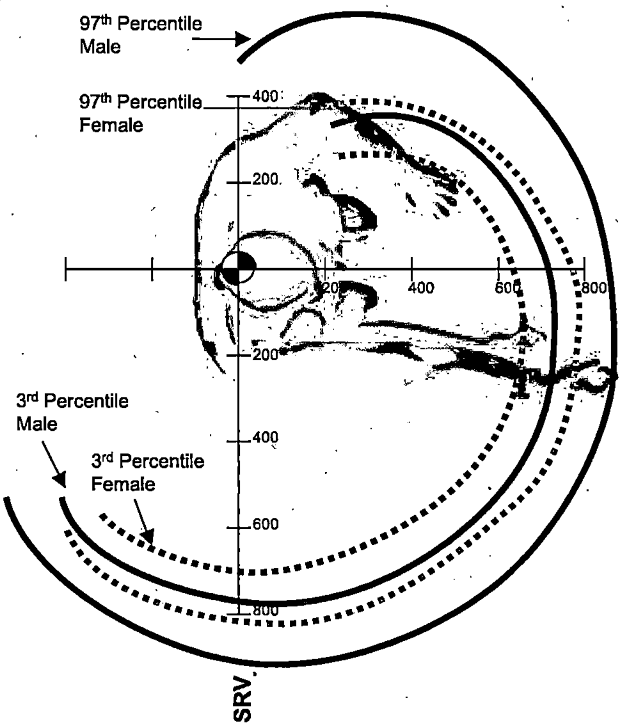


Figure 15 – Male and Female Military Personnel Forward Functional Reach Envelopes (see text for description of Seat Reference Vertical, SRV)

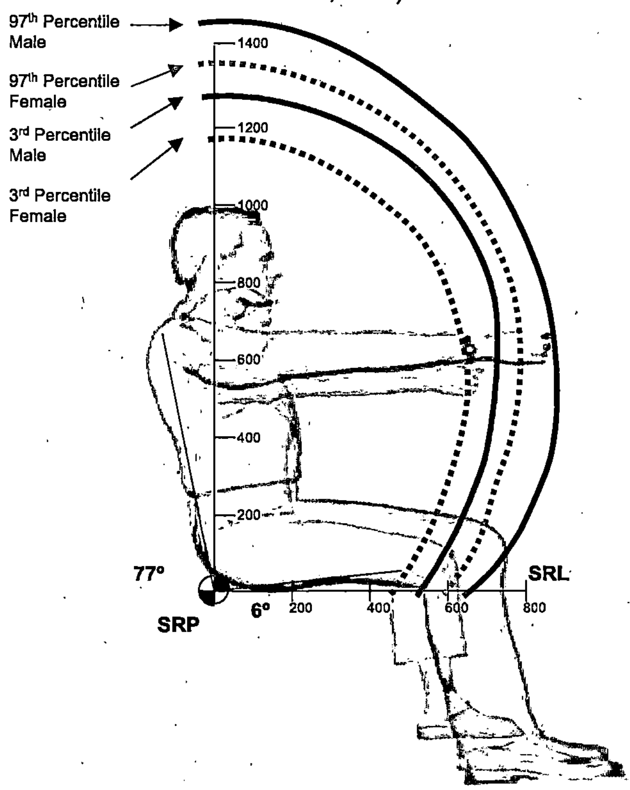


Figure 16 – Male and Female Military Personnel Forward Functional Reach Envelopes

Arm reach data are essential for equipment design and workspace layout simply because different controls demand varying degrees of precision of movement and force. Arm length measurements, originally taken from standing subjects as a maximum length to qualify anatomical difference, have

now proliferated into numerous dimensions, standing and sitting, involving various combinations of position of the hand, arm and shoulder.

Whilst providing a convenient approach, it is an oversimplification to consider the zone that is defined by the rotation of the upper limb (arm) about the shoulder joint anatomically resembling a ball and socket (see section 9.1 regarding the range of movement of body members). Reach may be affected by the nature of the grip required. See Figure 17 for functional grip dimensions and Table 9 for grip correction factors.

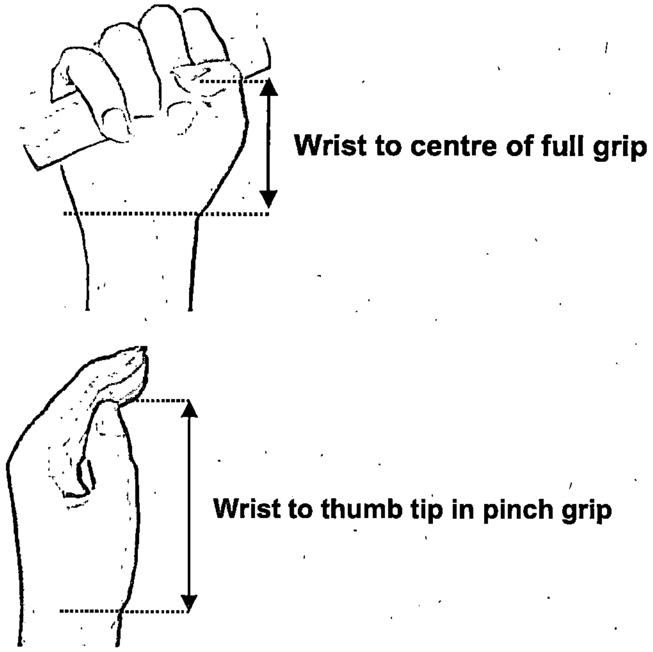


Figure 17 – Functional Grip Correction Factor Terminology

Table 9 – Grip Correction Factors

Serial	Dimensional Descriptions	Percentage of Overall Hand Length (Dimension 33)	UK Military (2000 est.)					
			3RD %le		50th %le		97th %le	
			M	F	M	F	M	F
1	Wrist to the centre of a full grip	35	62	56	68	62	74	68
2	Wrist to thumb tip in a pinch grip	60	107	97	117	106	127	116

Add a correction for gloves if necessary (see section 7.1)

Note 1: Reach corrections may be calculated using the hand length data in Appendix H.

Note 2: In typical cases: for men - fingertip reach is 78 millimetres further than thumb tip, and 70 for women; for men - thumb tip reach is 50 millimetres further than full grip and 44 for women.

8.3 HEAD AND EYE POINTING BOUNDARIES

When considering Helmet-Mounted Sighting Systems for weapon aiming, the designer needs to be aware of possible head and eye movement limitations caused by equipment or protective clothing interference.

Figure 18 and Figure 19 show typical head and eye movement boundaries for fighter pilots, for both the slack and tight restraining harness cases. Both figures show a side elevation view of a sphere with the pilot looking forwards (to the left). The pilot's eye datum is at the 90°; 0° coordinate at the centre of the sphere. From this position the 3rd percentile male pilot (in terms of head movement – not stature) can only point his head 40° upwards, with a slack harness when looking straight ahead. When looking sideways (90° he can look only 26° upwards and 10° downwards.

The side of the cockpit prevents the eye from looking downwards more than 40° to the side, even for the 90th percentile pilot with a slack harness.

This is a general guide to pilots' head and eye pointing ability and the following points should be noted:

(a) There is considerable variability in head mobility between subjects. This mobility has little correlation with subject dimensions, such as Sitting Eye Height, but appears to be dependent upon the pilot's postural strategy.
(b) When wearing a tight harness, head movement upwards and rearwards is severely restricted by interference between an ejection seat head box and a pilot's protective helmet (Figure 19);
(c) Head movement is limited also by interference between a life-saving jacket and an oxygen mask/helmet assembly;
(d) Eye pointing is sometimes limited by the bulk of an oxygen mask;
(e) If a harness is worn in the unlocked or slack state, then an additional 10° to 20° of head movement can be achieved; and
(f) If the eye, rather than the head, can be used for aiming, then an additional 50° becomes available to use.

See Lovesey (1988) for further information.

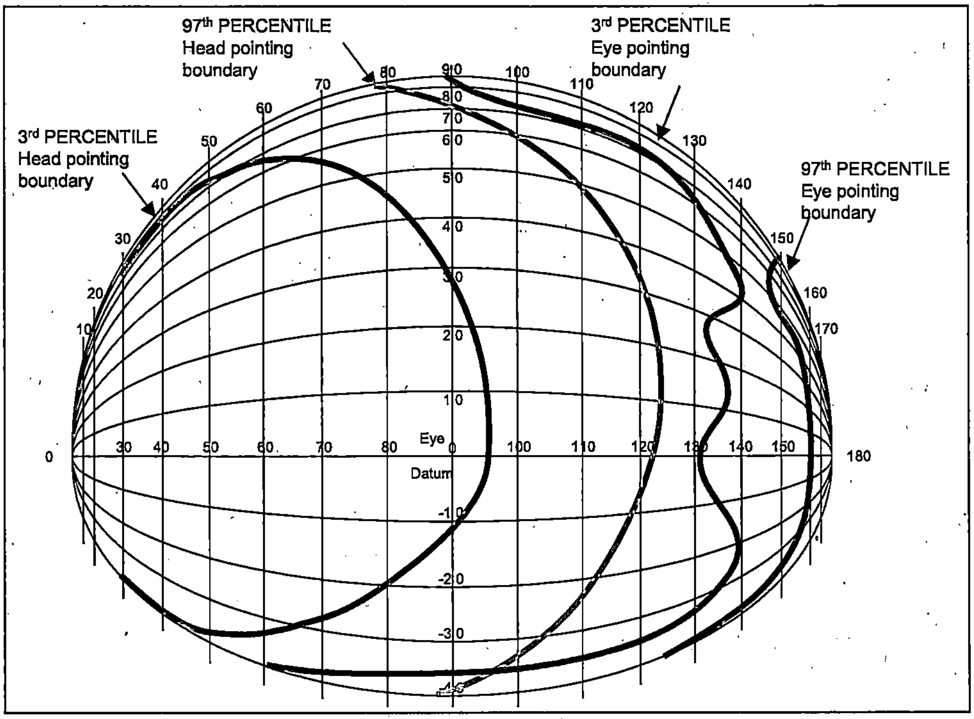


Figure 18 – Head and Eye Pointing Boundaries with a Slack Harness

Note: Data typical of Fast Jet Aircrew in Ejection Seat with Helmet, Oxygen Mask, Life Saving Jacket and Flying Clothes

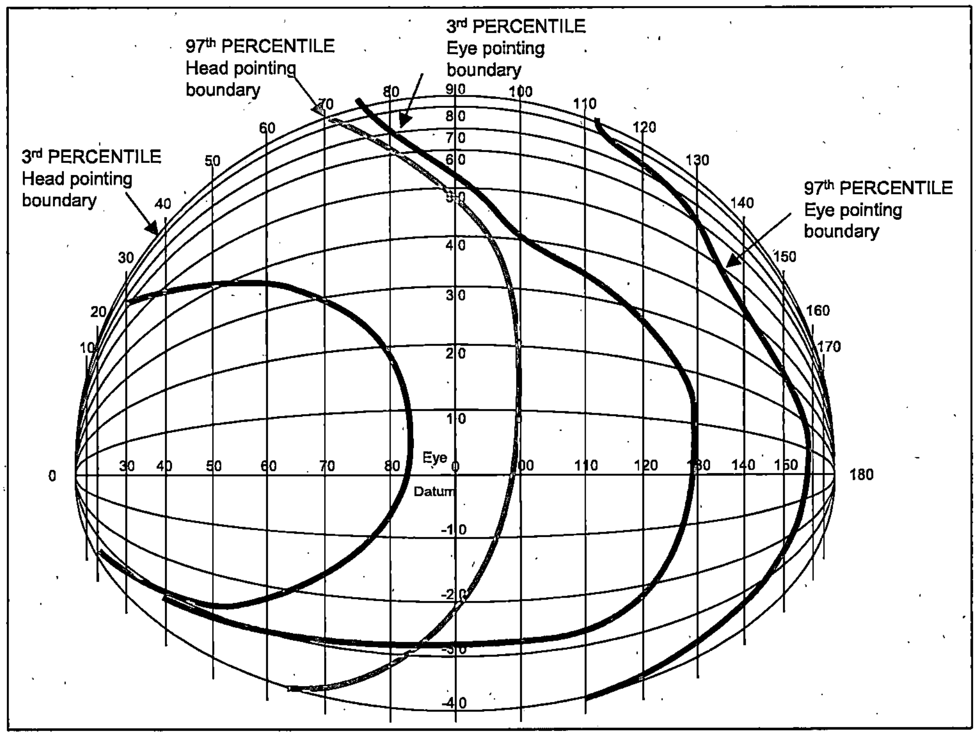


Figure 19 – Head and Eye Pointing Boundaries with a Tight Harness

Note: Data typical of Fast Jet Aircrew in Ejection Seat with Helmet, Oxygen Mask, Life Saving Jacket and Flying Clothes

9 ANTHROPOMETRIC MOVEMENT OF BODY PARTS

9.1 ANTHROPOMETRIC MOVEMENT OF BODY MEMBERS

The human body may be generally described as a small number of rigid links, connected at specific points about which they are free to rotate. When a user is wearing PPE or Load Carriage Equipment, their movement will be restricted, and particular attention will need to be paid to this when considering factors such as reach and dexterity.

9.1.1 BODY LINKAGES

To plan the positioning and operation of controls, a designer requires data concerning the range of movement of the torso, arms and legs in order to establish the comfortable limits for maximum efficiency.

The movable joints of the body, articulated by means of ligaments (tough fibrous bands), are of several types; the three most important are: hinge joints (e.g. fingers), pivot joints (e.g. elbow), and ball and socket joints (e.g. shoulder and hip). Thus, the human body is basically an open chain system of 'links' moving around joints. The end members of these open-chain links, the hands and feet, can occupy a large number of positions in space as a result of the cumulative ranges of these joints. See reference (Pheasant & Haslegrave, 2005) for further information.

9.1.2 DYNAMIC RANGE OF MOVEMENT

The functional (or dynamic) data presented so far have been empirically determined in ad hoc studies to solve specific, practical problems. The application of such data is of necessity limited to a narrow range of situations, similar to those in which the data were originally gathered. There are times when a designer needs to reach an approximate solution to a novel problem in functional anthropometrics.

Design Best Practice Note 32: The system design must accommodate the range of dexterity in the proposed User population (see TG 1.4 "Physical Capabilities").

The movement of the body is described in terms of movement relative to the three anatomical planes; the sagittal plane; the coronal plane and the transverse plane. These are illustrated below in Figure 20.

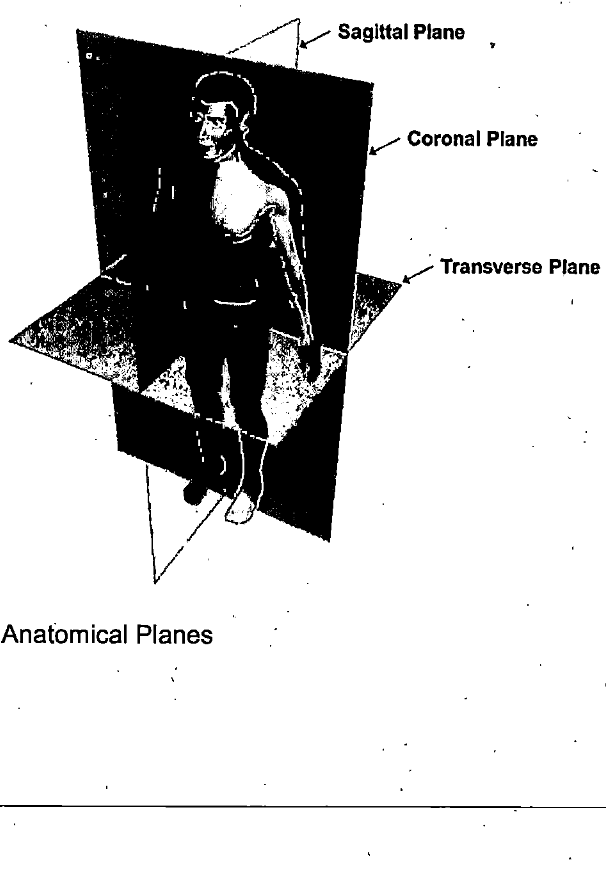


Figure 20 – The Three Anatomical Planes

The body can be considered in terms of a number of interlinked joints (the distance between these joints are described as body linkages). For example, the thigh link extends from the centre of rotation of the hip joint to that of the knee. The shank or lower leg link extends from the knee to the ankle, etc. Anthropometric data provided in Appendix H describe the external dimensions of the body, but do not necessarily describe the distance between joint centres. An estimation of the distance between joint centres can be derived from the stature dimension. The average lengths of these body linkages are expressed as a percentage of the stature in Table 10.

Design Best Practice Note 33: The system design may have to make allowances for restricted physical abilities (e.g. wounded personnel).

Designations 1 to 17 in Table 10 refer to dimensions of the body as seen in side elevation (known to anatomists as the sagittal plane, see Figure 21), whereas designations 18 and 19 refer to dimensions of the body as seen in front elevation (known to anatomists as the coronal plane, see Figure 22).

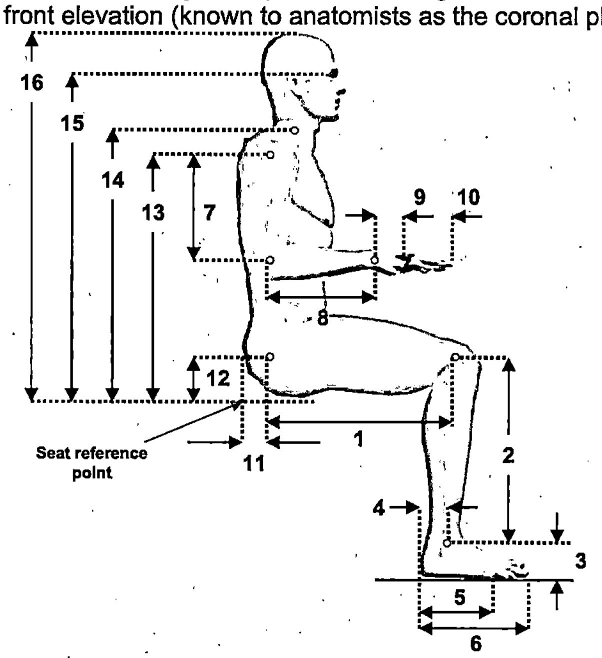


Figure 21 – Sagittal Plane Body Linkages

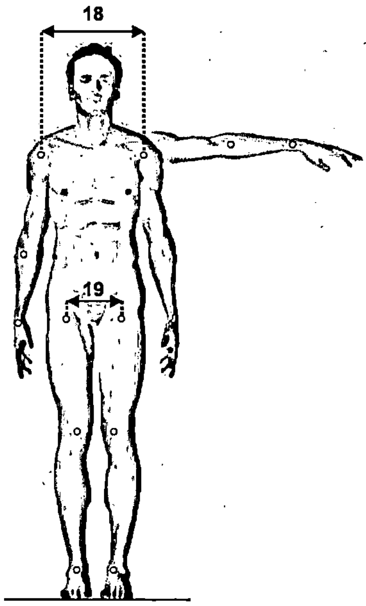


Figure 22 – Coronal Plane Body Linkages

Table 10 – Dimensions of Body Linkages Expressed as an Average Percentage of Stature

Serial	Description	Average Percentage of Stature
1	Thigh	28.4
2	Shank (Lower Leg)	23.4
3	Ankle Height	4.7
4	Heel to Ankle (Horizontal Projection)	3.3
5	Heel to Ball Of Foot	11.2
6	Foot Length	15.3
7	Arm (i.e. Shoulder to Elbow)	17.3
8	Forearm	15.5
9	Wrist to Centre of Grip	3.8
10	Hand Length	10.9
11	Hip to SRP (Horizontal)	6.9*
12	Hip to SRP(Vertical)	5.2*
13	Shoulder to Seat	32.0
14	Lower Neck (C7 Vertebra) to Seat	37.8
15	Eye Level to Seat	45.9
16	Sitting Height	52.3
17	Eye to Axis of Head (Horizontal)	5.7
18	Transverse Shoulders	22.5
19	Transverse Hips	9.8

* The Seat Reference Point (SRP) is the centre point of a line formed by the intersection of the planes of the back and base of a fully compressed seat, and tangents of the mid-line contours of the seated person (see Figure 14).

It should be emphasised that the dimensions in Table 10 are only an approximation to the truth; the trunk, for example, is not a rigid link and the spine is flexible in all three anatomical planes. The centre of rotation of the shoulder joint is not static; the clavicle and scapula (or collar bone and shoulder blade, respectively) are mobile with respect to the rib cage, as indicated in Figure 23.

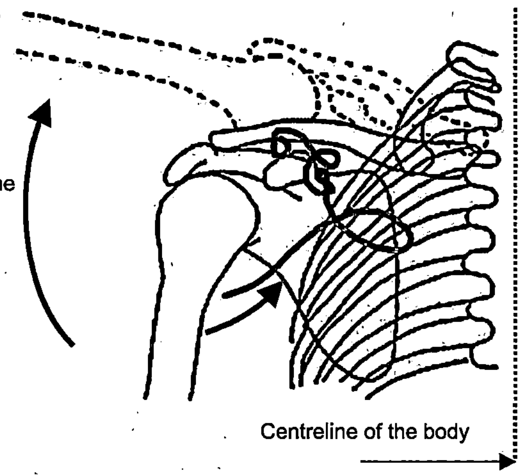


Figure 23 – Path of Instantaneous Centre of Shoulder Rotation

In using the link system to visualise the reaches possible with the limbs for a given posture, it must be remembered that the actual body joints are not simple centres of rotation, and that some of the body links are not rigid (for example, the shoulder joint is not positively located at the upper end of a rigid upper trunk link; see Figure 23 which illustrates the very large and erratic pathway for the effective centre of rotation of the shoulder during movement of the upper limb).

The possible range of joint movements is dependent on the joint and the fact that muscular movements of one link about another may vary considerably, not only with the angular disposition of the links, but also with the postural relationships of adjacent links. Thus, the postures and reach possible with a manikin may be of little or no practical significance for the person. Computer human models may provide better approximations than manikins.

The designer should bear these limitations in mind. The model would, for example, make a highly conservative estimate of a reach envelope when considering the interaction between working posture and workspace.

9.2 MOVEMENT RANGE

The mean angular ranges of joint movements in US Military male personnel, together with the ranges encompassing 94% of the population, are summarised in Table 11, Table 12 and Table 13.

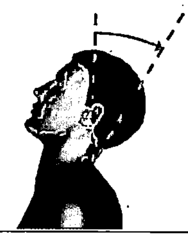
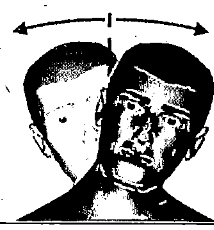
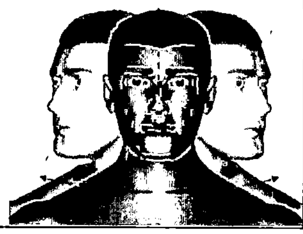
The Solution Provider should use these joint ranges to represent the maximum expected range of movement. The ranges of movement have been generated using nude personnel; therefore, allowances should be made to reflect the restrictions that clothing would impose on joint movement. Generally, the lower specified limit should be used as an assumption when personnel must operate or maintain a component. The upper limit should be used in designing for freedom of movement (Department of Defense, 2012).

Design Best Practice Note 34: The possible movement range of joints varies significantly from person to person. The variation in movement range is illustrated in Table 11, Table 12 and Table 13 below.

9.2.1 NECK AND HEAD MOVEMENT

The normal range of movement of the neck is illustrated below in Table 11 (Department of Defense, 2012). It must be emphasised that head movement can be further severely restricted by clothing, a seat restraining harness and surrounding equipment, such as an ejection seat head box.

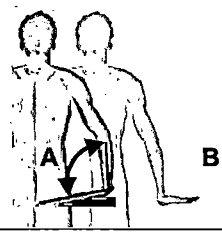
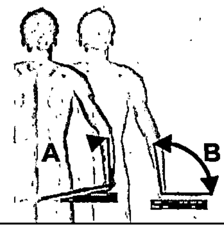
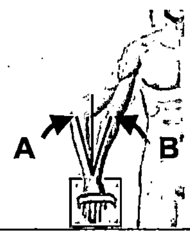
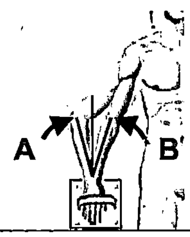
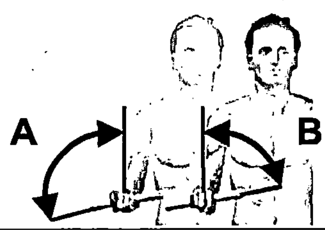
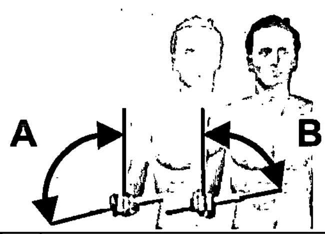
Table 11 – Range of Movement at the Joint of the Neck

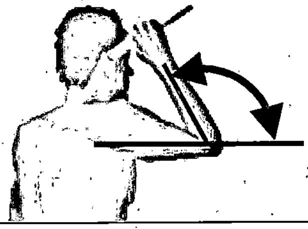
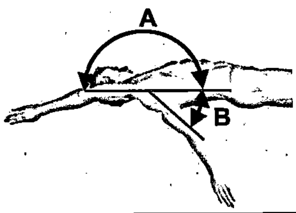
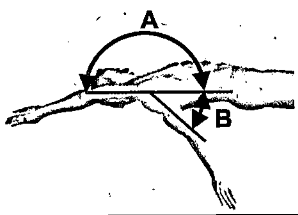
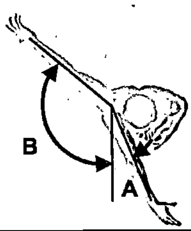
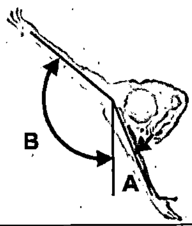
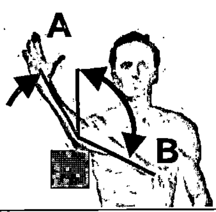
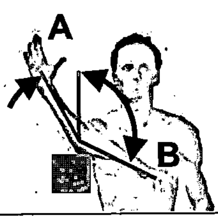
Serial	Type of Movement	Pictorial Representation	Lower Limit	Average	Upper Limit
1	Dorsal flexion (backward)		44°	61°	88°
2	Ventral flexion (forward)		48°	60°	72°
3	Lateral flexion (right or left)		34°	41°	48°
4	Rotation (right or left)		65°	79°	93°

9.2.2 HAND, WRIST, SHOULDER AND ELBOW MOVEMENT

The normal range of movement of the hand, wrist, shoulder and elbow is illustrated below in Table 12 (Department of Defense, 2012) .

Table 12 – Range of Movement at the Joints of the Hand and Arm

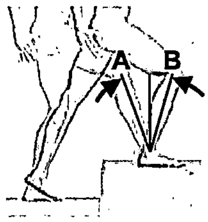
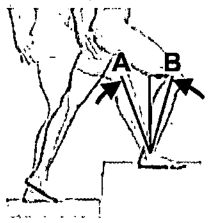
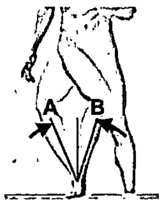
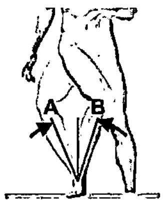
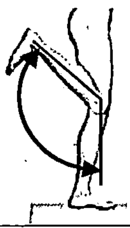
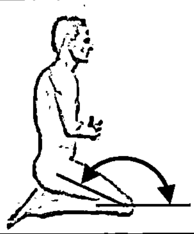
Serial	Type of Movement	Pictorial Representation	Lower Limit	Average	Upper Limit
1	Wrist Flexion - the movement of the palm down, towards the wrist		78°	90°	102°
2	Wrist Extension - the movement of the palm up, away from the wrist (raising the back of the hand)		86°	99°	112°
3	Abduction (A) – motion away from the midline of the body (sagittal plane)		40°	47°	54°
4	Adduction (B) - motion towards the midline of the body (sagittal plane)		18°	27°	36°
5	Forearm Supination (A) - the rotation of the forearm into a palm up position		91°	113°	135°
6	Forearm Pronation (B) - the rotation of the forearm into a palm down position		53°	77°	101°

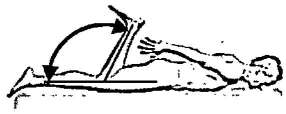
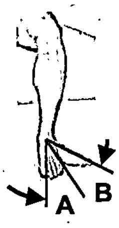
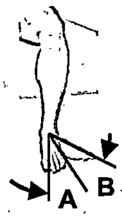
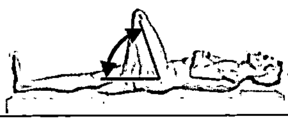
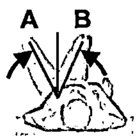
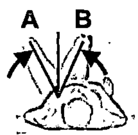
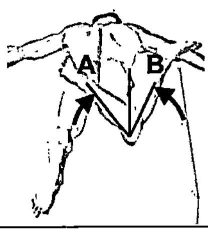
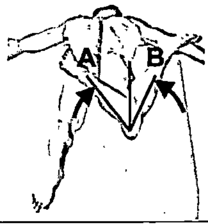
Serial	Type of Movement	Pictorial Representation	Lower Limit	Average	Upper Limit
7	Elbow Flexion - decreasing the angle between the upper and lower arm		132°	142°	152°
8	Shoulder Flexion (A) - moving the upper arm upward to the front		176°	188°	200°
9	Shoulder Extension (B) - moving the upper arm down to the rear		47°	61°	75°
10	Shoulder Adduction (A) - moving the upper arm down to the side toward the body		39°	48°	57°
11	Shoulder Abduction (B) - moving the upper arm up to the side away from the body		117°	134°	151°
12	Shoulder Lateral Rotation (A) - turning the upper arm outward away from the centre of the body		21°	34°	47°
13	Rotation: Medial Rotation (B) - turning the upper arm inward toward the centre of the body		75°	97°	119°

9.2.3 LEG, ANKLE, KNEE AND HIP MOVEMENT

The normal range of movement of the leg, ankle, knee and hip is illustrated below in Table 13 (Department of Defense, 2012).

Table 13 – Range of Movement at the Joints of the Foot and Leg of Male USAF Personnel

Serial	Type of Movement	Pictorial Representation	Lower Limit	Average	Upper Limit
1	Ankle Plantar Flexion (A) - extension of the ankle resulting in the forefoot moving away from the body (moving onto tip toes)		26°	38°	50°
2	Ankle Dorsiflexion (B) - flexion of the ankle resulting in the forefoot moving towards the body (lifting toes towards the shins)		28°	35°	42°
3	Ankle Abduction (A) - motion towards the midline of the body (sagittal plane)		16°	23°	30°
4	Ankle Adduction (B) - motion away from the midline of the body (sagittal plane)		15°	24°	33°
5	Knee Flexion: Standing – bending of the knee while standing (pulling the foot towards the buttocks)		100°	113°	126°
6	Knee Flexion: Kneeling – bending of the knee while kneeling (pulling the foot towards the buttocks)		150°	159°	168°

Serial	Type of Movement	Pictorial Representation	Lower Limit	Average	Upper Limit
7	Knee Flexion: Prone bending of the knee while laying prone on the floor (pulling the foot towards the buttocks)		115°	125°	135°
8	Knee Rotation: Medial (A) - Rotary movement around the longitudinal axis of the bone toward the centre of the body; with the knee bent, turning the lower leg inward towards the sagittal plane		23°	35°	47°
9	Knee Rotation: Lateral (B) - Rotary movement around the longitudinal axis of the bone away the centre of the body; with the knee bent, turning the lower leg outward away from the sagittal plane		31°	43°	55°
10	Hip Flexion- Movement of the knee up towards the chest		100°	113°	126°
11	Hip Adduction (A) – Movement of the knee towards the midline of the body (bringing knees together)		19°	31°	43°
12	Hip Abduction (B) - Movement of the knee away from the midline of the body (bringing knees apart)		41°	53°	65°
13	Hip Rotation (Prone): Medial (A) - turning the thigh or pelvis inward		29°	39°	49°
14	Hip Rotation (Prone): Lateral (B) turning the thigh or pelvis outward		24°	34°	44°

Serial	Type of Movement	Pictorial Representation	Lower Limit	Average	Upper Limit
15	Hip Rotation (Sitting): Lateral (A) - turning the thigh or pelvis inwards while sitting		21°	30°	39°
16	Hip Rotation (Sitting): Medial (B) - turning the thigh or pelvis outwards while sitting		22°	31°	40°

NOTE: Ranges of movement at the joints of the foot and leg of male USAF personnel are tabulated. A decrease in the range of knee movement may be encountered in those over 50 years of age.

10 USE OF MANIKINS

While manikins in design have their origins in articulated 2D paper cut-out silhouettes of human forms, to be tested against engineering drawings, the widespread use of CAD has meant that conceptual workspaces can be realistically tested against 3D virtual representations of their users. In fact, virtual workspace can be tested against a wider virtual population than is likely to be available for testing physical mock-ups, which are often regarded as a "gold-standard" in testing. It is also possible to take into account secular trends provided appropriate data is available for the relevant populations (see 4.1.1).

There are several different general categories of digital human model, examples of which are:

- Standalone specialised computer manikin packages such as SAMMIE CAD, Jack, Safework, RAMSIS, Santos and HumanCAD;
- Computer manikins incorporated in larger CAD systems such as PTC Creo Manikin in Pro-Engineer; and
- Standalone biomechanical modelling systems such as Anybody and Biomechanics of Bodies.

Many Defence Systems are designed using two sets of CAD manikins. The first set is "Design Manikins", native to the CAD package. The figures are usually relatively simple and provide basic anthropometric scaling and joint movement. Design manikins are generally difficult to manipulate but provide a space claim for the operator. Example design manikins are illustrated below in Figure 24.

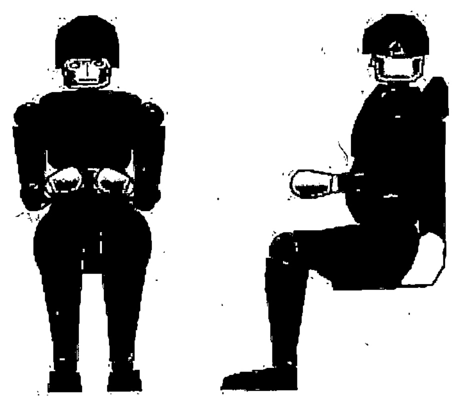


Figure 24 – Example Design Manikins (Cummings, et al., 2015)

The second set is "Assessment Manikins". These generally exist in a specialised DHM tool separate from the CAD system. While various DHM tools are described as "stand-alone", there are usually mechanisms for exchanging data between such tools and CAD systems. When doing so, it may be necessary to make judgements on the acceptability of necessary approximations to the various geometries involved and the trade-offs in speed at which the computer system subsequently runs. Management of CAD data, version and change control are particularly important when considering the use of manikins in design. The Human Factors Integration Manager (HFIM) in the Solution Provider organisation should ensure that processes are in place to manage CAD and DHM data appropriately. This may form part of the Solution Provider's Human Factors Integration Plan (HFIP).

Assessment Manikins are generally easier to scale and manipulate in order to conduct HF assessments than Design Manikins. The capabilities of existing DHM tools vary significantly. The designer will have to decide which model offers the best overall solution to meet their requirements. Existing tools take different approaches to representing user populations; some allow generation of manikins directly from input data or sometimes the tool will select a best fit from a selected population. The treatment of clothing varies between tools also. Examples of Assessment Manikins (from Jack) are illustrated below in Figure 25.

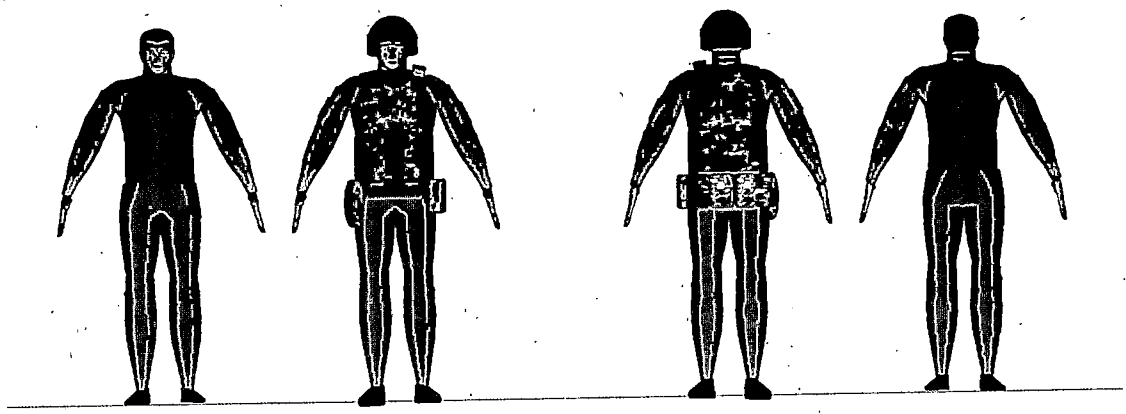


Figure 25 – Example Jack Assessment Manikins (Modelled With and Without Equipment Additions)

Many Design Manikins are generated using the "Percentile Man Approach" in which each body dimension is specified using 95th percentile values. This results in a manikin significantly larger than the 95th percentile of the target population, because a person who is the 95th percentile in one dimension will not be 95th percentile in all other dimensions. The number of manikins used in design assessments should vary with the tasks being assessed and critical dimensions identified. Some compromise is required when using only two boundary cases (small female dressed in light clothing and large male dressed in maximum clothing bulk), as proportionality constraints in the tools will often limit the selection of anthropometric measures.

When using manikins, caution must be exercised to ensure that the manikins selected represent the full range of users defined in the TAD. Although representing the large male and small female cases may account for the two extremes of the population, there is a risk that this will not fully account for the inherent variability of body dimensions between individuals (i.e. it is wholly possible for users to be short and stout as well as short and thin).

CAD "Boundary" manikins can be developed to represent the extreme anthropometric measurements of a defined population. The number of manikins used in design assessment should be managed to ensure that the population is properly accommodated while minimising the burden on the Solution Provider's HF team. A number of boundary manikins can be used to capture the anthropometric diversity of the user population (Bertilsson, et al., 2012). Likely measurement combinations can be derived by mathematical treatment of the anthropometric data using methods such as Principal Component Analysis (PCA), Cluster Analysis and Proportionality constants to generate a set of assessment manikins. Some of these methods are built into DHM packages; Jack, for example, includes a PCA module. A set of boundary manikins is illustrated below in Figure 26.

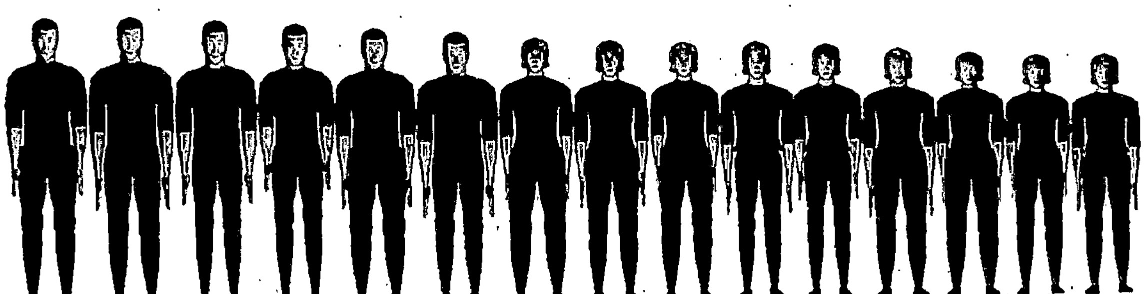


Figure 26 – Boundary Manikins Generated from the ANSUR Database in Jack (Cummings, et al., 2015)

Case Study: Driver Head-Out Vision

During the development of the driver's crewstation in an armoured vehicle contract, additional manikins had to be generated to assess head-out driving. Assessment of the task identified that the worst case would be a large female of short stature, as the low female sitting eye height, combined with a large thigh thickness and large chest depth would have the greatest influence on the operability of controls and driver vision while operating in this position.

A manikin was therefore generated for assessing head-out driver vision, where thigh thickness under the steering device and chest depth to the front of the hatch aperture placed additional constraints on the eye position, informing the adjustability of seating and the positioning of driver's controls.

Lessons Learned:

1. *Assessing only the extremes of the population on a univariate basis may not identify problematic anthropometric attributes.*
2. *All testing whether virtual (through DHM) or physical (through the use of mock-ups and prototypes) must assess the full breadth of the target audience to ensure that issues are identified and mitigated early in the design process.*

Alternative methods for generating manikins may include body scanning of fully equipped users. Currently, this can be achieved easily to generate a static manikin with a unique posture but creating dynamic manikins for use in assessments can be fraught with problems. DHM tools such as Jack provide a smooth-skin mesh manikin, whose skin could (theoretically at least) be replaced with scanned data. However, the skin of the manikin is likely to follow the underlying skeleton in an unpredictable manner; it might appear to tear, or scanned components (such as pouches) might stretch as the posture is adjusted. At the time of writing, only the tool provider (Siemens, in the case of Jack) can generate such manikins (Cummings, Launchbury, Wilson, & Usher, 2015).

DHM packages are becoming increasingly capable and reduce the need for physical mock-up trials. Current DHM tools enable the assessment of a wide range of HF issues and tasks, and are increasingly being used in the assessment of requirement compliance. Particular uses of DHM include the definition of requirements, and the testing against requirements, for:

- Anthropometric Fit;
- Reach;
- Posture;
- Comfort;
- Task performance (assessment of crew tasks including reversionary modes);
- Emergency egress (in all vehicle orientations);
- CASEVAC;
- Vision; and
- Vehicle maintenance & manual handling.

Physical mock-ups are costly to produce and DHM tools offer the ability to de-risk key issues before committing to mock-ups. The particular benefit of using DHM tools is that designs that will not work can be rapidly dismissed. However, these tools cannot fully de-risk the design, as requirements such as emergency egress and CASEVAC times would be very difficult to simulate and assess in a DHM environment. Individual differences in the way people sit and operate equipment are also difficult to replicate in DHM tools without underlying postural models, based on the clothing and equipment ensemble worn by the operator. DHM assessments should therefore be validated using mock-ups and trials participants representing the critical anthropometric dimensions of the target population. It is possible to be seduced by the power of these computerised methods and care needs to be taken to ensure that postures adopted by manikins are plausible as well as possible.

11 APPLYING ANTHROPOMETRIC DATA TO THE DESIGN OF SYSTEMS

Anthropometric data have a variety of uses in design. In a typical programme the data presented in the preceding sections of this TG may be applied in the following activities:

- Requirements Analysis;
- Design Assessment; and
- Requirements Assurance.

11.1 REQUIREMENTS ANALYSIS

In the first instance, anthropometric data may be applied in Solution Provider organisations to conduct requirements analysis. The requirements analysis phase should start as early as possible in the contract. This phase involves establishing the baseline for the anthropometric elements of the design. The requirements analysis phase will form part of the wider EHFA activities conducted by the Solution Provider organisation, and therefore may need to be revisited periodically through the acquisition process, particularly in response to any changes in the requirements set, or to a change of assumptions (or if there are any changes to the TAD through the course of the life of the system).

Case Study: Changes to Clothing and Equipment Ensembles Once In-Service

The Titan Bridge Layer was designed in accordance with a Target Audience Description which included Enhanced Combat Body Armour and cold weather clothing. During the acceptance process the vehicle was tested using these clothing configurations and passed its requirement acceptance tests. However, once in service, the introduction of Osprey Body Armour presented major issues for vehicle crews as they entered and exited the vehicle. The ingress route into the Driver's crewstation is up the front glacis plate and underneath the bridge laying equipment mounted on the front of the vehicle. The gap under the bridge laying equipment will accommodate the nude chest depth of the user population with some allowance for cold weather and CBRN clothing; however, changes to the body armour policy and the use of Osprey body armour by Armoured Vehicle crews mean that few vehicle crews can safely fit under the bridging equipment. This has led to crews having to remove their body armour during egress or having revert to earlier body armour configurations to prevent becoming stuck under the bridging equipment (particularly during egress). (Cummings & Launchbury, 2014).

Figure 27 – Titan Driver Egress Route (Cummings, et al., 2015)

Lessons Learned:

1. *Changes in the 'wider system' must be monitored through-life and where possible predicted at the requirements stage to prevent a decrement to performance through life.*
2. *If a change to any element of the system design is made, the impact of this change must be assessed to ensure that it does not have an effect on the capability as a whole.*
3. *Although the introduction of more capable body armour should enhance crew safety, the impact that it had on crew egress presented a safety hazard to vehicle crews.*
4. *The impact of a change may not affect all tasks equally. For example, while crews could still ingress the vehicle, egress was a greater risk as the armour snagged and rode up during this process.*

The requirements analysis activity should populate and develop any context of use information provided as part of the Invitation To Tender. The Solution Provider should seek to gather (or generate) information regarding:

- The TAD;
- The tasks / functions that the users will perform (through Use Cases and Task Analysis);
- The equipment that users will interact with;
- The environment in which the Users will have to operate; and
- Any particular anthropometric issues and risks.

The Solution Provider HFIM should work closely with the Human Factors Integration Focus in DE&S to identify and record any assumptions made and prioritise any particular issues and risks that need to be addressed in the design solution. The Context of Use information can then be applied to the anthropometric data provided in order to generate design guidance and design specifications for particular equipment.

Statistical information about body size is not, in itself, directly applicable to a design problem (Pheasant & Haslegrave, 2005). The choice between using the minimum, maximum or a range of dimensions needs to be made, and the chosen population percentile range and associated measurements need to be matched to the design application. For example, a low percentile is chosen in determining the maximum height of a door handle so that the smallest adult in the population will be able to reach it. For example, minimum dimensions are also used to specify the placement of controls, whilst a high percentile is chosen in determining the minimum dimension for seat width. The most difficult problems arise in those workplaces where several dimensions are all critical for various reasons; cockpits and drivers' seats are good examples.

There are seven main design scenarios to describe the ways in which anthropometric data can be applied to design (Peebles & Norris, 1998). These are presented below in Table 14.