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SIZING AND FITTING OF MILITARY COMBAT CLOTHING, INDIVIDUAL EQUIPMENT AND PROTECTION

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NATO LETTER OF PROMULGATION

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TABLE OF CONTENTS

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CHAPTER 1 INTRODUCTION

This STANREC aims to provide a stepwise approach to the design and evaluation of military clothing and equipment sizing systems such that a major part of the user population is accommodated with a good fitting product combined with a minimum number of product sizes. The STANREC is meant for NATO staff responsible for, or related to, clothing & equipment procurement or issuing. A recent survey showed that over 80% of the investigated 20 NATO country representatives would appreciate a manual on sizing [1].

A good fit is the result of a good match between body shape / size and product shape / size. Movement restrictions may occur when fit is too tight and snagging hazards may occur when fit is too loose. Inadequate fit is not only related to discomfort, but may also affect effectiveness of military operations. Even more, inadequate fit will also affect the soldier's safety, for example with regards to fit of CBRN (Chemical, Biological, Radiological and Nuclear) protective clothing and equipment where a protective mask that is too wide may result in leakage.

The importance of fit is increasingly gaining attention. New sensors and actuators are integrated in soldier systems that can only function when fitted properly. For instance, vision aids attached to helmets can only be used when the helmet fits properly, providing enough stability, on the soldiers head. Considerable differences exist in body dimensions between NATO countries and these body dimensions are also changing within countries (e.g. [2]) which makes it a challenge to design sizing systems that can accommodate the military population. In several countries the variation in the population is increasing, for instance due to increases in body weight, secular growing trends or due to migration. Although it is realized that most clothing and equipment is specific for each NATO country, the focus on interoperability in NATO requires attention since joint operations are becoming increasingly common. Therefore, NATO shares a sizing codification system, so grading and fit needs to be consistent.

It is acknowledged that this STANREC is not an in depth analysis but intended as a guide for clothing and equipment sizing. The reader is referred to two books dedicated to this issue for further reading [3, 4]. For information on military clothing and equipment, refer to the NATO CCIEP (Combat Clothing, Individual Equipment & Protection) working group that acts under the NATO/NAAG/LCG DSS (NATO Army Armament Group/Land Capability Group Dismounted Soldier Systems).

Document structure

The flow chart in Fig. 1 provides a description of how military equipment is commonly designed; the actual body dimensions of the end users are not considered until the equipment is fit to the soldier during fit mapping. This explains the often realized poor fit that results from using a non-existent "average" person to guide product sizing, instead of the dimensions of the end users.

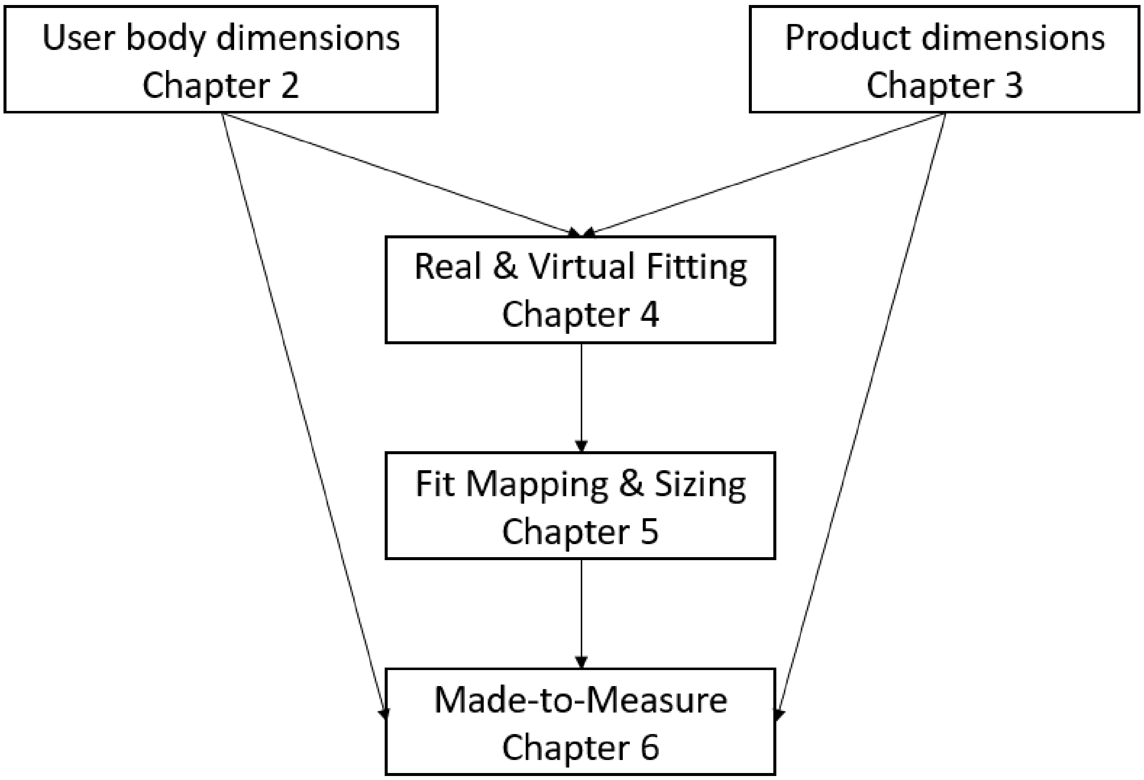


Fig. 1. Flow chart for fitting and sizing of military clothing and equipment.

Chapter 2 *Body Dimensions*, gives an overview of how to obtain accurate body dimensions. Ideally, all military personnel should be measured prior to clothing issuing. In the 20 NATO countries investigated, over 90% take manual measures and 30% use 3D body scanning. Only 60% of the countries store these data [1].

Chapter 3 *Military Clothing and Equipment*, focuses on the product (clothing or equipment). For sizing and fitting, information on the product has to be known such as the intended use and general idea of the product dimensions. For garments, the clothing pattern dimensions are required as well as the link between body dimensions and garment dimensions.

Chapter 4 *Fit Testing,* discusses the fitting process – establishing the relation between a product and the human wearer. The relevant body dimensions of the user population that fit in a certain product, is called the 'fit map'. Fitting is time-consuming. Therefore, new techniques are described that enable virtual fitting, in which a copy of the body (a 3D scan) is interfaced with the product in a specific computer program, which is also described. It is described how to extend fit on an individual basis to fit of a larger population.

Chapter 5 *Designing a sizing system*, covers sizing issues. One-size-fits-all is generally not feasible since the variation in human body dimensions usually exceeds the products flexibility. Guidelines for setting up a sizing system are provided in this chapter.

Chapter 6 *Individual made-to-measure***,** describes a methodology to make fitting garments for an individual. A sizing system that accommodates the entire user population is generally unaffordable since some humans have extreme body dimensions. Therefore, sizing systems are made in such a way that they cover the majority of the user population, e.g. 95%. For the remaining 5% made-to-measure solutions are often less expensive than incorporating them in the sizing system.

CHAPTER 2 BODY DIMENSIONS

For sizing and fitting of military clothing and equipment, information on the body dimensions of the user population is a prerequisite. If no anthropometric data are available, one may consider conducting an anthropometric survey. If the dimensions are available, they should preferably be stored in an anthropometric database with each record containing the information of a single soldier. Body dimensions can be determined manually using simple devices like measuring tapes and calipers, but can also be determined using more sophisticated systems like 3D whole body scanners. Although 3D scanning for clothing fit and sizing is recommended, most NATO countries do not have these systems (survey) and therefore 1D manual measurements are included in this STANREC. When 3D scans of the soldiers are available, these files should have a link to the record containing demographic data (ISO 20685 [10]).

2.1. Manual one-dimensional body dimensions

For clothing fit, important body dimensions are for instance chest circumference, back length, waist circumference, hip circumference and inner leg length. Descriptions of how to determine these dimensions correctly can be found in ISO 8559 [5]. This document can be purchased from the national standardization agencies or from the International Organization for Standardization (ISO) in Geneva (www.iso.org). An example is given in Fig. 2. The description of hip circumference (girth) for instance is: The horizontal girth measured round the buttocks at the level of the greatest lateral trochanteric projections, with the subject standing upright.

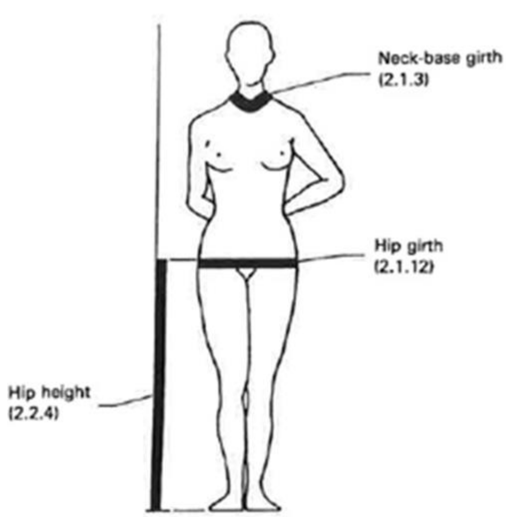


Fig. 2. Example from ISO 8559.

NATO also had a standard on anthropometric data determination – STANAG 2177 [6], but this was cancelled in 2013. The aim of this agreement was to standardize the methods by which body measurements are taken for inclusion in anthropometrical surveys and for the implementation of STANAG 2335 Interchangeability of Combat Clothing Sizes [22]. The methods are intended to enable more accurate comparisons of data between nations. STANAG 2177 was last updated in 2002, therefore the ISO 8559 standard (dated 2017) is preferred.

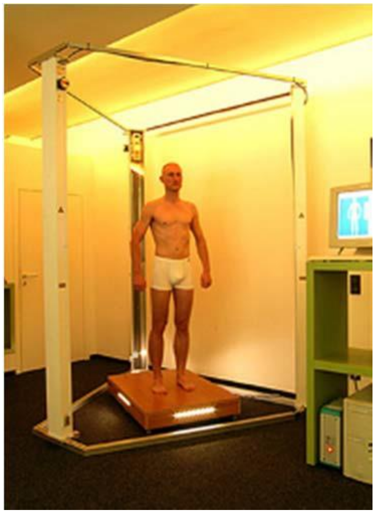
For body dimensions related to the design of cars, rooms, cockpits etc. ISO 7250 [7] is the standard.

2.1.1. Tips and notes

1. It is not easy to measure with high reproducibility. Training courses are available all over the world from anthropometric specialists;
2. When using a measuring tape do not pull it too tight, do not put a finger underneath; the real body dimensions are important;
3. We recommend not to use a plastic or fabric tape as they may stretch, but to use a metal tape; Anthropometry measuring tapes are widely available;
4. Follow the ISO 8559 standard for measurements to avoid ambiguity and describe the ISO measurement code, it enables international exchange of reliable data;
5. When measuring a subject, let the subject move to adopt the posture that is best to perform the measurement, limit the movements of the measurer. Ensure that the measurement tools are of good quality and calibrated;
6. Ensure the equipment is not damaged and maintained regularly;
7. Put the measured data in a spreadsheet with the subject data in rows and the body dimensions in columns;
8. Before starting a measurement survey, think carefully which body dimensions are needed. It is hard to access the subjects for a second time;
9. Take care not to use the end of the tape; instead, use the 10cm mark as the zero line;
10. Use a tool to quantify inter-individual differences and identify outliers (e.g. type the data in Excel and give a warning when the value exceeds the average ± two times the standard deviation);
11. To save time, enter data directly into spreadsheet. Clear communication between the measurer and recorder is important;
12. Use repeated measurements to identify and control inter- and intra-observer measurement error. Avoid taking consecutive measurements that is, take all measures once, then repeat in the same order. This eliminates memory bias and gives time for the measurement site to recover.

2.2. 3D Scanning

In the last two decades, 3D whole body scanners have come to the market. They make a copy of the surface of the human body. From this copy body dimensions can be calculated. Also, and more importantly, the 3D data can be stored for further processing later on.
Fig. 3 shows a 3D scanning device and Fig. 4 shows a 3D scan with some body dimensions indicated (derived from website of Human Solutions).



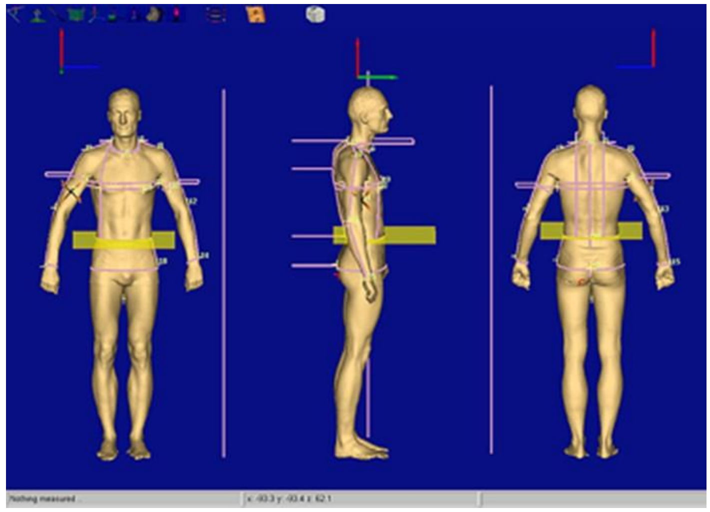


Fig 3. 3D body scanner Fig. 4. Scan seen from 3 sides with body dimensions

The 3D body scans have a large advantage as they contain the crucial geometry needed for clothing and equipment design [8]. However, 3D body scans are not currently used to their full potential. This may be caused by the fact that some scanners only provide 1D information derived from the scanner. It seems to be difficult to harvest the 3D information needed for clothing and equipment design from the currently existing large databases with body scans. Shape descriptors are not standardized and lead to confusion. Another factor may be that 3D databases are large in size. Using a human model may be helpful since it reduces the amount of data to the essential parts (see paragraph 5.2.1 for more info). Also, a 3D library representing the target population, including design extremes, can be made and may be used by manufacturers as well as in procurement. This library might be the solution to enable proper use of anthropometric data in clothing and equipment design & procurement.

2.2.1. Tips and notes

1 The accuracy of 3D body scanners has increased over the last decades and the average costs have dropped significantly [9]. 3D body scanners come in a wide price range. A scanner of 10 thousand Euro may be adequate for clothing issuing; for scientific research the scanner has to be more accurate and the price range is much higher. The yearly conference on 3D body scanning (www.3dbodyscanning.org) provides a good platform to get the latest information on new developments.

2 The 3D scan consists of a cloud of thousands of small points (x,y,z – coordinates) that can be connected together to form a mesh surface duplicating the scanned subjects skin. This surface can be shaded to give a nice view as shown in Fig. 4.

3 Note that body dimensions derived from 3D scans are not identical to manual

measures. Not all measurement extraction software algorithms are alike either. Differences between algorithms can result in differences in measures. Unlike a human measurer who can palpate the subject being measured, a scanner cannot determine where the underlying bony structure is located. In general 3D scan derived body circumferences are slightly larger than manual measures due to the lack of tissue compression and the ability of computers to easily calculate the maximum circumference. The reproducibility of scan derived body dimensions is generally better than manual measures since measurers use their own specific method to determine circumferences with for instance specific force applied to the measurement tape. ISO 20685 [10] refers to the allowable differences between manual and 3D scanning.

4 Ensure that the subject only wears form fitting non-compressing clothing in a color that is captured by the scanner, is bareheaded or wearing a wig cap, and without shoes during the measurements.

5 The software used to calculate body dimensions from the scanner is often included with the scanner. Try to use the full 3D information that is available next to the simple scan derived body dimensions. 3D scans can be reprocessed when new software emerges to calculate scan derived body dimensions.

6 Ensure the scanner provides an accurate copy of the human body: the resolution of the scanner should be high and occlusion should be minimized. Use a calibration procedure. For a detailed method see Kouchi [11].

7 Realize that 3D scans can easily be identified as a person. Privacy and confidentiality regulations differ from country to country and should be followed. Also, consider encryption when transferring or storing data and de-identification using scrambling techniques like blurring parts of the face for publication.

8 Carefully select a 3D scanner that is appropriate for the job. Consider using the list in Annex A as guidance.

9 Ensure that personnel are sufficiently trained to operate the 3D scanner. Operators should check the posture and the scan quality.

2.3. Databases

Store the body dimensions and other relevant information such as demographic and fit data in a database. ISO 20685 [10] sets requirements for 3D databases and gives recommendations. Automatic cleaning procedures for military anthropometric databases are also available [12]. Ensure that the body measurement database being used to develop the design of an item is representative of the user population in terms of gender, age, ethnicity, location in the country and occupation. Also, the database should have sufficient number of subjects included and representative for the current population [10].

CHAPTER 3 MILITARY CLOTHING AND EQUIPMENT

The size of the clothing / equipment item should match the body dimensions of the user. Generally, differences in circumference between body and product are quantified. For instance, the chest girth of a combat suit should be equal to the chest circumference of the soldier with a certain number of cm's added (this is called the 'ease'). In this way the differences between the girth of the clothing and the girth of the fit model (user) or mannequin are unambiguous. The clothing or equipment design rules should be based on and critically evaluated with the user population as a reference.
If no product dimensions are available and a product has to be designed from scratch, it is important that the initial design is made using a representative member of the user population, keeping in mind that there is no perfect average of the user population to be found. When the initial design fits the body, the design rules (e.g. the ease for clothing at different body locations) can to be specified so that later the sizing system can be quantified.

3.1. Clothing patterns

Military clothing and equipment is diverse in nature: underwear, combat suit, gloves, uniforms, helmets, ballistic protection, vest, socks, shoes, jackets etc.
Most products are made from textile materials like a combat suit. In this case the clothing patterns define the dimensions of the suit. A typical pattern for a pair of trousers is shown in Fig. 5.

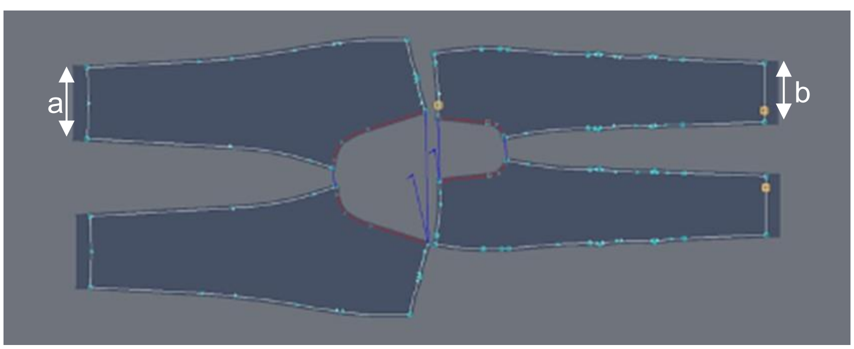


Fig. 5. Example of the simplified clothing pattern of a pair of trousers. These four parts are sewn together. The sum of the distances a and b define the minimal circumference of the trousers leg circumference at bottom excluding seam allowances and should be sufficiently wide.

Most manufacturers of garments use computer aided design software for apparel in which the patterns of the garments are stored, e.g. Lectra, Gerber, Assyst. When the material has stretch properties, the dimensions of the patterns can be adapted. The dimensions of the clothing and equipment pattern should be related to body dimensions. For instance, the distance a+b in Fig. 5 is related to foot size for the trousers in the Dutch armed forces.

3.2. Product shape

Other products, like helmets or ballistic plates, are rigid and require a different form of fitting. The shape of a helmet should represent the shape of the human head. Ballistic requirements demand a minimum distance between the inside of the helmet, and the head maintained by the suspension system for safety reasons (STANAG 2902 - Non-Ballistic test methods and evaluation criteria for combat helmets [13]. The use of (3D) anthropometric data to improve helmet design and determine the optimal size range is described in the literature [14, 15].

CHAPTER 4 FIT TESTING

Fit-testing is the process of determining the relation between the product dimensions and human dimensions. Three aspects are important for fit-testing: determination of the human body dimensions (Chapter 2), determination of the product dimensions (Chapter 3) and defining and quantifying fit i.e. the determination of the unambiguous relation between body and product dimensions. Fit testing leads to insights in how well the products fit the body and what adjustments will lead to a better fit, but also on how many sizes are required. Choi et al. provide a comprehensive guide to fit testing [16]. An example of fit testing from this document is shown in Annex B. Fit is not only important for wearing comfort, but also for safety, in particular when protective clothing is worn. Multilayer clothing systems make evaluation of fit more complex.

4.1. Quantifying fit

Fit has to fulfill static, dynamic and occupational-related criteria (including functional requirements such as ease to move, insulation and moisture removal properties). Thus fit scores should also reflect mobility scores as well as static tests. Fit tests should be carried out on multiple individuals representing the user population. Generally, more than 50 subjects of each gender are needed to get sufficient data to cover the wide variability in fit assessment between subjects.

Different fit scores can be used. A possibility that is easy to process is using a fit rating scale; 0 for good fit, -1 for too tight and +1 for too wide. Also, the adjustment of the clothing (in cm) necessary to get a good fit can be quantified (see the column sleeve adaptation in Table 1). Fig. 6 shows a simple method how to determine the difference between the end of the sleeve and bony landmarks of the wrist. Similar techniques may be used for chest girth, jacket length etc. Another option is to specify pass/fail criteria (Annex B). An example of fit testing for military hats is given in Annex C.

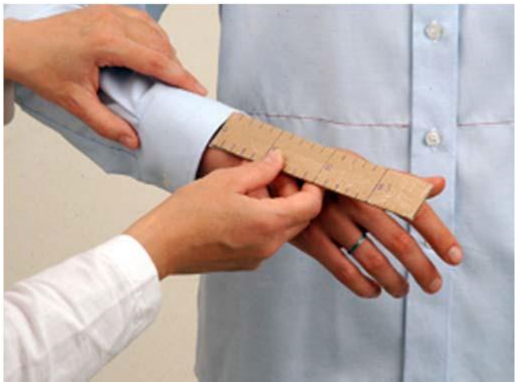


Fig. 6. Determination of adjustment in sleeve length.

An example of a fit test score form for a static test is shown in Table 1. Columns 3-6 are body dimensions related to the garment in cm. Column 7 is the NATO size of the garment in accordance with STANAG 2335 [22]. Column 8 is the self-reported fit score of each military subject (-1 = too small, 0 = OK, 1= too wide). Column 9 is the fit judged by an expert (-1 = too small, 0 = OK, 1= too wide). Column 10 shows the alteration that has to be made in sleeve length (in cm).

Table 1 – Example of a fit test score form with selected items for a combat jacket (circ. = circumference).

Sub-ject	Iden-tifier	Chest circ. (cm)	Hip circ. (cm)	Waist circ. (cm)	Stature (cm)	Jacket size	Fit score subject	Fit score expert	Sleeve adaptation (cm)	Re-marks
1	9999	100	110	90	180	8000/8000	0	-1	-2	..
2										

In this example the fit is assessed by each military subject and an expert. The expert assesses the jacket as being too tight while the subject is satisfied. It should be realized that the expert has a good overview of fit and takes care of homogeneous fitting and operational functioning. On the other hand, incorporation of the fit scores of the military subject increases the user involvement. Differences between expert and participant fit estimation may provide insights in user appreciation.

Another example is for coveralls. Here users preferred more baggy coveralls than experts since this is more comfortable to wear, while experts focused on esthetic looks [17]. The fit tests should therefore be conducted in postures and using movements that represent the tasks that the military subject should perform.

4.1.1. Tips and notes

1. Ask the participant to move during the fit test and adopt body positions for the tasks he/she has to fulfill in representative environments (see also Annex B).
2. Take the fit results back to the designer so that the product can be optimized.
3. Refer to STANAG 2333 [18].

4.2. Virtual fitting

The process of fit-testing is time consuming since every subject has to fit one or more garments. Therefore, it is interesting to consider virtual fitting. In virtual fitting, 3D scans of the user population are matched with the digitized patterns of clothing and equipment. Virtual fitting is an emerging technology; validation reports are scarce. It is too time consuming to make a virtual fit of every individual, therefore a statistical subset of virtual human models that represent the whole population may be used to speed up the process.

4.2.1 Virtual fitting of garments

For virtual fitting, software tools are required. Several software systems are available like Lectra Modaris, Gerber, Optitex and Vidya Assyst. A recent overview is recently published [19]. An example of a virtual fit is shown in Fig. 7. The Lectra Modaris system compares differences between circumferences of the naked body and dressed body on a horizontal plane and color codes the difference. Some other packages like Clo3D visualize the distance between the skin and the garment perpendicular to the skin, which is a better method. When the clothing is tight fitting, an option can be selected to visualize the strain in the garments. A third method is to make the clothing transparent to visualize the interface between the human subject and military garments (Fig. 8). Software for virtual fitting is often focusing on visual representation of fit; quantitative analyses are lacking.

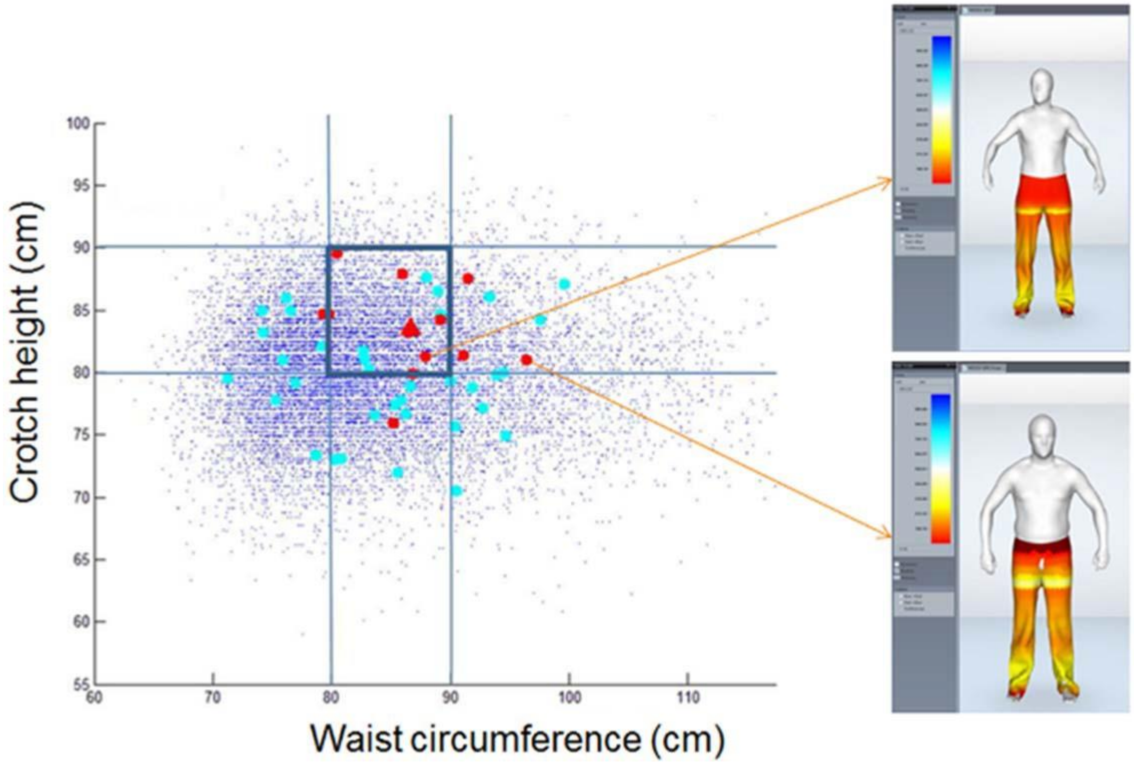


Fig. 7. Example of virtual fitting of military trousers using Lectra Modaris software. Each small blue dot in the left panel represents the crotch height and waist circumference of a Dutch soldier. The large red dots represent the dimensions of subjects that selected trousers size 8090/8090 in the physical fitting session. This size indication means that both waist circumference and crotch height are in the range of 80 to 90 cm. The light blue dots represent subjects that selected another trousers size. The 3D scans of two soldiers in the right panels are derived from the database. Both soldiers selected NATO size 8090/8090 during clothing fitting tests. The subject in the upper right panel had a waist circumference of 88 cm and crotch height of 82 cm and showed a good virtual fit (no blue or dark red color). The subject in the lower right panel had a waist circumference of 96 cm and crotch height of 82 cm. The trousers were too tight at waist level (dark red color). Trouser length was not considered in fit analysis since the bottom parts are tied up.

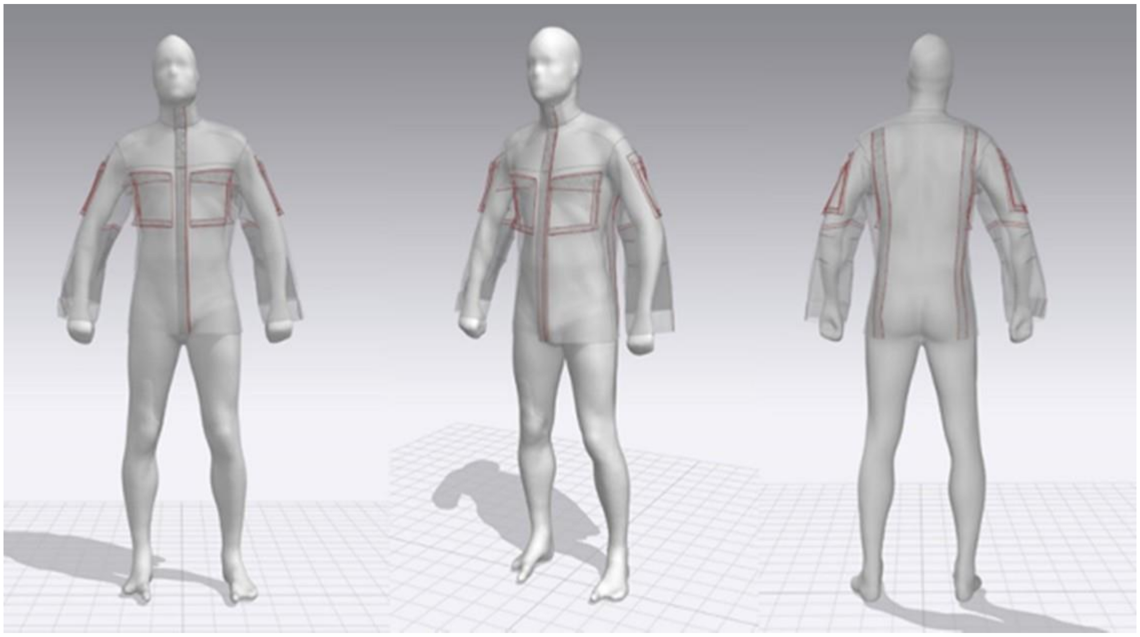


Fig. 8. Visualization of the fit of a military jacket on a selected military subject using Clo3D. The clothing is made transparent to visualize the interface with the human body.

Virtual fitting can be used in the design phase (e.g. Fig. 8) or in the evaluation phase (e.g. Fig. 7). Next to visual assessment of fit, a quantitative assessment can be made. An interesting option is to calculate the trapped air in between the skin and clothing [20] and to set a threshold for what is acceptable and what not. More specific fit allowances can be used at predefined locations at the human body. In Fig. 8 for example, the jacket seems to be a bit tight at the level of the hip and loose at the level of the lower arm.

4.2.2. Virtual fitting of rigid products

For rigid bodies, such as helmets, a simple way to assess fit is to make a photo of a subject with and without the product, to superimpose the two images and make the product transparent (Fig. 9). A simple camera and an inexpensive tool like Fantamorph (www.fantamorph.com) can do the job. However, it has to be realized that hair is an issue that should be considered. A compressing wig cap may mitigate the problem.

Fig. 9. Superimposed images of a photo of a head and head/helmet combination to provide insight in fit.

3D information is more accurate and informative. The approach is similar to photos: 3D scans of the body and product can be subtracted and the interface evaluated. A nice example is given for helmets [14]. A method to use 3D shapes of head forms is described in Annex D.

4.2.3. Tips and notes

1. Virtual fitting takes time to learn. Several software systems like Clo3D offer free trial versions. This is a good way to learn the benefits and pitfalls.
2. Look at what parameters are needed in the virtual clothing fitting to quantify material properties (e.g., stiffness, bending force). Ask the textile manufacturer to supply these values. When not available, send a textile sample to a dedicated textile research center to derive the values.
3. Do not only use side views, but also front and rear views to get a complete picture in virtual fitting of rigid products.

CHAPTER 5 DESIGNING A SIZING SYSTEM

5.1 Methodology

Most often the commercial clothing suppliers provide a sizing system, but these are often not optimal. Take the initiative to encourage industry partners to design the system in a way that results in a minimum number of clothing sizes with a maximum coverage of the total population, or ensure that the industry proves that this is taken into account. The sizing system will only be as good as the basic information that is provided (anthropometric, key body dimensions that control design, and fit, operational requirement, fit intent, sizing intent).

The following steps are proposed as a methodology for sizing system development [4]:

1. Fieldwork preparation
2. Anthropometric planning
3. Anthropometric survey
4. Anthropometric analysis
5. Multivariate data examination
6. Principal component analysis
7. Cluster analysis
8. Decision tree analysis
9. Size system development
10. Size system validation (fit tests)
11. Size designation

This approach has a strong focus on the body dimensions of the user population. The product and product dimensions come into play in step 9.

Ad 1. The fieldwork preparation consists of approval from the authorities, making the measurement protocol and training the measurers.

Ad 2. The anthropometric planning involves the execution of a pilot and calculation of the sample size. Obviously, determining the body dimensions of each soldier is to be preferred over using a sample when it can be incorporated in the clothing supply process.

Ad 3. The anthropometric survey can be performed using different methods. This is covered in chapter 2 of this STANREC.

Ad 4. The measurements have to be cleaned and analyzed. For 3D scan data cleaning and processing methods are described [12].

Ad 5. Multivariate analysis refers to statistical techniques used to analyze data that arises from more than one variable. For instance, it can be analyzed how stature is related to inner leg length and arm length. Multivariate analysis is often used to see if the next step (principle component analysis) can be made.

Ad 6. Principal component analysis (PCA) identifies the main components that are important in sizing. PCA can be performed on manual measures, but also using 3D scans. The computer calculates step by step where most variation occurs. Generally, the first principal component (PC) is related to length (stature, leg length, arm length) and the second PC is related to circumference and body weight (Fig. 10). The third PC is often related to the relative arm/leg length, but can also be related to posture (e.g. standing erect or slightly crouched). If not the whole body, but only body parts are included in the analysis, such as head or torso scans, the PC's will be different.

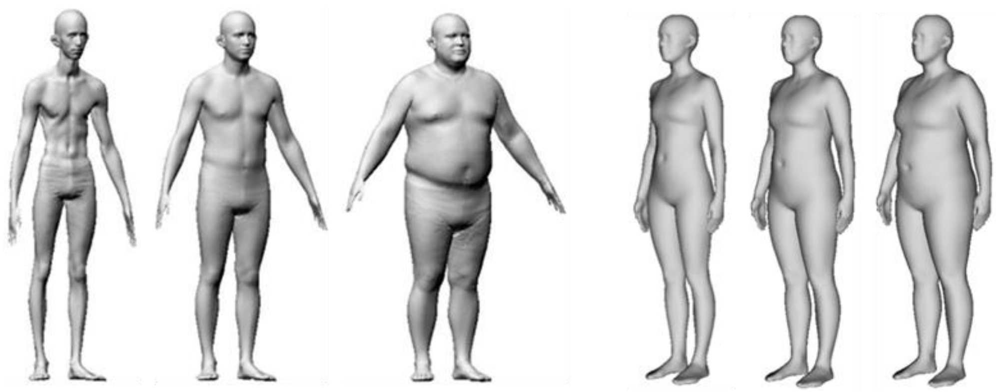


Fig. 10. Visualisation of the principal component related to weight/circumference using human models. **Male images**: 1, 50 and 99% of CAESAR survey (Source: Shu, NRC Canada). Please note that increasing weight is related to shorter inner leg length. **Female images**: 5, 50 and 95%. Model based on military subjects created with DRDC/NRC Anthrotools v2.4.8 (CFAS data).

Ad 7. Cluster analysis is a method to segment a population in homogeneous subgroups. However, in most countries such clusters do not exist (except for male/female clusters) and the data is more or less continuous.

Ad 8. Classification analysis is used to determine how many components should be included in the sizing system. The first principle component explains most variation, the second a little bit less and there comes a point in which a component does not add useful information.

A more practical but less accurate way to determine the main components for a sizing system is provided by ISO 8559-2 [21]. The standard includes a list of the most important body dimension related to garments. For instance, for overcoats the primary dimension is chest girth and the secondary dimension is body height. STANAG 2335 [22] uses a similar approach: for military garments a circumference measure and a length measure constitute the basis for the sizing system.

Ad 9. For the size system, it is important to define the size range and size interval.

The size range refers to the difference between the smallest and the largest size. When the size range is large, many subjects can be accommodated but the extreme sizes will be rarely used. It may therefore be more efficient to limit the sizing system to for instance 95% of the user population and make the final 5% made-to-measure (chapter 6).

The size interval relates to the steps between sizes. Often, these steps reflect tradition, e.g. 1-inch steps for jeans waist circumference. Ideally, the size interval should be such that each user should get a fitting size. The size range and size interval determine the size roll, which is the total number of sizes obtained for a sizing system. The size roll should be minimal for logistic reasons. Design and fabrics have an impact on fit and size range; consider materials, cut of patterns, types of garment, functional requirements, adjustments within the design – all of these have an effect on the variability of fit.

Ad 10. Size system validation

The developed sizing system does not always perform as expected. For instance, unisex clothing may not work well for men and women; it may require modifications to fit some women (e.g. larger waist to hip ratio). Sex-specific patterns may be required in some cases. Therefore, the sizing system should continuously be evaluated. One reason is that the population may change. An example is given in Fig. 11. The existing sizing systems of Dutch military trousers consisted of 9 sizes (white boxes). The percentage coverage of the military population is shown in the boxes. The two sizes with waist circumferences of 70-80 cm were only appropriate for 1.8% of the user population since the secular trend in body weight increase is also visible in Dutch recruits. Abolishing these sizes and size 9000/8090 leads to 2.3% less coverage. However, adding size 7080/0010 leads to a net coverage of 80% (previously 78%) with 7 sizes (previously 9 sizes): less sizes and better coverage.

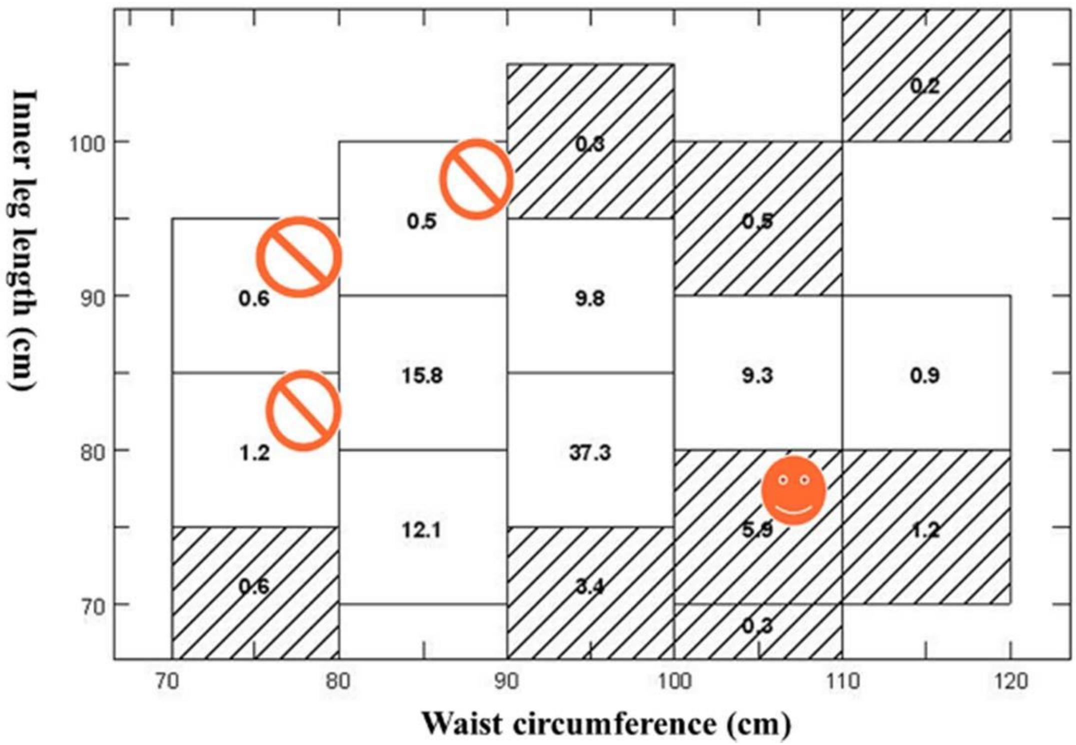


Fig. 11. Sizes for military trousers (white boxes) with percentage coverage of the military population. Stopping sizes 7585/7080, 8595/7080 and 9000/8090, while adding size 7080/0010 results in a drop from 9 to 7 sizes and an increase in coverage from 78 to 80%. Size 7585/7080 means an inner leg length of 75 to 85 cm and a waist circumference of 70 to 80 cm, according to STANAG 2335 [22].

Ad 11. Size designation for most operational military garments is given by STANAG 2335 [22]. The first two numbers relate to the lower limit of a length measure, the second two numbers to the upper limit of the length measure; the third two numbers relate to the lower limit of a circumference measure and the last two numbers to the upper limit of the circumference measure. An example is given in Fig. 12.

Fig. 12. Size designation of an extreme cold weather jacket.

5.2 Grading

5.2.1 First prototype

When a new product has to be designed, ensure that the first prototype is fitted for a user with close to average body dimensions. Having your 'master' in the middle of your range allows you to maintain your design more effectively throughout the entire size range.

BODY FORM
When using a dress form, design the product around it until it fits. Measure the dimensions of the manikin (e.g. waist circumference) and the dimensions of the product at that spot. The difference between these two dimensions is the ease at that location (Table 2).

Table 2. Example of the calculation of ease from the difference between dress form measurements and jacket dimensions.

	Dress form	Jacket	Ease
Neck circumference (cm)	40	42	2
Chest circumference (cm)	100	104	4

Waist circumference (cm)	88	100	12
Hip circumference (cm)	102	106	4

3D SCAN

Another option is to design and fit directly on an individual or to use a 3D printed copy of this individual. Find a subject that 1) represents the average of 3D coordinates (for instance using PCA) or 2) has average 1D body dimensions (e.g. stature, chest circumference, inner leg length, waist circumference, arm length).

VIRTUAL BODY

Instead of using a 3D scan of an individual, one may consider to use a human model or a part of it that represents a specific population (Fig. 13).

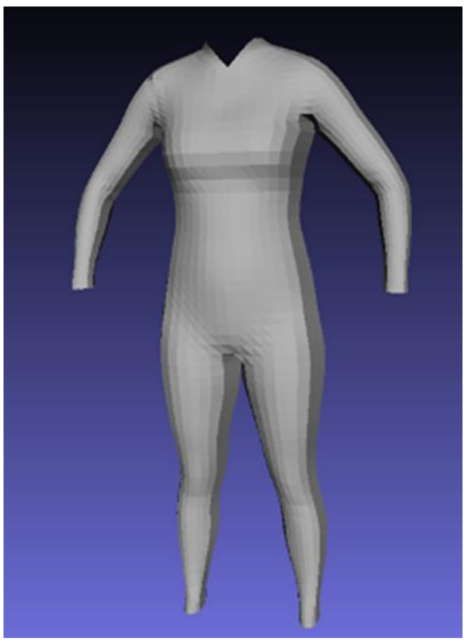


Fig. 13. 3D shape representing the average military Dutch female.

5.2.2 Traditional grading

When a first design of a military clothing or equipment has been made, the next step is to grade it. This means that other sizes have to be made to cover the entire population. One-size-fits-all is only possible when a garment or piece of equipment is not very critical in fit, such as ponchos for rain protection.

The most common option for grading is to use standard grading steps. STANAG 2335 [22] recommends steps of 5 cm for grading or a multiple thereof for each dimension. A nice example is shown if Fig. 14. If the first design is made for a soldier with chest circumference of 100 cm and stature of 175 cm, a standard size block can be made, resulting in NATO size 7080/9505 [22]. Additional blocks can be made, such that the population is covered. The system covers soldiers ranging from 150 to 200 cm in stature and 75 to 135 cm in chest circumference. These systems are simple to understand. However, the combat jacket for each size is linearly changed and does not reflect the shape differences in humans (see Fig. 14). The human body does not scale linearly; a 5 cm grade for a small person is a much greater step (as a percentage) than it is for a larger person.

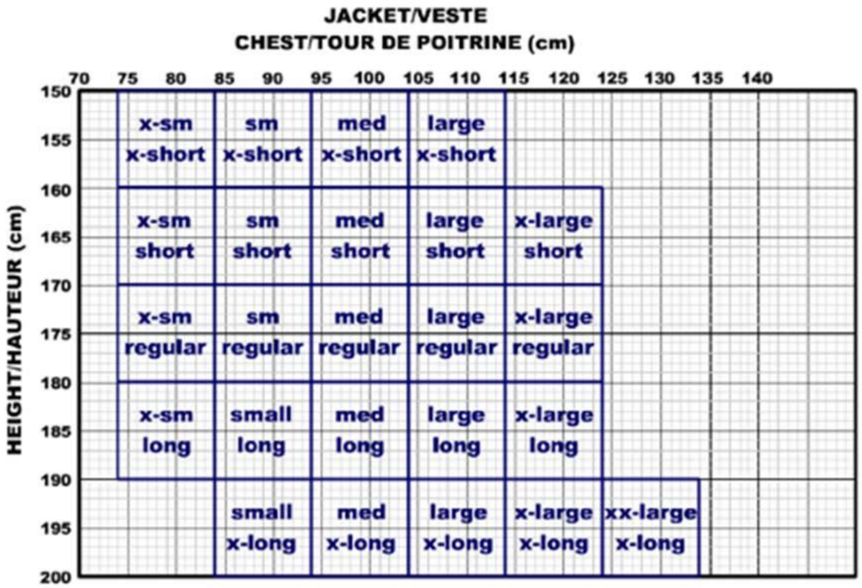


Fig. 14 Sizing system of US combat jackets [22].

5.2.3 Grouped grading

An alternative method is to make a differently shaped product for each size block. Instead of making a single prototype (paragraph 5.2.1), a specific product is made for each size block.
When 3D scans are available, the soldiers in a certain size block can be retrieved from the database and an average shape can be calculated using human body modeling [19]. The preferred ease (paragraph 5.2.1) can be added and the product can be shaped.
Using this method, there is a higher chance that the product will fit. However, it is more time consuming to design the garments.

5.2.4 Fit-mapping

This method starts with identification of who fits in a certain product. Fit tests are conducted and an envelope is drawn around the subjects that fit the garment. An example is shown in Fig. 15 for a combat jacket. The envelope is called a fit-map [23]. The envelopes can be reshaped to a square for easier understanding.

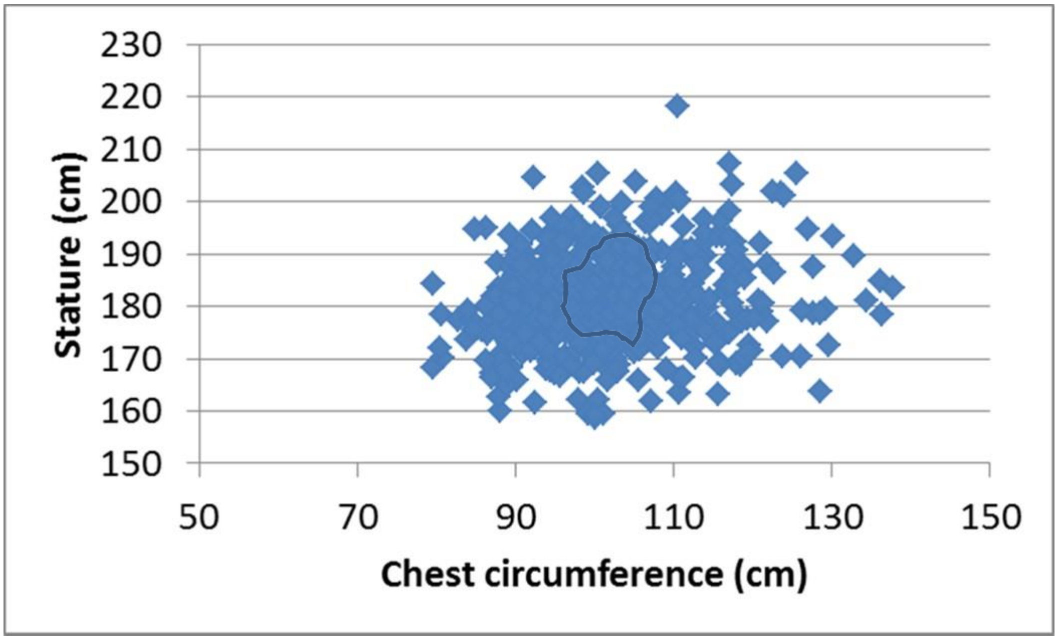


Fig. 15. Stature (cm) and chest circumference (cm) for a large group of military subjects. Each symbol represents a military subject with a certain chest circumference and stature. The envelope surrounds subjects that indicate that a certain jacket fits them.

The next step is to map the fit maps to the population. An example is given in Fig. 16. It is assumed that the fit-map stays the same in shape. It can be argued, however, that for large sizes the fit-map may be slightly larger. In the example, the majority of the population is accommodated with 6 sizes.
The advantage of this method is that the size steps are not based on tradition, but on the actual limits within a single size. This method will probably lead to a minimal number of sizes covering the population. Labeling is not an issue: it is proposed to use the boundaries of the fit-map for size indication, for instance 7595/9505 for Fig. 15, similar to traditional labeling.
A disadvantage may be that many subjects have to fit the garment. However, virtual fitting can also be used (paragraph 4.3.1) and this will speed up the process, but is obviously less accurate than real (life) fitting. Also, a combination of real and virtual fitting can be considered, combining the strong points.

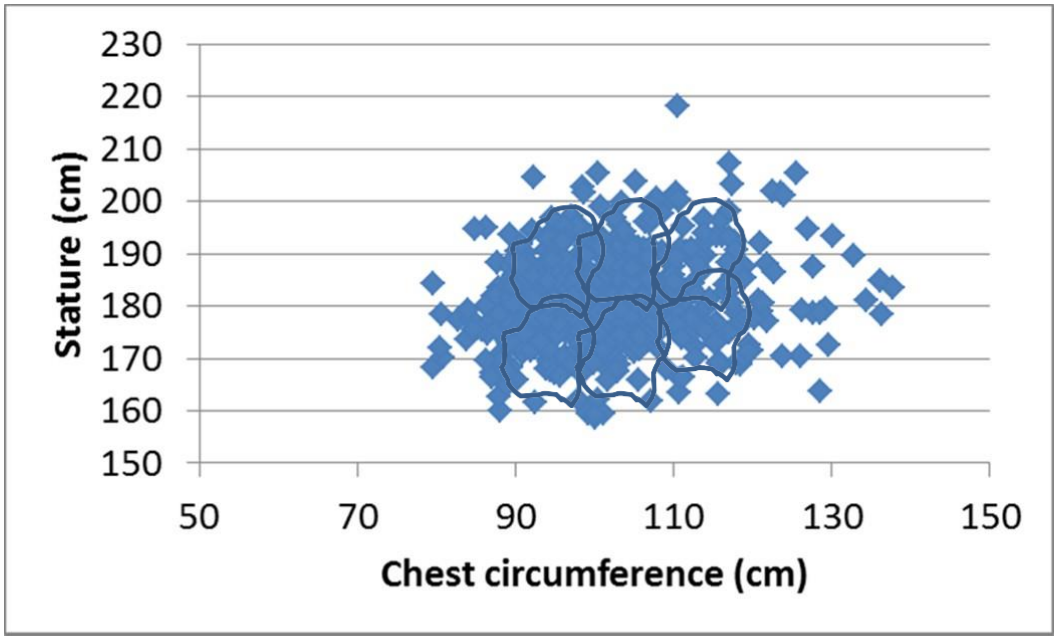


Fig. 16. Stature (cm) and chest circumference (cm) for a large group of military subjects. Each symbol represents a military subject with a certain chest circumference and stature. The envelopes or fit-maps are placed over the population to get optimal coverage.

In the examples given above, only two traditional dimensions are included. It can also be considered to replace stature and chest circumference with the first and second principal component of the PCA analysis. Also, the number of variables can be extended to three or more. In the case of 3 variables, the data-points will likely have the shape of a rugby ball and the 3D fit-maps have to be correctly located in the 'rugby ball'.

5.3. Selection of the best fitting size

Whatever system is used to make the sizing system (traditional grading, group size grading or fit-mapping), the best fitting size has to be determined when the soldier comes to pick up the clothing and equipment.
There are three methods to pick the best size:

- Selection based on primary and secondary dimensions (possibly tertiary)
- Selection based on set of rules or regression
- Selection based on virtual fitting

5.3.1 Selection based on primary and secondary dimensions

In this method, the soldier is measured manually to determine chest circumference and stature for jackets and waist circumference and inner leg length for trousers. Also, 3D scanning can be used and the derived body dimensions used.

The determined body dimensions are used as input for the chart and the correct garment size is selected. For Fig. 14 for instance, a subject with stature 165 cm and chest circumference 120 cm will get size X-Large/Short or 6070/1525 in NATO size.

5.3.2 Selection based on set of rules

If the soldier happens to have a protruding belly, it is likely that the size X- Large/Short in the given example will not fit. Therefore, rules are often added. Such a rule can be that if the waist circumference exceeds the chest circumference a larger size will be selected. Generally, the largest size is taken as the guide for the selected garment.
Those rules are often supplied by the manufacturers of 3D scanning systems in a black box. The body is scanned, and over a hundred traditional body dimensions are calculated from the scan. Then the rules are applied and a size recommendation is given. The manufacturers have deducted the rules from time-consuming fit sessions and are therefore not eager to share the results. The system may work fine, but improvements can only be made in close cooperation with the manufacturer of the software for the 3D scanner.
Therefore, one may consider investing in determining your own sizing rules. It makes it easier to adapt and allows for a better insight in the sizing system.

5.3.3 Selection based on virtual fitting

The most sophisticated but most complex size selection methodology is to use dedicated software to interface the 3D scan of the soldier with the clothing patterns (paragraph 4.3.1). However, this is currently too time consuming in the clothing and equipment supply process. Batch processing and more automation are required. It is expected that these tools will come in the near future.

CHAPTER 6 INDIVIDUAL MADE-TO-MEASURE

It is impractical and inefficient to specify a sizing roll that accommodates everyone, including those at the extremes of the population; it is better to make made-to-measure for subjects with extreme body dimensions: extremely tall, short, slim or obese but also for subjects with uncommon body shapes. The costs for keeping these extreme sizes on stock exceed the costs of making made-to-measure garments.
However, making made-to-measure garments is time consuming: the soldiers are individually measured, the patterns have to be cut by hand or single layer cutters, the patterns have to be sewn together and the clothing has to be individually fitted and refitted.
When a 3D body scan is available and when patterns of the garment are available for the closest matching size, it can be considered to partially automate the process. Software packages like Lectra Modaris, Gerber, Optitex and Assyst enable the adaptation of the patterns to the individual and visualize the results. When satisfied, the patterns can be printed and cut, so that this part of the made-to-measure process can be speeded up.

CHAPTER 7 CONCLUSIONS

For adequate sizing and fitting of military clothing and equipment, the start is to know the relevant body dimensions of the user population. It is recommended to adhere to international standards (ISO 8559) to measure the human body. 3D body scanning is an alternative for manual measures. The pros and cons are summarized in Table 3.

Table 3. Pros and cons of manual measurements versus scan derived body dimensions.

	Plus	**Minus**
Manual	• Less expensive • In line with ISO standards • Links to existing data	• Measurer dependent • Time consuming • Limited data • Extensive training required • Intimate measure
Scan - derived	• Reproducible • Shape info • Fast • Extract additional data • Transfer of scans to models for clothing fit analysis and crew station design	• Investment • Privacy concerns • IT skills required for big data processing

The body dimensions can be used to make a sizing system. Leading is to have a minimum number of clothing/equipment sizes and a maximum coverage of the user population. While traditional sizing systems use fixed grading steps, the STANREC describes an alternative method to make a sizing system based on fitting tests. Fitting is time-consuming, but in the future virtual fitting may speed up the process.

Once a sizing system is present, the challenge is to fit the military member in the right size. Again, accurate body dimensions should be taken and these should provide a link to the best fitting clothing or equipment size. The current status of technology is such that real fitting is still often necessary due to the great variation in human shape.

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ANNEX A *3D Anthropometric Scanner requirements*

3D Anthropometric Scanner is a device that analyses human subjects to collect body size data. The collected data can then be used to construct digital three-dimensional models, to match or optimize personal equipment (e.g. clothing, PPE) and work environment (driver space, cockpit design etc.).

For military use, the following shall comply:

- Automatically identify common body landmarks and provide anthropometric data collection functionality;
- Provide a feature that users can integrate own clothing charts, so the scanner;
- program can output garment sizes or other personal equipment items;
- Robust hardware and software; easy to install, operate, and maintain;
- Private and comfortable scan experience;
- Provision of security for an individual's data;
- Accurate and automatic post-scan data processing;
- Safety: eye and skin safe;
- Data output format interchangeable with other software programs, allows freedom to choose third party software, if required;
- Stability toward working environment (e.g. ambient light condition, temperature change etc.);
- Warranty and support.

The following should comply:

- High speed: avoid movement artifacts;
- Measuring sitting posture capability;
- Automated calibration procedure, if calibration required;
- Fail Safe with certain hardware;
- Small footprint (minimize space use);
- Statistic capability to look up collected data;
- Reverse engineering capability, i.e. feed the program with manual measurements, simulate out subject/profile etc. for visualization.

ANNEX B *Example of a part of coverall fit procedures*

Range of hand and arm motion: Dynamic and Occupation specific [16]

a. Initial Posture: Standing

b. Task: Raise arm up to the sides and overhead. When raising the arms overhead, first make a "Y" shape with the arms at the 10 and 2 o'clock positions, then make an "I" shape with both arms at 12 o'clock position, and finally bend the arms and place the hands on the top of the head.

c. Pass/Fail
i. Pass: Perform the task without any difficulty
ii. Pass with difficulty: when the subject makes an extra effort, relative to that subject's performance in the scanning garment, or the task is completed but difficulty is observed
iii. Fail: When the task is not completed or tension around the crotch is unbearable.

Figure B1(a-d). Task descriptions for "Range of hand and arm motion"

ANNEX C *Example: Fit of military hats*

In order to determine the amount of sizes and size range for male military hats, a fit- test was performed in which 44 males donned a hat of different sizes [24]. Fig. C1 shows an example of the fit of a typical subject with 3 hat sizes. Evaluation of hats is relatively easy since only one body dimension is required in the analysis: head circumference.

Fig. C1. Fit-testing of military hats for a typical subject wearing size 57 (left), 58 (middle) and 59 (right).

48% of the subjects indicated that only 1 size fitted. For the subject in Fig. C1 also only one size (58) was considered to fit. However, 11% indicated that no size fitted properly, 21% indicated that 2 sizes fitted properly and 21% that even more sizes fitted properly. For military fur hats, it appeared that 66% accepted two sizes or more; therefore, the step size of these hats was increased from 1 to 2 cm, saving 5 sizes and thus simplifying logistics and costs.
There is a nice way to combine all this information in a single graph. This is shown in Fig. C2. The variability between subjects is considerable. On average, a good fitting hat has a size that is 1.2 cm bigger than the head circumference of a subject.
Since a database is available on head circumferences of the Dutch military population, it could be established which sizes are required and in what amount. For males, sizes 53-63 are required. To accommodate females, size 52 has to be added.

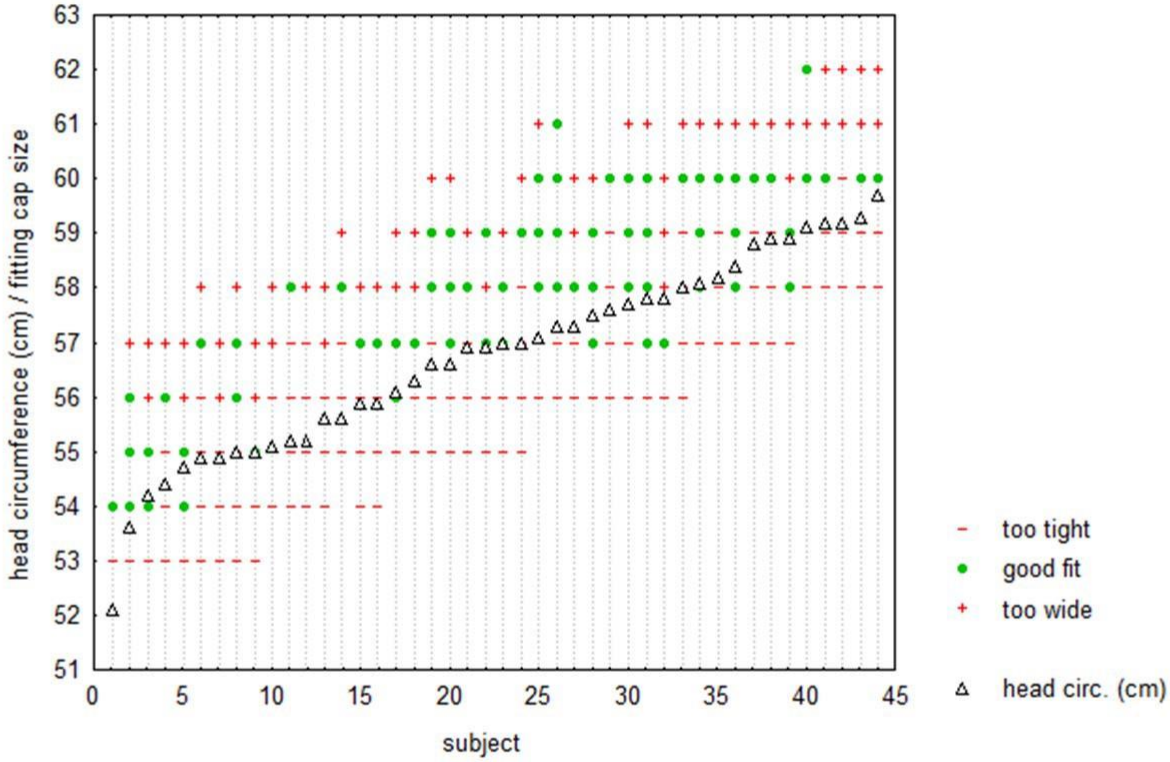

Fig. C2. Combined information from the fitting test is a single figure. The head circumference of the subjects is indicated with a triangle. Green dots show good fit of a certain hat size, a minus signifies that fit is considered too tight and a plus sign that it is too wide. Opinions of the expert and subject were combined on agreement.

ANNEX D *Using 3D head shapes for helmet fit*

Meunier et al. [14] scanned the heads of military subjects with and without their helmets and superimposed the images. In this way the interface between head shape and helmet shape can be visualized. Fig. D1 shows examples from TNO (courtesy Aernout Oudenhuijzen).

Fig. D1 Relation between human head shape and helmet shape.

Virtual testing is gaining terrain over field fit testing. An intermediate test method, lying between field testing and virtual testing for combat helmets is described [25]. In this study seven digital head avatars with various head dimensions were selected from a database of 3D whole body scans of the Dutch Military Forces. Multiple head dimensions were used to select these seven head avatars which were then 3D printed in real size. Different helmet configurations were placed onto the digital head avatars as well physically on a set of subjects (male, n = 29) with comparable head dimensions, following the manufacturers guidelines. Each subject and head avatar was scanned with and without the helmet. After digitizing these helmet configurations, the orientation and position of each helmet was analyzed using 3D CAD. The results revealed that the helmet orientation and position was similar for the real subjects and for the digital head avatars. Hence, the use of helmet fit testing on digital head avatars has been validated, which opens the path to use digital head avatars for combat helmet fit testing. Currently this method is applied in the replacement of the Dutch combat helmet. It partly replaces field trials with the focus on the helmet fit, other aspects such as thermal comfort, pressure points, compatibility with government furnished equipment still has to be evaluated in field trials.

ANNEX E *Glossary of terms*

1D, 3D – One, Three dimensional
CAD – Computer Assisted Design
CAESAR - Civilian American and European Surface Anthropometry Resource
CFAS – Canadian Forces Anthropometric Survey
DRDC – Defence Research and Development Canada
NRC – National Research Council of Canada
ISO – International Organization for Standardization
NATO – North Atlantic Treaty Organisation
PC – Principal Component
PCA – Principal Component Analysis
PPE – Personal Protective Equipment
STANAG – NATO Standardization Agreement
STANREC – NATO Standardization Recommendation

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