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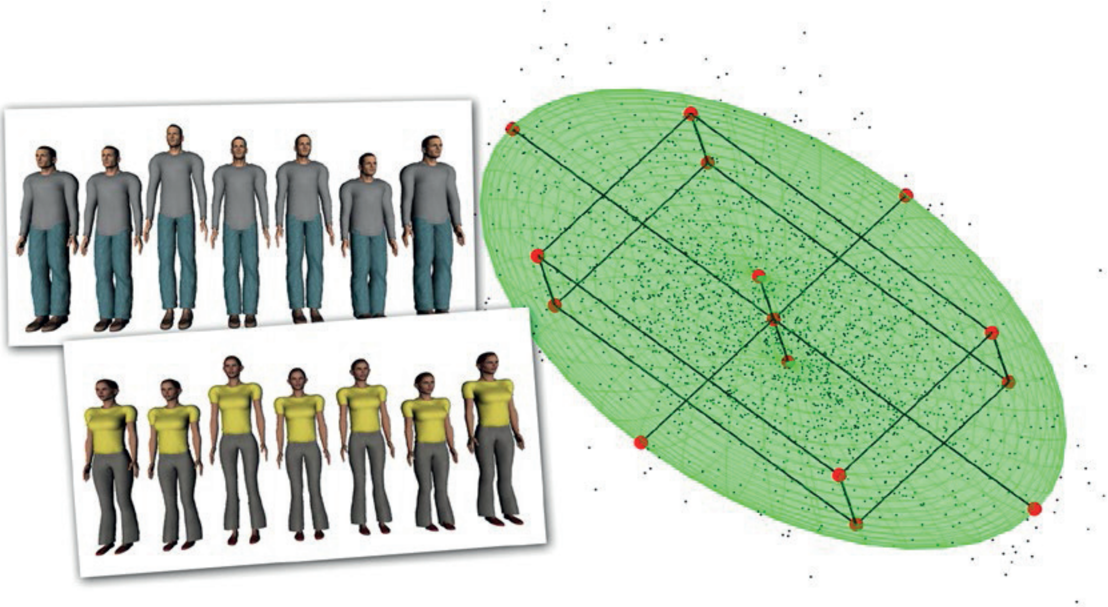

Consideration of anthropometric diversity

– Methods for virtual product and production development

ERIK BROLIN

Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2012

THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

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Cover: A three dimensional confidence ellipsoid as well as a female and male manikin family calculated from a two dimensional confidence ellipse.

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Abstract

Ergonomics and Human Factors address factors important to consider in the product and production development process. This is done through a User Centred Design process where focus is put on human-machine interactions. Digital human modelling (DHM) tools provide and facilitate rapid simulations, visualisations and analyses of the human-machine interactions in a virtual environment. Anthropometry, the study of human measurements, is central in DHM simulations due to the necessity of ensuring intended accommodation levels. Several methods have been described to consider the anthropometric diversity that exists within human populations. Still, many simulations are done with few human models, so called manikins, in industry today due to the time consuming processes when working with many manikins in current DHM tools. Hence, there is a need for better tools and methods. To increase the understanding among DHM users there is also a need to illustrate differences in results when using different approaches, and to evaluate the validity of the assumptions that methods for anthropometric diversity consideration are based upon.

In this thesis current methods for anthropometric diversity considerations have been reviewed and the differences in evaluation results when utilizing different approaches have been analysed. New methods and functionality have been developed and implemented in DHM tools and the possibilities to include more physical characteristics and in turn consider more aspects of human diversity have been explored. Results shows that the proposed methods are advantageous compared to approaches often used in industry today and will, if used, increase the consideration of anthropometric diversity when using DHM tools for the design of products and workplaces.

Keywords: Ergonomics, Human Factors, Anthropometry, Diversity, Digital Human Modelling, Simulation, Visualisation, User Centred Design, Workplace Design, Product Design, Accommodation.

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Erik Brolin
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[1] The IMMA project started in July 2009 and is expected to end in December 2013. It is financially supported by the Swedish Foundation for Strategic Research within the ProViking program under the grant no. PV09.13 and by the participating industrial organisations (AB Volvo, Fraunhofer-Chalmers Centrum (FCC), Innovatum AB, SAAB Automobile, Scania CV AB, Virtual Manufacturing Sweden AB, Volvo Car Corporation).

Appended papers

Paper A

Description of boundary case methodology for anthropometric diversity consideration

Brolin, E., Högberg, D. and Hanson, L. (2012).

Accepted for publication in the *International Journal of Human Factors Modelling and Simulation (IJHFMS)*.

Brolin gathered and analysed the empirical data and wrote the paper with Högberg and Hanson. Brolin was the corresponding author.

Paper B

Creation of the IMMA manikin with consideration of anthropometric diversity

Bertilsson[2], E., Hanson, L., Högberg, D. and Rhén, I.M. (2011).

Proceedings of the 21st International Conference on Production Research (ICPR 21): Innovation in Product and Production, Spath, D., Ilg, R. and Krause, T. (Eds.), Fraunhofer-Verlag, Stuttgart, Germany.

Brolin performed the literature review, gathered the data and coded the anthropometric part in the IMMA software. Brolin wrote the paper with Hanson, Högberg and Rhen.

Paper C

Using experimental design to define boundary manikins

Bertilsson[2], E., Högberg, D. and Hanson, L. (2012).

Published in *Work: A Journal of Prevention, Assessment and Rehabilitation*, Vol. 41, Suppl.1, pp. 4598-4605

Brolin initiated the study, gathered and analysed the empirical data and wrote the paper with Högberg and Hanson. Brolin was the corresponding author.

[2] Erik Brolin altered his last name from Bertilsson to Brolin in 2012.

Additional publications

2012

Högberg, D., Bertilsson, E. and Hanson, L. (2012). A pragmatic approach to define anthropometric boundary manikins for multiple populations. *Proceeding of the 44th Annual International Nordic Ergonomics and Human Factors Society Conference (NES2012)*, Ergonomics for sustainability and growth, Antonsson, A-B. and Hägg, G.M. (Eds.), KTH Royal Institute of Technology, Sweden.

Bertilsson, E., Keyvani, A., Högberg, D. and Hanson, L. (2012). Assessment of manikin motions in IMMA. *Advances in Applied Human Modeling and Simulation*. Duffy, V.G. (Ed.). CRC Press. pp. 235-244.

2011

Bertilsson, E., Högberg, D., Hanson, L. and Wondmagegne Y. (2011). Multidimensional consideration of anthropometric diversity. *Proceedings of the 1st International Symposium on Digital Human Modeling (DHM2011)*, Lyon, France.

Högberg, D, Bertilsson, E. and Hanson, L. (2011). A basic step towards increased accommodation level accuracy when using DHM tools. *Proceedings of the 1st International Symposium on Digital Human Modeling (DHM2011)*, Lyon, France.

Bertilsson, E., Gustafsson, E., Hanson, L. and Högberg, D. (2011). Swedish Engineering Anthropometric Web Resource. *Proceedings of the 43rd Annual Nordic Ergonomics Society Conference (NES2011)*, Wellbeing and Innovations Through Ergonomics, Lindfors, J., Merja Savolainen, M. and Väyrynen, S. (Eds.), Oulu, Finland, pp. 442-446.

2010

Bertilsson, E., Svensson, E., Högberg, D. and Hanson, L. (2010). Use of digital human modelling and consideration of anthropometric diversity in Swedish industry. *Proceedings of the 42nd Annual Nordic Ergonomic Society Conference (NES2010)*, Stavanger, Norway.

Bertilsson, E., Högberg, D. and Hanson, L. (2010). Digital Human Model Module and Work Process for Considering Anthropometric Diversity. *Proceedings of 3rd Applied Human Factors and Ergonomics (AHFE) International Conference 2010*, Karwowski, W. and Salvendy, G. (Eds.), Miami, USA.

Table of contents

1 Introduction

This introductory chapter describes the background and challenges of the targeted research area and states the purpose and aim of the research of the thesis.

1.1 Background

To achieve a successful product development process, i.e. to develop, produce and sell a product with expected profit, one must consider a number of aspects such as product quality, product cost, development time, development cost and development capability (Ulrich and Eppinger, 2012). All these factors will affect the outcome of the development project and need to be considered simultaneously and through collaboration in multidisciplinary teams to decrease development time and achieve high quality products (Andreasen, 2011). In today's complex development processes there is high volume of information that needs to be processed to make better-informed decisions and to support this decision process there exists a number of computational and virtual support tools (Chandrasegaran et al., 2013). Today, product and production development are done with more in mind than just the technical capabilities of the product or production system, such as ease of assembly or good usability (Andreasen, 2011) An important part in the product and production development process is to identify and take into account the customer's needs (Ulrich and Eppinger, 2012). During the development process focus needs to be put on creating value for the customers and users (Ward, 2009). Ergonomics and human factors therefore play an important role by studying how a product, tool, workplace or task[3] will affect a potential user and vice versa, employing a systems view (Bridger, 2009). Using a User Centred Design approach, attention is put on developing a product or workplace that matches the capabilities and diversity of humans.

[3] In a development process the item interacting with the user could be a product, tool, workplace or task even though product or workplace will be the most repeated definitions further in the text.

In order to be able to consider ergonomics and human factors in virtual environments, Digital human modelling (DHM) software is used, which are computer based tools that provide and facilitate rapid simulations, visualisations and analyses of the interaction between the user and the product. This in turn enables a proactive work in the design process when seeking feasible solutions on how the design could meet set ergonomics requirements early in the development process (Chaffin et al., 2001; Duffy, 2009). DHM software includes a digital human model, also called a manikin, i.e. a changeable digital version of a human. DHM tools are used to create, modify, present and analyse human-machine interactions. When using DHM tools it is important to consider the diversity that exists within and between human populations. Anthropometry, the study of human measurements, is therefore central in DHM systems to ensure intended accommodation levels in ergonomics simulations and analyses, eventually to be offered by the final product or workplace. The variation for an anthropometric measurement within a population can most often by approximated with a normal distribution. There is also a variation between measurements, which can be approximated with a correlation coefficient, and needs to be considered through a multidimensional approach (Roebuck et al., 1975; Pheasant and Haslegrave, 2006). Several methods have been developed to facilitate consideration of multidimensional anthropometric diversity in design (Bittner et al., 1987; Meindl et al., 1993; Speyer, 1996; Bittner, 2000; Jolliffe, 2002; Dainoff et al., 2004).

Still, studies throughout the years have reported that industry practice often is based on the basic approach of just including stature in the analysis, also called the univariate approach (Daniels, 1952; Roebuck et al., 1975; Ziolek and Wawrow, 2004; Robinette and Hudson, 2006; Bertilsson et al., 2010b). The design of products and workplaces is often being affected by variation in several body dimensions. Because of the fact that humans vary a lot in sizes and shapes, there is considerable uncertainty whether the expected proportion of the target population is covered by the analyses being performed by the basic approach sometimes used in industry today. The research community and DHM developers are aware of the problems associated with analyses where only one key variable is used (Roebuck et al., 1975; Robinette and Hudson, 2006). Reasons for the rough approach used in industry can be connected to the functionality of current DHM tools where manipulation of manikins most often has to be done manually. This procedure is time consuming and the time needed for each extra virtual test person to be included in the simulations is not considered worth the possible increase in accuracy in assessing and meeting set accommodation levels. In addition, the manual manipulation of manikins is non-robust when comparing simulation results between different users as well as different simulations done by only one user (Lämkull et al., 2008). This adds to the uncertainty of the simulation results. Methods and functionality in DHM tools that supports the multidimensional consideration of anthropometric diversity are sometimes hidden or containing variables that are difficult to specify. Furthermore, the existing methods presented in scientific papers have mathematical procedures often presented in condensed form, making them difficult to follow. Hence, there is a need for better methods and to more clearly present the theory behind the definition of cases, i.e. sets of body dimensions to be accommodated in the design (Dainoff et al., 2004). To increase the understanding among DHM users there is also a need to illustrate differences in results when using different approaches, and to evaluate the validity of the assumptions that methods for anthropometric diversity consideration are based upon.

1.2 Purpose of the research and thesis

The general purposes of the research presented in this Licentiate thesis is to evaluate existing methods for anthropometric diversity consideration and, based on this review of existing methods, develop and implement new and improved methods. The intention is that these methods should be possible to use as a framework when including additional physical characteristics, for example muscle strength, range-of-motion and motion behaviour, when defining test manikins used in DHM simulations.

2 Research questions

This chapter includes the starting point of the research in the form of research questions derived from the introductory chapter and identified research needs.

2.1 Research questions

The purpose for this research is to explore how increased consideration of anthropometric diversity can be achieved in virtual development processes. The research is done in context of DHM tool use and will as a result take its point of origin from the needs of DHM users identified in the introductory chapter. The research should benefit designers, ergonomists, engineers and product and production developers who need to include physical characteristics in their development processes. By taking these aspects into consideration the following research questions have been formulated:

Research question 1 *How can anthropometric diversity be taken into consideration in virtual product and production development processes?*

Research question 2 *How is it possible to increase the accommodation accuracy for a design and a defined target group?*

Consequently, objectives of the research in this thesis are to:

- review current methods for anthropometric diversity considerations and analyse the differences in evaluation results when utilising different approaches,
- develop and implement new methods and functionality in DHM tools,
- determine aspects that needs to be considered to be certain that a high accommodation level accuracy is achieved, and
- explore the possibilities to include more physical characteristics and in turn consider more aspects of human diversity.

2.2 Delimitations

Although a number of different physical characteristics are of interest to measure and include in simulations and analyses, the remainder of this thesis will focus on fundamental anthropometric data such as length, depth, width, circumference and weight measurements. This delimitation is defined in order to narrow the field during the research process even though the research will be done with expectations of generalizability.

3 Frame of reference

This chapter provides concepts of theory that are important to understand: Ergonomics and User Centred Design, Anthropometry and sources of anthropometric data and Virtual Product and Production Development.

3.1 Ergonomics

As a research field, ergonomics emerged from the problems and needs of efficiently interacting with the ever more advanced and demanding technology and industry in the mid-20th century (Pheasant and Haslegrave, 2006). Focus of ergonomics is the optimisation of the interaction between human and machines, employing a systems view. Machines in this case should not solely be seen as industrial machines but also workplaces, tools, products and public spaces. An interaction depends on factors connected to the human, machine or environment and can have different directions. The aim is to consider the factors that affect the interaction and to improve the performance of human-machine systems (Bridger, 2009). The interaction is improved by changing the interface by which the user interact and gets feedback through, as well as by considering the environmental factors that affect the interaction, Figure 1 (Chapanis, 1996).

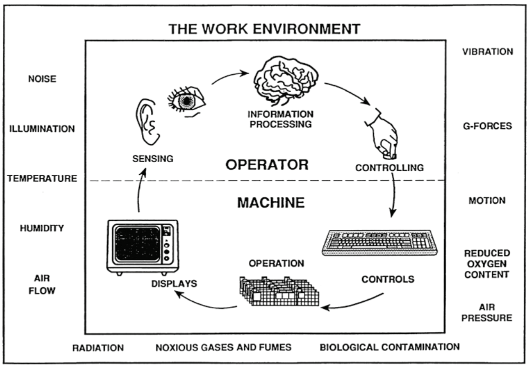

Figure 1 A model of the interaction between man and machine surrounded by the environment with the interface as the dashed line (Chapanis, 1996)

The research field has through time evolved and widened its already big scope. Today it is possible to identify three fields or domains of specialisation within ergonomics (IEA, 2000):

- *Physical Ergonomics* concerned with human anatomical, anthropometric, physiological and biomechanical characteristics.
- *Cognitive Ergonomics* concerned with mental processes, such as perception, memory, reasoning and motor response.
- *Organisational Ergonomics* concerned with the optimisation of sociotechnical systems, including their organisational structures, policies and processes.

Both physical and cognitive ergonomics focus on the users' closest surrounding and these two fields are also called *Micro-Ergonomics*. They stand in contrast to organisational ergonomics or *Macro-Ergonomics,* which have a wider context and emerged more recently during the 1980s. These three fields can also be seen in the definition of ergonomics presented by IEA (2000).

> *Ergonomics (or human factors) is the scientific discipline concerned with the understanding of the interactions among humans and other elements of a system, and the profession that applies theoretical principles, data and methods to design in order to optimise human well-being and overall system performance.*
>
> *(IEA, 2000)*

3.1.1 User Centred Design

In a design process it is of great importance to consider the capabilities of the intended users. Good ergonomics is achieved when the capabilities of human match the demands given by the machine or task, and this is achieved through a user centred design process. There exist a number of theories and methods for identifying users and their needs. A common method found in the literature is to create a number of user characters (a.k.a. *personas*) to visualise and communicate different users and their needs (Buur and Nielsen, 1995). These user characters are to be defined based on knowledge about real users and in a way with information that makes the character 'alive' (name, family situation, hobbies, age etc.). The use of personas is common in the design approach Inclusive design, also called Universal design or Design for all (EIDD, 2004). Inclusive design has its aim on creating design for human diversity, social inclusion and equality and to enable all people to have equal opportunities to participate in every aspect of society. This can be done by focusing on so called extreme users who use the product in unusual ways or who have special needs, e.g.

disabled persons or persons with impaired strength and movement. User capabilities can be categorised into seven capability categories: Vision, Hearing, Thinking, Communication, Locomotion, Reach & stretch and Dexterity. The capability levels are assessed for each category to identify mismatches between user and product, Figure 2 (University of Cambridge, 2011).

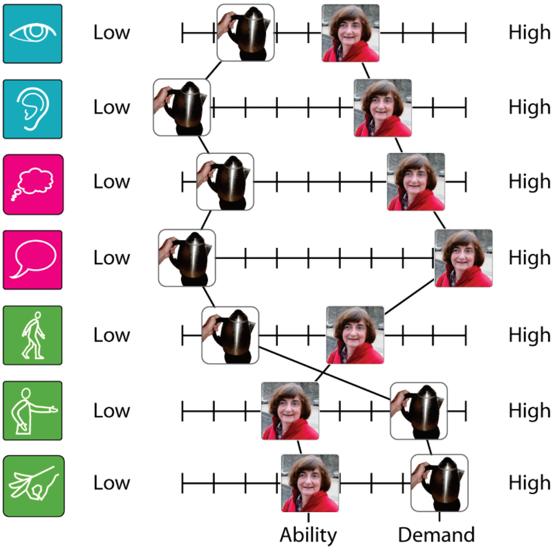

Figure 2 Seven capability categories used to measure a person's capability and assess the ability level that the product demands in order to use it, courtesy of University of Cambridge (2011)

Another approach to find user needs is the lead user approach introduced by Von Hippel (1986). Lead users are users that experience needs months or years before the majority of the user population, e.g. professional craftsmen or athletes. These lead users have great knowledge of the product and its use and can explain problems with existing products but also provide input in form of new ideas and product concepts. Using the approach of lead user or extreme users both has the same goal; to find user needs that, when fulfilled, will fulfil the needs of less extreme users. In this way lead users can also be seen as extreme users but being very able to use the product, hence they may find problems when pushing the product to its limits. Less able users instead typically find problems when trying to use the product as intended but being unable to do so. A notion is that a user can still have special needs while being an extreme user, e.g. a professional craftsman with a shoulder injury. What these methods and especially the Inclusive design approach try to do is to consider the great diversity that exists within a human population. Another conclusion is that user needs depends on capabilities of the user. This is especially evident when studying extreme users who have disabilities. Many of these needs can be connected to physical capabilities such as vision, hearing, strength, range-of-motion and body size. Needs and requirements can also be connected to cognitive capabilities such as experience, attention and perception. Cognitive capabilities can be difficult to measure but most physical capabilities can be measured and quantified in some way. This gives the possibility to statistically analyse the physical diversity that exist within a population, e.g. related to variation in anthropometry.

3.1.2 Anthropometry

Anthropometry is a research area within physical ergonomics that is concerned with body measurements such as body size, shape, strength, mobility, flexibility and work capacity (Pheasant and Haslegrave, 2006). Utilising anthropometric data is often a fundamental part of the process to achieve good fit between capabilities of humans and design of products or workplaces. Anthropometric data can usually be divided into either functional (dynamic) dimensions or structural (static) dimensions. Functional dimensions are for example measurements of an operating room and range during activity, Figure 3. These measurements are generally for special situations and can be difficult to measure but are often valuable in the design of products and workplaces.

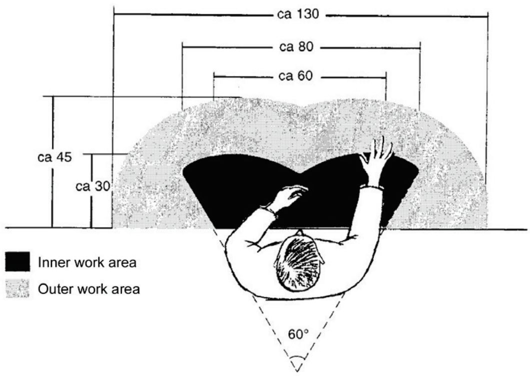

Figure 3 Functional dimensions of horizontal arc of grasp and normal working area, measurements in centimetres (Swedish Work Environment Authority, 1998)

Structural dimensions are measurements between anatomical landmarks defined for standardised postures at rest, Figure 4. These measurements are relatively easy to measure, but may have limited value in a design context since they can be too artificial to use as input in the design process (Pheasant and Haslegrave, 2006).

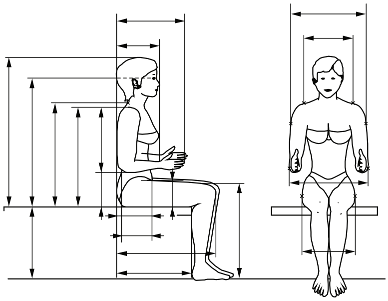

Figure 4 Structural dimensions in predefined static postures (University of Skövde, 2011)

Collecting anthropometric data has traditionally been done by manually measuring people with big callipers and tape measures. In order to get faster measuring processes, more data and data that can be reused for subsequent analyses, an increasing number of measuring studies are done using digital laser scanning techniques, Figure 5 (Hanson et al., 2009; Godil and Ressler, 2009).

Figure 5 Results of body scanning in four different body postures (Hanson et al., 2009)

Existing anthropometric data can be acquired from a number of sources such as books, articles, software and web sources, most often given as mean and standard deviation value for each measurement (Pheasant and Haslegrave, 2006; Hanson et al., 2009; PeopleSize, 2008; Delft University of Technology, 2012). It is desirable to perform statistical analysis of anthropometric data on so called raw data with values for each measurement given on an individual level. Such data exists but may be outdated or only be available for specific populations that differs significantly in body size and demography from the target population of a product or workplace, e.g. the ANSUR data that was measured 1988 and on U.S. military personnel (Gordon et al., 1989). Something that problematizes the use of older anthropometric data is the so-called secular trend which means that it has been an increase in, among other things, adult stature during the last century, Figure 6 (Chapanis, 1996; Pheasant and Haslegrave, 2006). However, data that is more up to date and for civilian populations is often not free of charge. An example of an extensive and recent study is the Civilian American and European Surface Anthropometry Resource (CAESAR) (Robinette et al., 2002).

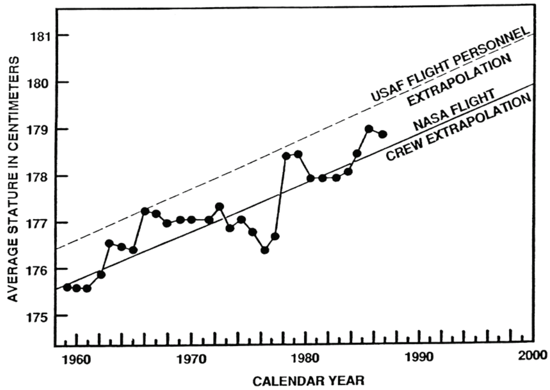

Figure 6 The secular trend here illustrated with increase in average stature for USAF flying personnel and NASA flight crews over a number of years (Chapanis, 1996)

In large ethnic, age and gender separated populations most body measurements can be considered normally distributed, Figure 7. However, weight and muscular strength often show a positively skewed distribution curve, Figure 7 (Pheasant and Haslegrave, 2006).

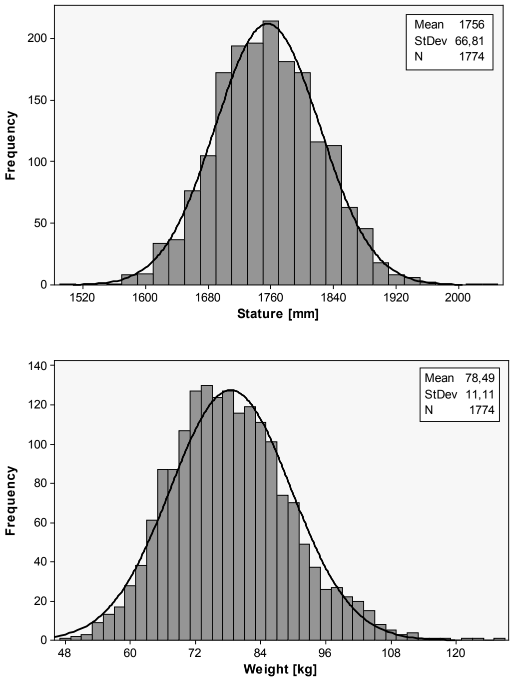

Figure 7 Histogram of stature and body weight for men, data from ANSUR (Gordon et al., 1989)

An additional fact is that the proportions of the human body vary from person to person, e.g. people of average stature do not necessarily have an average value for all body measurements (Roebuck et al., 1975; Pheasant and Haslegrave, 2006). The correlation coefficient between different anthropometric measurements can be analysed to see how strongly they are connected, Figure 8.

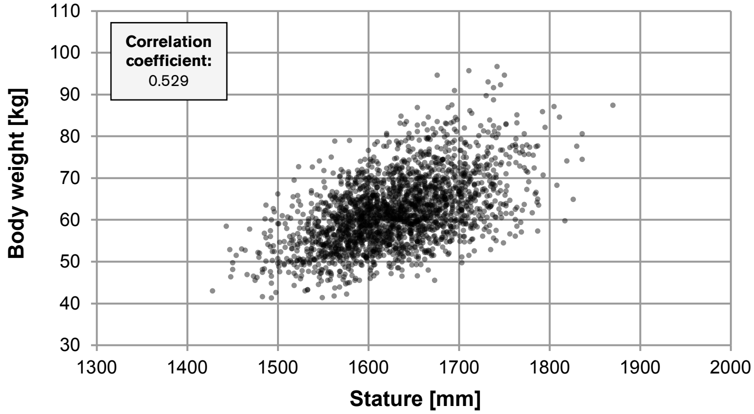

Figure 8 Scatterplot for stature and bodyweight for women, data from ANSUR (Gordon et al., 1989)

Table 1 Correlation matrix for length and width measurements for women, data from ANSUR (Gordon et al., 1989) which shows a high inter correlation within the length and width groups but low correlation between these groups

	Stature	**Trochanterion height**	**Shoulder elbow length**	**Forearm hand length**	**Body weight**	**Waist circumference**	**Thigh circumference**	**Chest depth**
Stature	1	0.85	0.80	0.71	0.53	0.19	0.26	0.16
Trochanterion height	0.85	1	0.83	0.83	0.46	0.19	0.25	0.16
Shoulder elbow length	0.80	0.83	1	0.78	0.44	0.19	0.22	0.16
Forearm hand length	0.71	0.83	0.78	1	0.43	0.17	0.23	0.15
Body weight	0.53	0.46	0.44	0.42	1	0.82	0.88	0.76
Waist circumference	0.19	0.19	0.19	0.17	0.82	1	0.71	0.80
Thigh circumference	0.26	0.25	0.22	0.23	0.88	0.71	1	0.66
Chest depth	0.16	0.16	0.16	0.15	0.76	0.80	0.66	1

Length measurements usually have high mutual correlation and the same can be seen when analysing depth and width measurements, Table 1. However, in total, body measurements have low correlation dependencies (McConville and Churchill, 1976; Greil and Jürgens, 2000). This fact leads to a reduction in accommodation when multiple measurements are affecting the design and only a few are incorporated in the simulation and analysis, Figure 9 (Moroney and Smith, 1972; Roebuck et al., 1975).

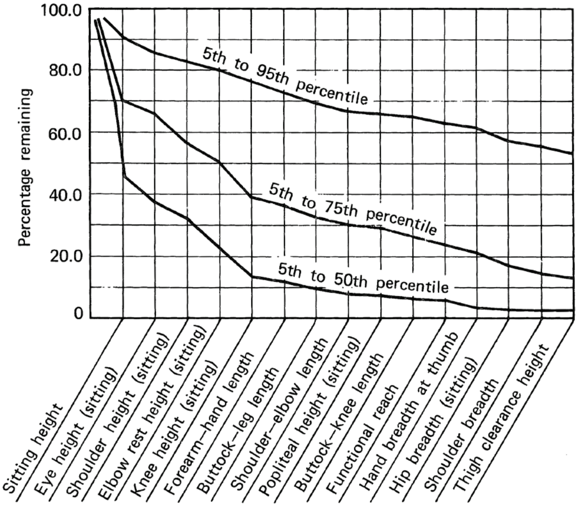

Figure 9 Illustration of decline in accommodation when a serial univariate approach is used in multidimensional design case (Roebuck et al., 1975)

Several methods have been developed to facilitate multidimensional consideration of anthropometric diversity in a design process. Most of these methods are based on one or both of the fundamental methods: *boundary case* and *distributed case* method (Dainoff et al., 2004). These two methods are in many ways similar, which makes it possible to use them simultaneously. The concept is that a confidence interval is defined where boundary cases are points located towards the edges of the interval, and distributed cases are spread throughout the interval randomly or by some systematic approach. This confidence interval is based on the accommodation level, i.e. the proportion of the population that the evaluation aims to include. The aim is to include as many users as possible and thus choosing a big value for the accommodation level. However, the cost of including the whole population is often considered to be too high and an accommodation level of 90% is therefore often considered to be an appropriate compromise. Beyond cost demands there may be other product design characteristics that force a reduction of desired accommodation level. Such an approach means that the discarded 10% of users in the targeted population are considered to be too extreme. Instead, custom-build solutions are sometimes required to accommodate these users. Such an approach would not be according to the Inclusive design philosophy, especially when aspired accommodation levels are set at such low levels. The use of boundary cases are based on the same principle as the identification of extreme users in the approach of Inclusive design, i.e. that simulations and evaluations of boundary cases will be sufficient to meet the demands of the whole population. However, this assumption might be wrong in some cases and distributed cases can therefore be used to decrease the risk of missing key areas when using boundary cases. Also, the distributed cases approach is more relevant to apply for certain design tasks, e.g. design of clothes and similar (Dainoff et al., 2004).

The confidence intervals are mathematically defined based on the mean and standard deviation value of, as well as the correlation coefficients between, the anthropometric key measurements that are considered to affect the design. When two key anthropometric measurements are considered their combined distribution forms a two dimensional density function, Figure 10. Any plane parallel to the X-Y plane intersects the density function in an ellipse. Such a confidence ellipse is drawn from the centre point defined by the mean values for each measurement. The size, shape and orientation of the confidence ellipse are determined by the correlation value and the accommodation level. These confidence ellipses can also be seen in the contours of the density function, seen from above, Figure 11.

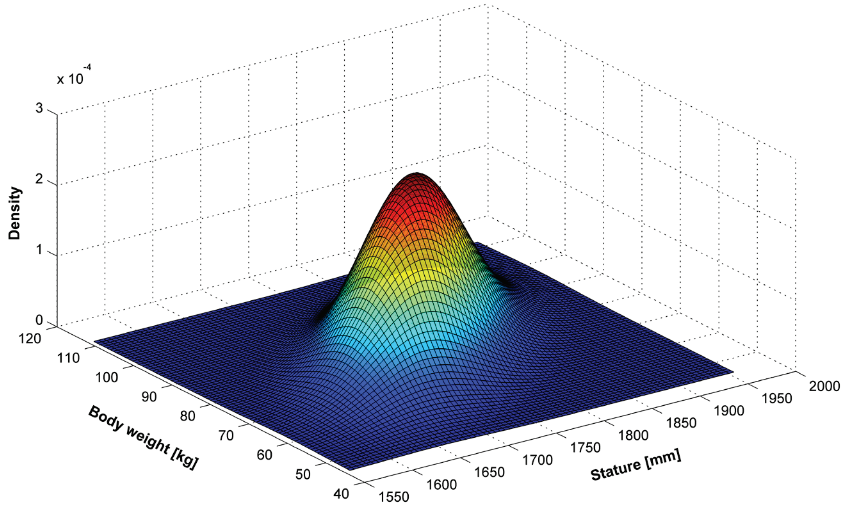

Figure 10 Two dimensional normal distribution for stature and bodyweight for men, data from ANSUR (Gordon et al., 1989)

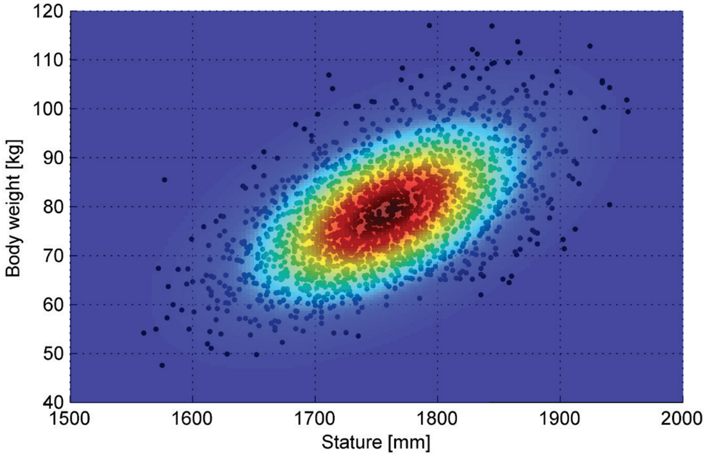

Figure 11 Two dimensional normal distribution for stature and bodyweight for men seen from above, data from ANSUR (Gordon et al., 1989)

When three dimensions are considered the confidence region forms the shape of an ellipsoid and if more dimensions are added the confidence region forms a so called multidimensional hyper ellipsoid. The mathematical calculations become more complex and the number of test cases necessary to cover the confidence region becomes overwhelming when many measurements are assumed to affect the design (Dainoff et al., 2004). Methods described in literature for creating confidence intervals often use Principal Component Analysis (PCA), which makes it possible to reduce the dimensionality of the problem without much loss of the variance of the analysed data (Johnson and Wichern, 1992; Meindl et al., 1993; Jolliffe, 2002). Speyer (1996) describes a method that is based on the finding that stature, ratio of sitting height over body height and waist circumference (as an indicator of weight) of an individual in many cases is an adequate method to predict other body dimensions for this person (Greil and Jürgens, 2000; Bubb et al., 2006). This method uses both boundary and distributed cases and is implemented in the DHM tool RAMSIS (Human Solutions, 2010). Another example is the development of A-CADRE (Bittner et al., 1987; Bittner, 2000), a collection of 17 manikins that all have different values for 19 body measurements, established with the objective of representing the boundary of the prevalent bodily variety of workstation users.

3.2 Digital human modelling and its application

Digital human modelling (DHM) tools are used in order to reduce the need for physical tests and to facilitate proactive consideration of ergonomics in virtual product and production development processes. DHM tools provide and facilitate rapid simulations, visualisations and analyses in the design process when seeking feasible solutions on how the design can meet set ergonomics requirements (Chaffin et al., 2001; Duffy, 2009). DHM tools are used to create, modify, present and analyse physical ergonomics and human-machine interactions. The development of DHM software started in the late 1960s and has continually increased since then. Several of the software that was initiated during the 1980s are still in use and commercially available such as JACK, DELMIA, RAMSIS and SAMMIE. More recent DHM software are ANYBODY and SANTOS, which has been developed during the last decade (Bubb and Fritzsche, 2009). In 2010 the DHM tool IMMA (Intelligently Moving Manikins) was introduced as a DHM tool that uses advanced path planning techniques to generate collision free and biomechanically acceptable motions for digital human models (as well as parts) in complex assembly situations. The aim of the IMMA project is to develop a non-expert tool with high usability, where the tool supports the tool user to consider human diversity, to easily instruct the manikin to perform tasks and functionality to perform time-dependent ergonomics evaluations to control and assess complete motions (Hanson et al., 2012).

DHM software consists of a virtual environment, CAD geometry of machines, tools and products and a digital human model to facilitate simulation of the interaction between the human, the machine and the environment as presented in Figure 1. These digital human models, also called manikins, are changeable and controllable virtual version of humans, Figure 12. The human models in the DHM tools consist of an interior model and an exterior model. The interior model represents the skeleton and is built up with rigid links connected by joints. The exterior model represents the skin and is built up by a mesh based on specific skin points. Both the number of joints and the resolution of mesh points, and thus the degrees of freedom of the human model, have increased in recent years in parallel with increased computing capacity. This has led to an increased resolution of digital human models and thus an increased coherence between these models and real humans. In addition to rigid links some human models have muscles that are included in the simulations and analyses (Bubb and Fritzsche, 2009). Still, currently only four of the seven capabilities presented in Figure 2 can be evaluated through DHM simulations. Capabilities related to cognitive ergonomics such as hearing, thinking and communication are hard to assess using DHM tools (Thorvald et al., 2012).

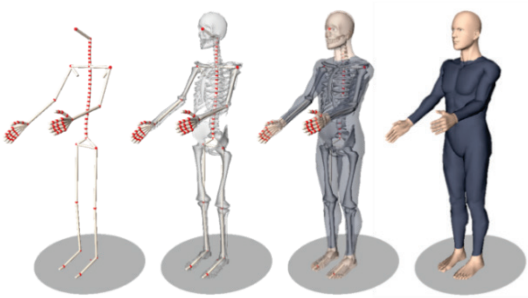

Figure 12 The human model in IMMA consists of an interior and an exterior model

An important part in DHM tools is the modelling of human movements where the simulations need to represent human characteristics and behaviour. The most common methods for manipulating manikin in DHM tools is by adjusting each joint or adjusting target points to move a part of the body, i.e. the arm or upper body, through inverse kinematics (IK) (Monnier et al., 2009). However these methods are time consuming and subjective and simulates only postures and not motions which are necessary to consider time aspects (Abdel-Malek and Arora, 2009). Methods for how to predict motions in DHM software can be classified into two groups (Pasciuto et al., 2011). The first group is *data-based methods* which base motion simulations on a database of captured motions and by doing so achieves motions of high credibility for specific tasks (Park, 2009). The other group, *physics-based methods*, bases their motions prediction on kinematic models of human body. These methods employ several inverse kinematic techniques while considering joint constraints such as range-of-motion (ROM), joint velocity and strength to solve and predict a motion. Using these methods makes it possible to predict motions for any given task (Abdel-Malek and Arora, 2009). Additional hybrid methods do also exist using both data of captured motions and data on joint constraints to predict motions. Anthropometry is central in DHM systems due to the necessity of ensuring intended accommodation levels in ergonomics simulations and analyses, eventually being offered by the final product or workplace. In DHM tools, human models can typically be created by quickly defining just stature and weight of a certain gender, age group and nationality, or by defining a more complete compilation of a specific manikin's measurements. In addition, some DHM tools, such as RAMSIS, have functionality to facilitate multidimensional consideration of anthropometric diversity when performing simulations and evaluations (Bubb et al., 2006).

Studies throughout the years have reported that industry practice often is based on the utilisation of rough approaches when considering anthropometric diversity (Daniels, 1952; Roebuck et al., 1975; Ziolek and Wawrow, 2004; Robinette and Hudson, 2006; Bertilsson et al., 2010b). As an example, Swedish vehicle manufacturing companies commonly only use a few human models as virtual test persons when designing workstations or evaluating manual work (Bertilsson et al., 2010b). Typically a small female and a large male, according to stature, are considered as sufficient when performing ergonomics evaluations using DHM tools. This approach means that one key measurement is used (stature) and that two cases, i.e. two boundary manikins are used (one small female and one large male). The study by Bertilsson et al. (2010b) gave that a common argument for this rough approach was the time needed for each extra virtual test person to be included in the simulations, and that this extra time was not considered worth the possible increase in accuracy in assessing and meeting set accommodation levels. Also, the study gave that the comprehension of the complexity of anthropometric diversity in design, and ways to deal with it, was rather scarce, which may also be a reason for the rough approach used. The design of products and workplaces is often being affected by variation in several body dimensions. Because of the fact that humans vary a lot in sizes and shapes, there is considerable uncertainty whether the expected proportion of the target population is covered by the analyses being performed by the basic approach sometimes used in industry today.

Efforts have been made to close the gap between methods described in literature and industrial practice, e.g. Hanson et al. (2006) suggest a digital guide and documentation system to support digital human modelling applications, and Högberg (2009) discusses the potentials of using DHM for user centred design and anthropometric analysis purposes. Which method and approach that is best suited to use for the consideration of anthropometric diversity depends on the design problem at hand and a flowchart can be used to support this decision process, Figure 14 (Dainoff et al., 2004; Hanson and Högberg, 2012). Other work have been focused on implementing specific design approaches, e.g. Inclusive design which has been applied in virtual development through the HADRIAN tool (Human Anthropometric Data Requirements Investigation and ANalysis) (Marshall et al., 2010). The HADRIAN project focuses on providing the user with data that is accessible, valid and applicable, but also means of utilising the data to assess the accessibility of design solutions. The method and data is implemented in the DHM tool SAMMIE and have for example been used for the evaluation of vehicle ingress/egress and utilisation of an automated teller machine (ATM), Figure 13. Hanson and Högberg (2012) have a similar aim when they evaluate a new bathtub footrest optimised for elderly home residents and caregivers using the method user characters to create manikins. To more accurately simulate elderly people the joint flexibility of the manikins are adjusted based on range-of-motion data.

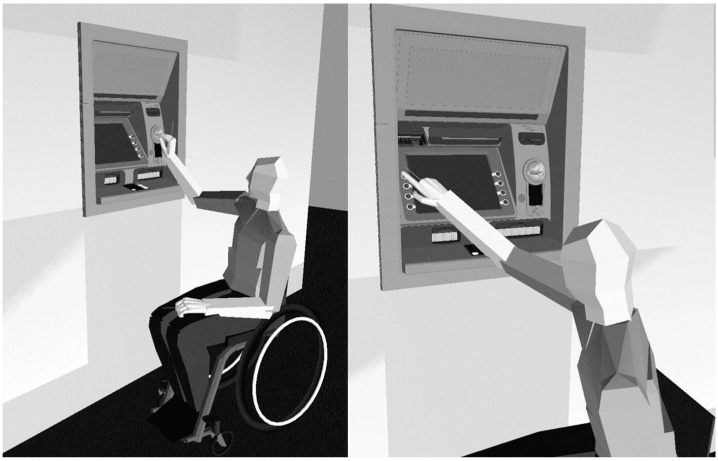

Figure 13 Validation of an ATM being performed in the SAMMIE system in HADRIAN (Marshall et al., 2010)

There are also other areas within the field of DHM development that needs further improvement to be able to produce simulations that correctly predict an evaluated task. These areas are connected to hand access, forces needed to push and pull objects but also leaning and balance behaviour and field of vision (Lämkull et al., 2009). Further development of DHM tools should also focus on functionality for collision detection and avoidance and calculation of static balance conditions as well as end point motion generation with consideration of human kinematics and dynamics (Zülch, 2012).

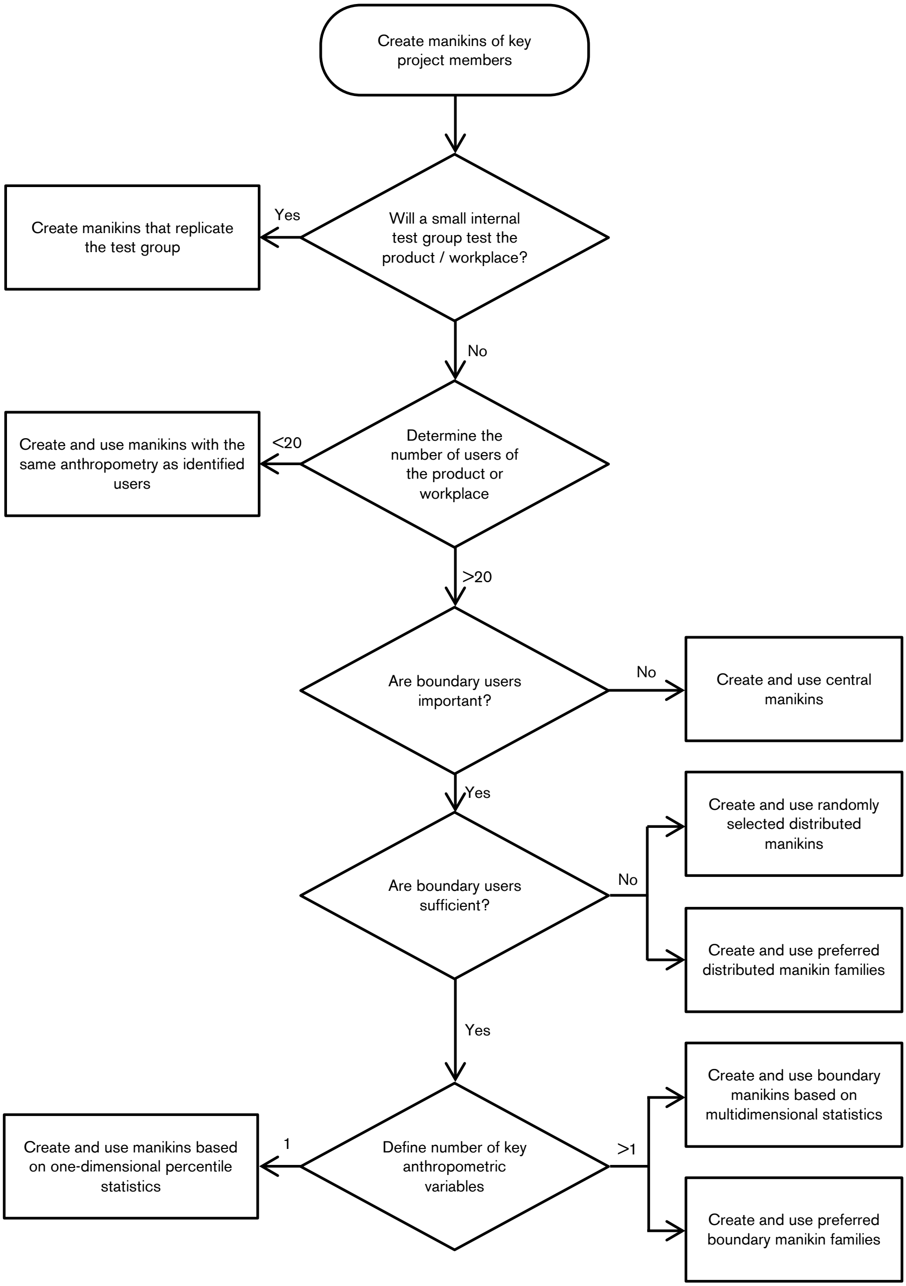

Figure 14 Flowchart as a guide to select user representation method: replicas of identified users, central, distributed or boundary manikins. The different methods are preferably combined. (Hanson and Högberg, 2012; modified from Dainoff et al., 2004)

4 Research methods and procedure

This chapter presents the general research approach and the specific methods used in the appended papers.

4.1 General research approach

The research has taken its point of departure in the state of current methods and DHM tools and the use and needs of DHM users, and has been based on findings acquired during an introductory study. This introductory study included a literature study on current theory and methods as well as an interview study on the use of DHM tools in Swedish automotive industry and studies of existing DHM tools (Bertilsson et al., 2010a; Bertilsson et al., 2010b). Results from these studies have been partially presented as a part of the introductory chapter and theoretical frame of reference.

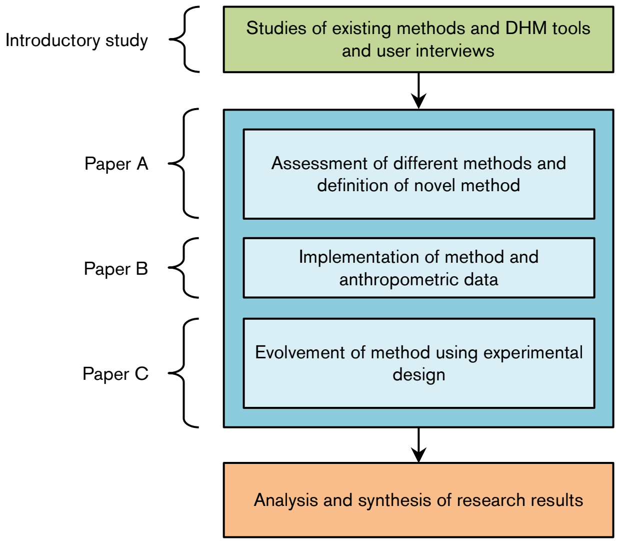

Figure 15 The research process and appended papers together with the exploratory design in mixed methods research adapted from Creswell and Clark (2007)

From the initial state where mostly a qualitative research approach was used the research became more quantitative involving calculations, simulations and statistical analysis in Paper A, Paper B and Paper C. This process follows the exploratory design in mixed methods research which starts with qualitative data and then builds to a second, quantitative phase (Creswell and Clark, 2007). The results from the qualitative methods in the introductory study are in this research process used as input to the quantitative methods used in Paper A, Paper B and Paper C, Figure 15. Results from both approaches are eventually used to assess the problem and the identified solutions.

In the three appended papers a number of different methods have been used and variety of design approaches have been assessed, Table 2. Paper A includes an additional literature review where the mathematical process of creating confidence regions is identified and simulation results when utilising the different approaches are evaluated. Paper B focuses on the implementation of the methodology derived from the results in paper A and the process of how digital human models are created within the IMMA software. This study is based on a literature review of how regression methods can be used to define complete set of measurements and how location of joint centres can be derived from anthropometric measurements from outer anatomical landmarks. In Paper C, methods and procedures from the area of Experimental Design and Response Surface Methodology are evaluated and used to choose and analyse boundary manikins.

Table 2 Different methods used and design approaches assessed in the appended papers

Content	Paper A	Paper B	Paper C
Literature review	Yes	Yes	Yes
Method description	Yes	Yes	Yes
Method implementation	No	Yes	No
DHM simulations	Yes	No	Yes
Percentile manikin approach	Yes	Yes	Yes
Boundary manikin approach	Yes	Yes	Yes
Use of Principal Component analysis	Yes	No	No
Use of Experimental design	No	No	Yes
Number of dimensions	2D & 3D	Any dimension	2D
Total number of manikins tested	18	N/A	11
DHM software used	Jack 7.1	IMMA	Jack 7.1

4.1.1 Paper A: Description of boundary case methodology for anthropometric diversity consideration

This paper describes and evaluates boundary case methodology for the simultaneous consideration of variance for a number of selected anthropometric variables. Current methods for considering anthropometric diversity were evaluated in terms of functionality and resulting definition of anthropometric measurements. The method for calculating confidence regions was adopted from the literature regarding linear algebra (Lay, 2006) and multivariate statistical analysis (Johnson and Wichern, 1992; Sokal and Rohlf, 1995; Brandt, 1999). The analysis was done based on the assumption that anthropometric data can be approximated with a normal distribution, which is appropriate in most cases (Pheasant and Haslegrave, 2006). Different manikin test groups were defined based on four different approaches that were of interest to evaluate. In the first two approaches two key measurements were chosen and the approach, here named percentile approach, where both key dimensions are set to a specific percentile value, was compared to the confidence ellipse approach in two dimensions. In the third and fourth approach a third key measurement was added to achieve a better description of the anthropometric diversity. The confidence ellipsoid approach in three dimensions was compared with using Principal Component Analysis (PCA) to reduce the number of dimensions (from three to two in this case). All test groups were intended to represent and accommodate 90% of the female population in the used ANSUR data set (Gordon et al., 1989). The study was limited to using female data to simplify the problem. In a real design situation data of both genders typically needs to be included in the analysis to get adequate results. The use of DHM was applied to a task of extracting important dimensions for the design of an office workplace through simulations in the DHM tool Jack 7.1 (Siemens, 2011), Figure 16.

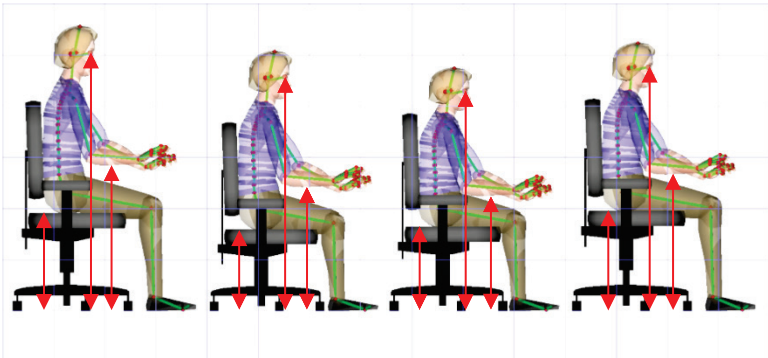

Figure 16 Manikins in seated posture with distances measured for each design dimension, seat height, table height and eye height

Each manikin was positioned in the predetermined “seated typing” posture and three dimensions important to the design, *seat height*, *table top height* and *eye height*, were measured the same way for each positioned manikin. Each group of manikins was analysed and maximum and minimum values for each design dimensions were recorded to determine an appropriate adjustment range.

4.1.2 Paper B: Creation of the IMMA manikin with consideration of anthropometric diversity

In this paper a module is described which facilitates a supportive way of working with anthropometric diversity in DHM systems, Figure 17. This anthropometric module is intended to be combined with a work process inspired by Hanson et al. (2006) and Hanson and Högberg (2012). Paper B describes the process of how this anthropometric module is created and implemented into the IMMA software.

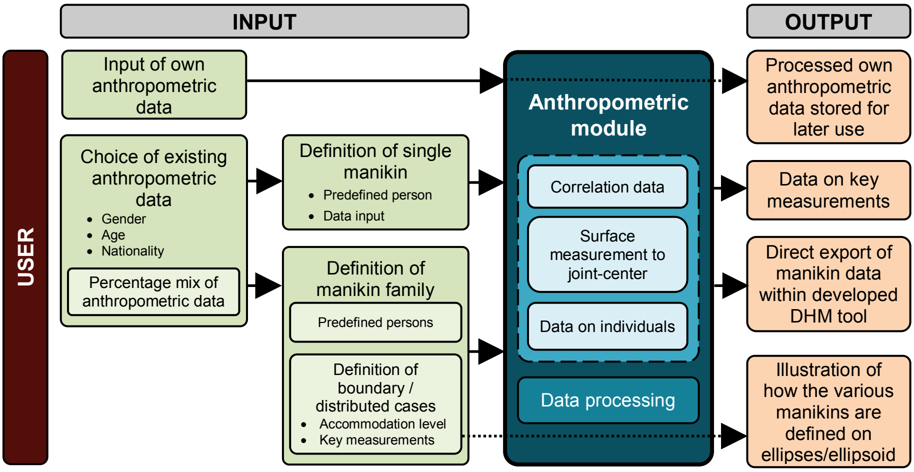

Figure 17 Flowchart depicting the anthropometric module and work process

The implementation of the anthropometric module is divided into three parts to facilitate all necessary functionality in the IMMA software and Figure 18 shows how these parts are connected and implemented in the manikin creation process within the anthropometric module.

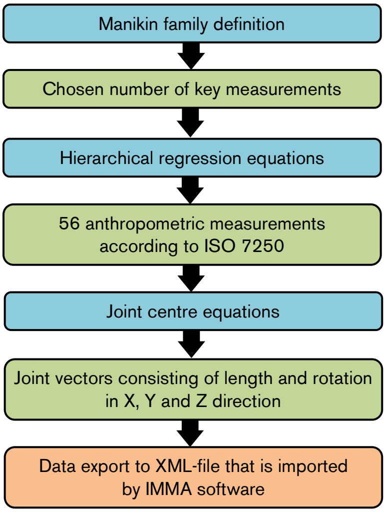

Figure 18 Flowchart depicting the manikin creation process within the anthropometric module

Manikin family method: The boundary case method for defining group of manikins described in Paper A is implemented in the IMMA software in the so-called manikin family method. Based on a confidence level and a number of variables of interest (i.e. key measurements) a confidence region is calculated. Boundary cases are chosen at the ends of the axes of the enclosing confidence region, and one manikin of mean values is also chosen.

Regression analysis: In this part regression equations are defined that calculates omitted anthropometric variables needed to define a complete manikin. These equations are based on the hierarchical estimation method for anthropometric variables described by You and Ryu (2005). This method is adapted to Swedish anthropometric data (Hanson et al., 2009) using statistical linear regression analysis. Because of certain body characteristics, different equations are defined for each gender separately. For 17 measurements the ANSUR data set (Gordon et al., 1989) or German data (PeopleSize, 2008) is used to be able to define values defined in ISO 7250 (ISO, 2008).

Joint-centre analysis: The third part defines the interior model of the IMMA manikin. Different sources were combined to define the positions of joint centres in relation with the position of the anthropometric measurements defined in the regression equations. Definitions for the foot (Witana et al., 2006), legs and arms (de Leva, 1996a; de Leva, 1996b), hip (Leardini et al., 1999; Henry Dreyfuss Associates, 2001) and spine (Keller et al., 2005) were found in literature. Positions of the joint centres in the shoulders and hands were estimated by using literature (Cacha, 1999) combined with measurements from an anatomical skeleton.

4.1.3 Paper C: Using experimental design to define boundary manikins

This paper examines the possibilities to adopt the methodology used in experimental design to define a group of manikins and apply analytical methods to evaluate the results from the ergonomic simulations done in a DHM tool. Using boundary cases only at the ends of each axis might not adequately describe the complete ellipse, ellipsoid or hyper-ellipsoid. Therefore boundary cases in-between the ends of the axes are determined to give a more appropriate representation of the analysed problem. When studying this matter, correspondence can be seen when comparing a three dimensional confidence region with a three factor Central Composite Design (CCD) defined with Response Surface methodology (Myers et al., 2009). Hence, different experimental designs, in which relationships between affecting factors of a process is studied by a systematic approach (Myers et al., 2009), were adopted to be used together with a confidence region and its axes. The lengths of the axes were chosen as a starting point when the high and low value in the different experimental designs were determined using the endpoints of the axes as the axial points in an inscribed central composite design. The ratio between an axial point and a factorial point along an axis is determined by the variable α in this study calculated to be 1.41 for two dimensions. Using α the cube points, which make up the factorial part of the design, could be found and used together with the axial points and a central point to determine values for the test cases in the standardised Z-score space. Anthropometric measurements were then calculated based on the values in the standardised Z-score space.

The method of using experimental design was tested using the same simulation procedure as described in Paper A where simulations in the DHM tool Jack 7.1 were used to extract important dimensions for the design of an office workplace, Figure 16. Two anthropometric measurements, stature and sitting height, were used as key variables for the design. The test groups were, as in Paper A, intended to represent and accommodate 90% of the female population in the ANSUR data set (Gordon et al., 1989). Each manikin was, as in Paper A, positioned in the predetermined "seated typing" posture and the three dimensions important to the design, *seat height*, *table top height* and *eye height*, were measured. Each group of manikins was analysed and maximum and minimum values for each design dimensions were recorded to determine the appropriate adjustment range. Additional analyses were done in this study using methods common in experimental design. Main effect analysis was done on the factorial design and a response surface analysis was done on the central composite design.

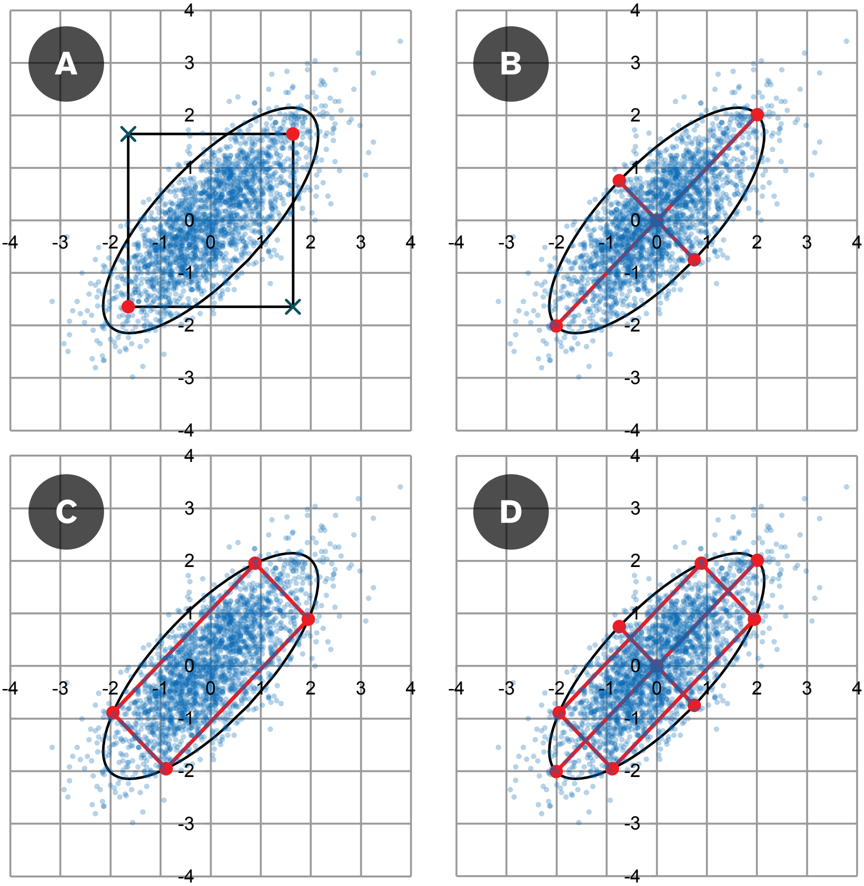

Figure 19 The four different approaches to choose test manikins in a two dimensional confidence region (Scales in z-score, X-axis: Stature, Y-axis: Sitting height), A: Percentile case, B: Axial cases with one centre case, C: Test cases based on a factorial design, D: Test cases based on the Central Composite Design

Four different manikin test groups were defined based on four different approaches where the first approach was identical with the percentile approach describe in Paper

A and used as a benchmark, graph A in Figure 19. In the second approach the axes and axial end points are used which give four boundary manikins. An additional manikin with mean values for both stature and sitting height is added, graph B in Figure 19. To define additional boundary manikins a factorial design was used in the third approach which gave four cube points but no manikins at the axial end points, graph C in Figure 19. In the fourth and final approach the second and third test approach was combined which formed an inscribed central composite design, graph D in Figure 19. This design gave eight boundary manikins on the border of the ellipse and one additional mean value manikin.

5 Results

This chapter provides a summary of the main results and conclusions of the research in the appended papers.

5.1 Paper A: Description of boundary case methodology for anthropometric diversity consideration

The aim of the paper was to clearly and completely describe the theory and mathematical procedure of creating boundary manikins for the consideration of anthropometric diversity in ergonomic analyses in DHM tools. The paper also presents how PCA can be used to reduce the number of dimensions when several key anthropometric measurements are defined. Furthermore, the paper contains two illustrative examples where differences in results are compared when using a one key measurement approach and the use of a multidimensional boundary case approach in a multidimensional design problem.

5.1.1 Description of mathematical procedure

The mathematical procedure to calculate a confidence region and thereafter define boundary cases on the surface consists of a number of steps. Mean and standard deviation values for chosen number of measurements are used as input together with a correlation matrix consisting of a correlation coefficient for each measurement combination. An accommodation level is used as additional input. This level decides how large part of the population that should be surrounded by the confidence region. A confidence region is defined by the length and direction of the axes of the ellipse (two dimensions), ellipsoid (three dimensions) or hyper-ellipsoid (four dimensions and more). The lengths of the axes are described by the square root of the eigenvalues of the correlation matrix multiplied with the scale factor k which is calculated from the chi-squared distribution, using the decided accommodation level and number of chosen key measurements as input. The directions of the axes are described by the eigenvectors of the correlation matrix. With the calculated values for the axis lengths and their directional vectors, boundary manikins can be defined as points on the border of the ellipse, or on the surface of the ellipsoid or multidimensional hyper-ellipsoid. The confidence region and the subsequently created boundary manikins are defined in dimensionless z-scores (standard scores). The real anthropometric values for each manikin are calculated by multiplying the z-score with the standard deviation and thereafter adding the mean value for the corresponding anthropometric measurement.

Principal Component Analysis (PCA) studies the Principal Components (PC), which are defined by the eigenvalues and their corresponding eigenvectors, and describes the size and direction of the variation of the analysed data. The principal components are orthogonal to each other meaning that they are completely uncorrelated. The methodology when using PCA to define boundary manikins is similar to the one previously described but with some differences. PCA is done by performing these steps:

Step 1: Discard minor PC so that the remaining PC contributes to the desired degree of explanation of variation of the original data.

Step 2: Define a confidence ellipse based on the remaining PC and calculate values for the desired number of boundary manikins on the border.

Step 3: Translate the PC values to actual body measurement values defined in standardised normal scores.

Step 4: Convert the standardised normal scores to real measurement values.

5.1.2 Experimental results

The simulation experiment was divided into two examples where the first example evaluated manikins defined from two key measurements chosen as stature and sitting height. In this example the confidence ellipse approach is compared with the approach, here named *percentile approach,* where both key dimensions are set to a specific percentile value. Using the length and direction of the axes a 90% confidence ellipse was defined as shown in Figure 20 for stature (x axis) and sitting height (y axis). Figure 20 also shows an imaginary square accommodation region formed by the 90% confidence intervals for each dimension separately. In reality one typically only uses the lower left case B (5 percentile in both dimensions) and the upper right case A (95 percentile in both dimensions) in simulations since the other two cases, C and D, are unlikely measurement combinations to exist in reality (as the scatter plot in Figure 20 suggests). Worth noting is that the ellipse theoretically encloses 90% of the individuals, whereas the square area encloses approximately 85% of the individuals in this case. Additionally, the area of the ellipse is approximately 12% less than the area of the rectangle in this case.

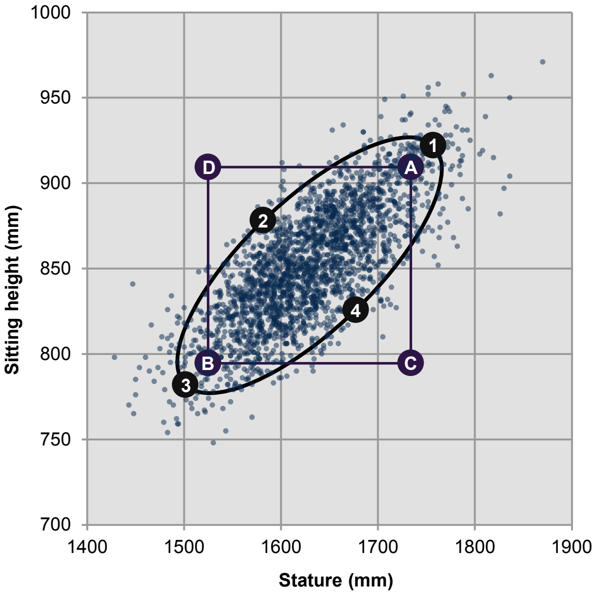

Figure 20 The bivariate 90% confidence ellipse as well as the square region shaped by the two univariate confidence intervals (scales in mm)

In the second example a third key measurement, in addition to stature and sitting height, is added, i.e. shoulder elbow length, to achieve a better description of anthropometric variation of the length of the arms within the targeted user group. The second example consists of a comparison between using PCA to reduce the number of dimensions (from three to two in this case) and by using the original number of dimensions (i.e. three in this case) and original measurements. Using the length and direction of the axes a 90% confidence ellipsoid can be defined as shown in Figure 21 for stature (x axis), sitting height (y axis) and shoulder elbow length (z axis). Figure 21 shows six boundary cases defined on the endpoints of each axis but also the coordinates for the six boundary cases defined in principal component space. The ellipse defined in the direction of the first two principal components, which together explain 97% of the variation of the data, is in real measurement space rotated and in line with the two biggest axes of the confidence ellipsoid.

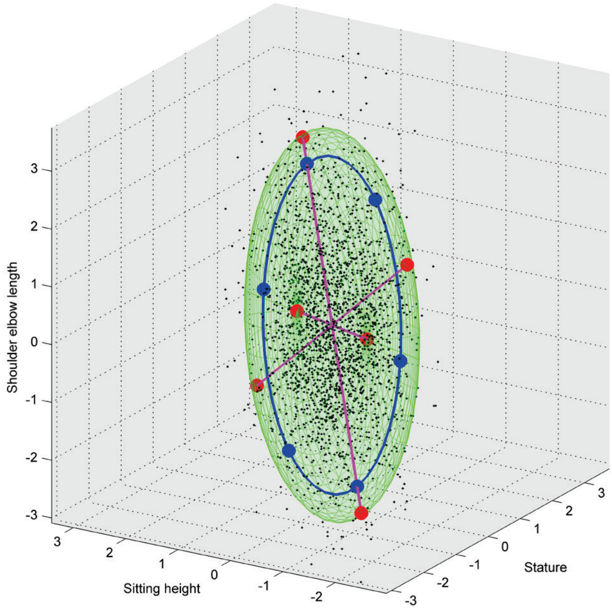

Figure 21 A three dimensional 90% confidence ellipsoid as well as boundary cases at the axial end points of the ellipsoid and in the direction of the first and second principal component (scales in standardised z-score)

The results from the simulations in Jack 7.1 were focused on the adjustment range for each design dimension that was created with each approach, Figure 22 and Table 3. The adjustment range is described by the difference between the highest and lowest value that was measured for each test group. The percentile approach gave a smaller adjustment range than the confidence ellipse approach in the first example and using PCA to reduce the number of dimensions gave a smaller adjustment range than using the original number of dimensions in the second example. Comparing the confidence region approach in Example 1 and Example 2 gives that defining only two measurements for each manikin gave approximately as big or even bigger adjustment ranges than by defining three measurements for each manikin. This can be explained by the values for the third key measurement (Shoulder-elbow length) that regression equations within the DHM tool Jack 7.1 calculates for the manikins defined only by the first two measurements (Stature and Sitting height). When plotting all three measurement values for the manikins determined in two dimensions together with the three dimensional ellipsoid it is evident that some of the manikins with values for the third measurement calculated by Jack 7.1 are far outside the intended 90% confidence region, Figure 23. Hence, using manikins defined by only two measurements will in this case give an unnecessary big adjustment range, which could be costly, or have other negative effects, when designing a product or workplace.

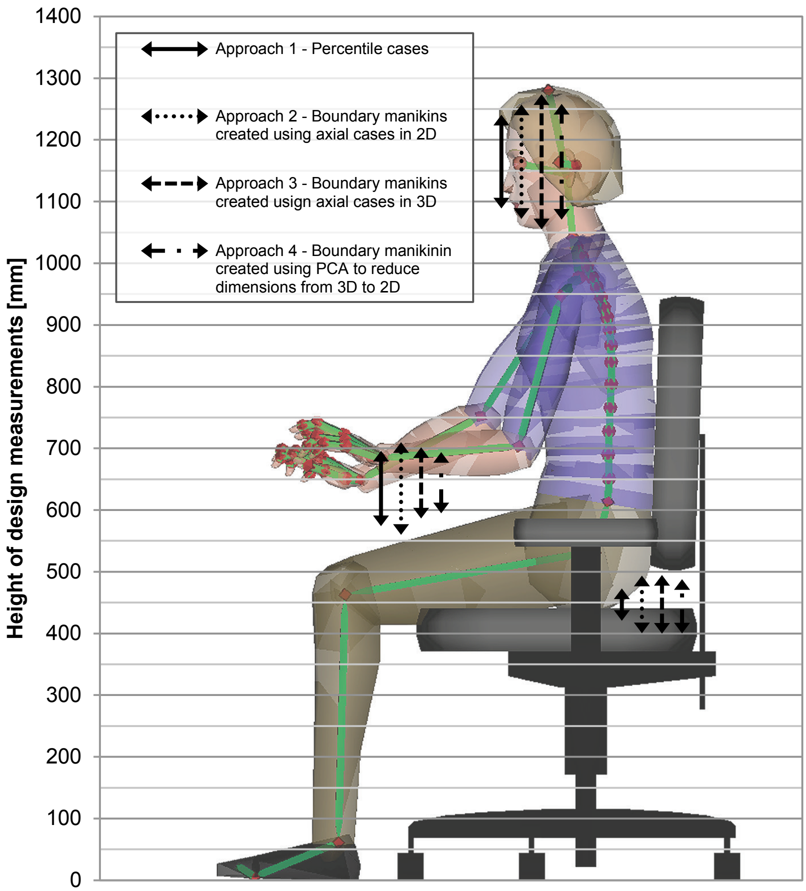

Figure 22 Results from simulation in the DHM tool Jack 7.1 for the four test groups

Table 3 Results from simulation in the DHM tool Jack 7.1 for the four test groups with values for the identified adjustment ranges and a percentage comparison

	Resulting values from simulations [mm]		
	Seat height	**Table height**	**Eye height**
Approach 1 - Percentile cases			
Max:	473	696	1241
Min:	421	574	1089
Range:	52	122	152
Approach 2 - Boundary manikins created using axial cases in 2D			
Max:	494	710	1257
Min:	400	560	1072
Range:	93	150	185
Relation to A1:	*178%*	*123%*	*122%*
Approach 3 - Boundary manikins created using axial cases in 3D			
Max:	495	702	1274
Min:	400	586	1055
Range:	95	115	219
Relation to A1:	*181%*	*94%*	*144%*
Approach 4 - Boundary manikins created using PCA to reduce dimensions from 3D to 2D			
Max:	488	694	1258
Min:	400	595	1071
Range:	88	99	188
Relation to A1:	*168%*	*81%*	*124%*

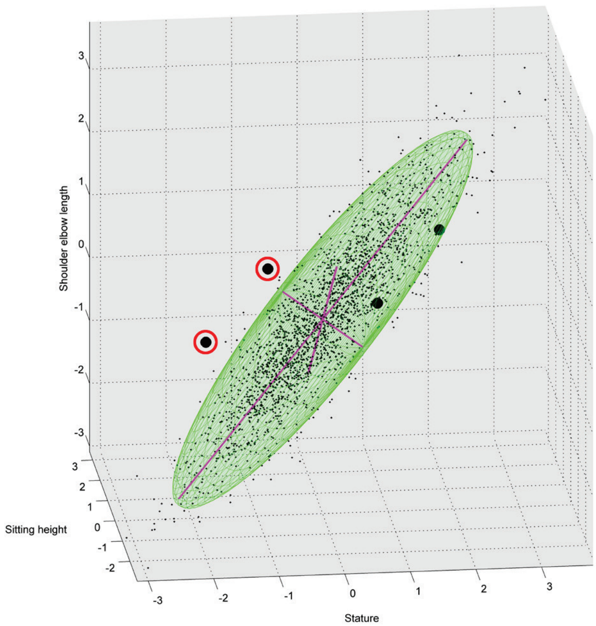

Figure 23 Manikins defined on the two dimensional ellipse with values for the measurement shoulder-elbow length calculated by Jack 7.1 outside the 90% confidence ellipsoid plotted in three dimensions (scales in standardised z-score)

5.2 Paper B: Creation of the IMMA manikin with consideration of anthropometric diversity

This paper describes creation and implementation of the anthropometric module and work process into the IMMA software. The manikin family method is based on the mathematical procedure presented in Paper A and defines boundary cases on the ends of the axes of the confidence region. By creating a manikin family by this method the number of manikins, *n*, are directly connected to the number of key measurements, *p*, as ($n=2 \cdot p+1$). If gender is treated separately, as it is done in many analyses, the number of manikins will be doubled. Values for key measurements for each manikin are defined and stored for later use in regression equations. Input to the regression equations in the IMMA software can be derived from the manikin family method but also from manual input for one single manikin. By using the hierarchical estimation method, weight and stature are on the top of the hierarchy and therefore necessary as key variables due to the necessity to know these two variables to be able to compute all regression equations. In addition to weight and stature more key measurements can be added to also be taken into consideration. If more and more measurements are added, the more similar the manikin will be to the human it is trying to represent. The results from the regression equations are used in the joint centre equations which calculate the length but also the rotation in X, Y and Z direction for every link in the biomechanical model. Like the regression equations, different joint centre equations are defined for each gender separately. The data for the biomechanical model of the manikin are exported to an XML-file that can be imported by the IMMA software.

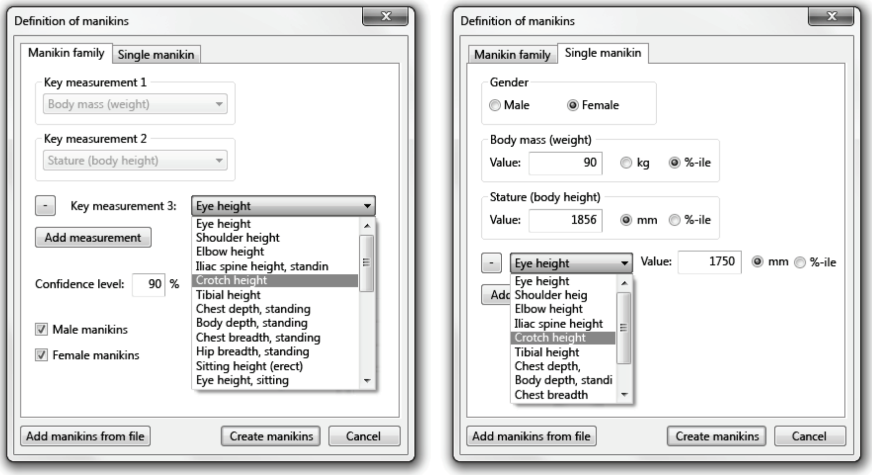

Figure 24 Graphical user interface of the boundary manikin creation functionality and the single manikin creation functionality in the IMMA software

Figure 24 shows how the resulting methods and equations have been combined with manual input in a graphical user interface (GUI) in the IMMA software. Via the GUI it is possible to create a single manikin but also a manikin family that can be used in automatic batch simulations. When creating a manikin family it is possible to add additional key measurements in addition to the two necessary key measurements weight and stature. Other choices that needs to be defined are the confidence level, i.e. the percentage that the confidence region will cover, and if manikins for one or both genders shall be created. Creating a single manikin is similar to the manikin family function. Necessary input is gender definition and values for weight and stature. As with the manikin family function, additional key measurements can be added, where this will render a manikin more similar to the human it is trying to represent. At present, it is not possible to manually change the anthropometric source regarding age and nationality in the IMMA tool because only Swedish anthropometrics is implemented. Figure 25 shows an example of manikins created using the manikin family functionality. Chosen key measurements are in this case the necessary weight and stature measurements. The confidence level is set to 90 % and both male and female manikins are created.

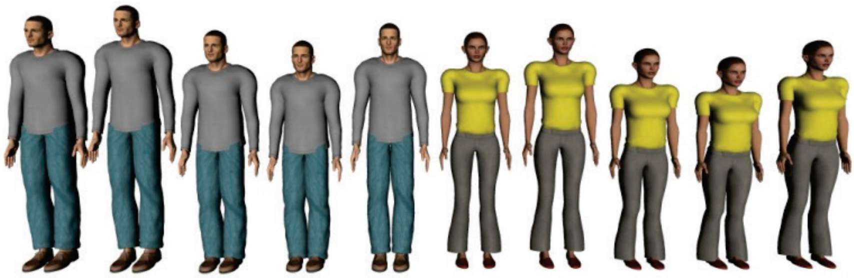

Figure 25 Manikin family created within the anthropometric module

5.3 Paper C: Using experimental design to define boundary manikins

The aim of the paper was to evaluate if experimental design methods can be useful in a context where boundary manikins are being analysed. Four different approaches were evaluated through experimental simulations in the DHM tool Jack 7.1. Each group of manikins was analysed and maximum and minimum values were observed, which in turn gave the adjustment range, for each design dimension (Table 4). As in Paper A, analysis showed that the percentile approach gave a smaller adjustment range than the other test groups. Approach 2, with boundary manikins at the axial end points, gave a larger adjustment range, especially for eye height. Compared to Approach 2, boundary manikins created using factorial design in Approach 3 gave a smaller adjustment range for eye height and a larger adjustment range for seat height. The adjustment range for table height was of similar size but not on the same height for Approach 2 and 3. Approach 4, which is a combination of Approach 2 and 3, gave the largest adjustment ranges. In Approach 4 manikins from Approach 2 defines the adjustment range for eye height and manikins from Approach 3 defines the adjustment range for seat height. The adjustment range for table height is defined with a combination of manikins from Approach 2 and 3.

Table 4 Results from simulation in the DHM tool Jack 7.1 for the four test groups with values for the identified adjustment ranges and a percentage comparison

	Resulting values from simulation [mm]		
	Seat height	**Table height**	**Eye height**
Approach 1 - Percentile cases			
Max:	461	681	1237
Min:	409	548	1085
Range:	52	133	152
Approach 2 - Boundary manikins created using axial cases			
Max:	482	710	1248
Min:	391	543	1066
Range:	91	167	182
Relation to A1:	*175%*	*126%*	*120%*
Approach 3 - Boundary manikins created using factorial design			
Max:	488	723	1235
Min:	378	561	1072
Range:	110	162	163
Relation to A1:	*212%*	*122%*	*107%*
Approach 4 - Boundary manikins created using response surface central composite design			
Max:	488	723	1248
Min:	378	543	1066
Range:	110	180	182
Relation to A1:	*212%*	*135%*	*120%*

Through the factorial design it was possible to analyse the effect that the axes of the ellipse had on the three design dimension (Bergman and Klefsjö, 2010). The main effects are the estimated effects of raising the value in standardised Z-space along the main (A_1) or secondary (A_2) axis. The interaction effect between the main and secondary axis can be estimated as the effect of raising A_1 when A_2 is on a high level minus the effect of raising A_1 when A_2 is on a low level. Table 5 shows the estimated main effects (A_1 and A_2) and interaction effect ($A_1 \times A_2$) along the axes for the three design dimensions. Note that these numbers show the effects of the axes of the ellipse in their respective direction and not the actual measurements.

Table 5 Estimated main and interaction effects along the major (A_1) and minor (A_2) axis

Seat height				
Test	**A_1**	**A_2**	**$A_1 \times A_2$**	**Result [mm]**
1	-	-	+	446
2	+	-	-	488
3	-	+	-	378
4	+	+	+	425
Estimated effects	**44.7**	**-65.4**	**2.15**	
Table height				
Test	**A_1**	**A_2**	**$A_1 \times A_2$**	**Result [mm]**
1	-	-	+	596
2	+	-	-	723
3	-	+	-	561
4	+	+	+	640
Estimated effects	**103**	**-59.3**	**-24.1**	
Eye height				
Test	**A_1**	**A_2**	**$A_1 \times A_2$**	**Result [mm]**
1	-	-	+	1109
2	+	-	-	1235
3	-	+	-	1072
4	+	+	+	1211
Estimated effects	**133**	**-30.7**	**6.00**	

Using a central composite design makes it possible to create a response surface which approximates resulting values for each design dimension based on any combination for the main and secondary axis. Figure 26, 27 and 28 show the surface plots for each design dimension in standardised measurement space of stature and sitting height[4]. The response surface are calculated from a second-degree polynomial as

$$Seat\ height = 437.6 - 43.240A_1 + 11.058A_2 - 1.485A_1^2 - 0.510A_2^2 + 0.712A_1A_2,$$

$$Table\ height = 652.1 - 27.411A_1 + 27.470A_2 - 24.684A_1^2 - 2.753A_2^2 - 7.981A_1A_2,$$

$$Eye\ height = 1156.2 - 23.187A_1 + 32.508A_2 + 1.363A_1^2 + 0.011A_2^2 + 1.987A_1A_2.$$

[4] In the appended papers the surface plots show the effects of the axes of the ellipse in their respective direction and only show the smaller factorial part of the test design in the direction of the axes.

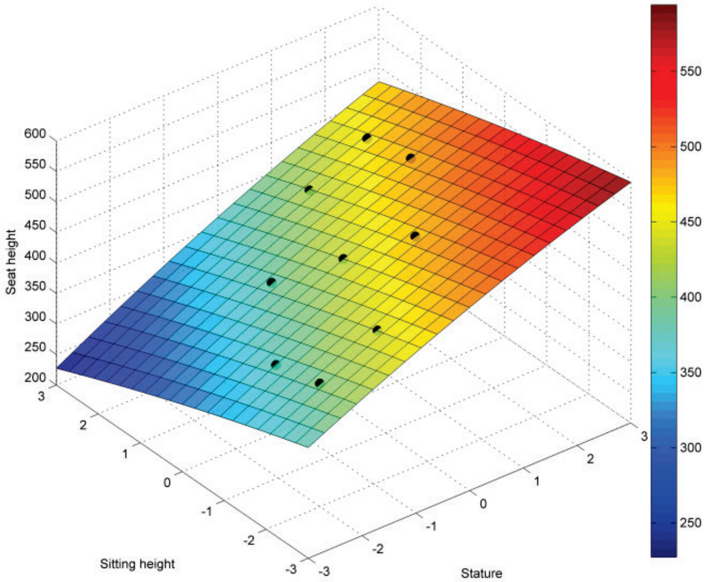

Figure 26 Surface plot of seat height (mm) with the nine test manikins determined by the Central Composite Design. Stature and sitting height in standardised Z-score

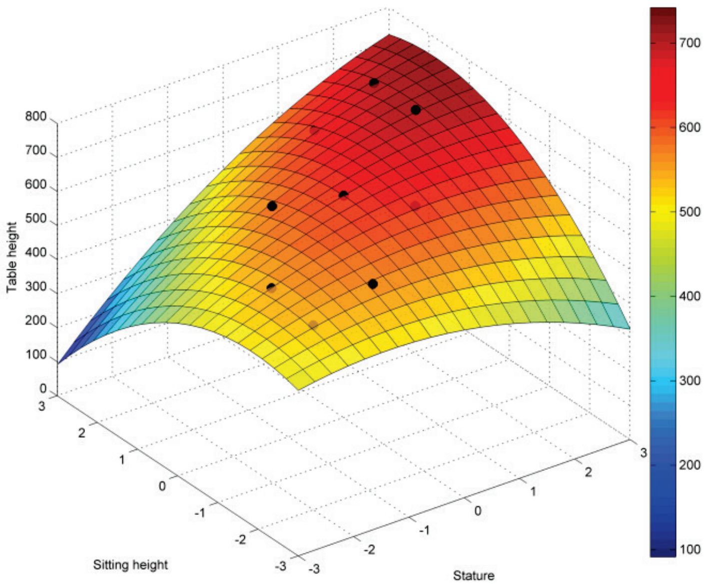

Figure 27 Surface plot of table height (mm) with the nine test manikins determined by the Central Composite Design. Stature and sitting height in standardised Z-score

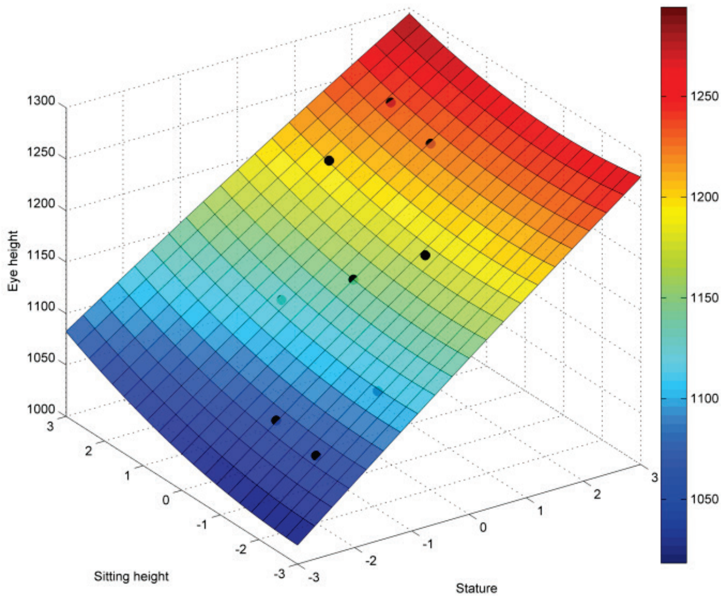

Figure 28 Surface plot of eye height (mm) with the nine test manikins determined by the Central Composite Design. Stature and sitting height in standardised Z-score

6 Discussion

This chapter discusses the research results and contributions in light of the research questions and the purpose of the thesis. The research process is discussed concerning aspects such as generalizability, validity and transferability of the results.

6.1 Consideration of anthropometric diversity

The research presented in this thesis was done to investigate how increased consideration of anthropometric diversity can be achieved in virtual development processes. A number of different areas were identified and evaluated and methods were developed and implemented resulting in a deeper understanding of the problem. During the research process, progress has continually been made in term of both knowledge and results. Focus was put on the nature of anthropometric data and the possibility of statistical and mathematical analysis of such data. This thesis and its appended papers can be viewed as a description of a process for working with anthropometric data in an enhanced way. This process can support designers, ergonomists, engineers and product and production developers who need to include anthropometric analyses in their development processes, even for those who do not necessarily use DHM software.

6.1.1 Multidimensional confidence regions

Calculation and mathematical procedure for defining confidence regions was described and evaluated in Paper A. Most existing methods use some variant of the boundary case methodology, often doing rough simplifications of the analysed problem. A common approach when assessing occupant packaging in vehicle interiors is to use the boundary case methodology based on three measurements; stature, weight or waist circumference (as an indicator of corpulence) and the ratio of the lower and upper body. However, the assumption that these three dimensions will predict the overall diversity of a population in a good way might not be valid in all cases. In some situations additional dimensions have to be added and sometimes other dimensions should rather be used. Due to the strong attention on the boundary case methodology and its use of confidence regions, much work has been put into examining and clarifying the mathematical process of defining these ellipses, ellipsoids and hyper-ellipsoids. The studies have shown that anthropometric data is well suited for statistical and mathematical analysis but some simplifying assumptions needs to be done. This means that the distribution of anthropometric measurements is approximated by a normal distribution and that the correlation coefficient is used as an approximation of the relationship between various anthropometric measurements. The validity of these approximations can be argued, especially if the sample of the population is small (Vasu and Mital, 2000). One thing that still needs to be discussed is that these approximations and the mathematical procedure lead to confidence regions in the shape of a hyper-ellipsoid being centred on a central case, or a so called "average person". A central case is the most likely case to be found in a multivariate distribution, i.e. the density is highest in this central point. Nonetheless, the probability to find measurements from a real person in this point are not high when higher number of dimensions are analysed (Daniels, 1952). This might however not be a problem when utilising a boundary case methodology and defining several test cases throughout the variation. The simulation results from Paper A also demonstrates that the proposed boundary case method is advantageous compared to approaches based on the use of univariate percentile data, as often used in industry today. According to the results it is favourable to incorporate all identified key measurements rather than just a few as this will have an impact on the simulations and analyses. If there still is a need to limit the number of manikins, PCA is adequate to use to reduce the number of dimensions. If PCA is used, based on the experimental results in Paper A, the size of the confidence region defined within the reduced principal component space should be scaled with a factor *k* calculated using the original number of dimensions. However, subsequent analyses have shown that confidence hyper-ellipsoid s in higher dimensional space will become very large and may actually give unrealistic test cases, e.g. the weight of test cases defined in a 32 dimensional hyper-ellipsoid might be negative. Another purpose of writing Paper A was to present a clear and concise explanation and description of the mathematical procedure behind the calculation of confidence regions and the boundary case methodology. Increased understanding of the mathematical procedure of multidimensional boundary cases and the advantages when using these methods is anticipated to lead to an increased usage.

6.1.2 Manikin creation in IMMA

Even if the mathematical procedure is fully explained the process can appear to be complicated. Because of the difficulty to simplify the mathematical procedure it is important that the methods and processes are implemented in a usable tool. This was one purpose of Paper B together with an implementation of a regression system and creation of the biomechanical model of the IMMA manikin. The combination of these three parts in the IMMA software offers an opportunity to consider and work with anthropometric diversity in an improved way compared to common practice identified in previous studies. To save time and encourage simulations with more manikins it is crucial that the manikin family function is combined with automatic batch simulation functionality to be able to utilise the advantages of the methodology. Still it is important to choose key variables with care. Both because choosing too many key measurements will lead to an overwhelming number of manikins, and in many evaluations the variance of certain key measurements will not be of interest. In addition, measurements with high mutual correlation will produce a manikin family in which some manikins are very similar. Hence, it is advantageous to choose key measurements with low mutual correlation. Currently both the regression system and the joint centre equations have disadvantages that decrease the functionality of the IMMA tool. Because the manikin creation process is using a hierarchical estimation method it is rational if key variables are chosen in respect to these regression equations with stature and weight as two necessary variables, both when creating manikin families but also when creating single manikins. Using a hierarchical estimation method also creates one and the same non-unique manikin if few key measurements are defined. To create a fully unique individual it is necessary to define all measurements as key variables. When choosing key variables for the manikin family this fact is in some degree balanced because extreme combinations are calculated for the defined key variables. The joint centre equations are connected with quite high uncertainty because of the lack of sufficient data reported in literature. The current results are combined from different and sometimes old sources. Hence there is a need to further improve the regression system and the joint centre equations to achieve a more flexible regression system and more accurate joint centre equations. Still, automated batch simulations with groups of manikins will decrease simulation time and gain accuracy of anthropometric diversity consideration when using DHM tools for the design of products and workplaces.

6.1.3 Boundary cases based on experimental design

The result from the study in Paper C shows that it is possible to adapt the methodology of experimental design when creating group of manikins. Examples in this paper only use two dimensions but the method works for any number of dimensions. In order to get cube points of a factorial design on the boundary surface of a confidence region, later studies have shown that the variable α should be calculated by the square root of the number of dimensions. The size of these groups of manikins depends heavily on the number of key measurements but also on the type of chosen experimental design. The result also shows that an increased accommodation level accuracy is achieved if more boundary manikins are included in the simulation. An important fact to realise is that additional boundary manikins added with the factorial design are just as extreme or unusual combinations as axial end point manikins. In fact the level of extremity, i.e. the probability to find a real person with the same measurements, is the same for any manikin that is situated on the border of the ellipse. Simulations should therefore be done with enough number of manikins that adequately describes the hyper-ellipsoid to ensure the intended accommodation level. Thus, focus should not only be put on which manikins to use in simulations but also how many manikins to use. Attentive readers may have noticed the different results from the simulations in Paper A and Paper C that was done with identical manikins. Reasons for this difference have not been identified but it shows the difficulty of maintaining a robust simulation procedure with current tools considering objectivity and repeatability.

By using experimental design methods the effect of the axes of the confidence region can be measured. Table 5 shows that the main axis had the greatest effect on both eye height and table height but for seat height the secondary axis had a slightly greater effect. These results indicate that it is not certain that the major axis or first principal component always have the greatest effect on the resulting variable being analysed. Therefore it could be useful to combine a factorial design with PCA in an initial study to analyse which principal components that have an effect on the resulting variable. Using the more advanced Central Composite Design gives additional possibilities to study the effect each axis have on the resulting variable. As the response surface can be rotated a direct connection can be analysed between the anthropometric measurements and the design dimensions as shown in Figure 26, 27 and 28. However, these response surfaces are only approximations and the validity of the approximations needs to be further studied. Still, using more boundary manikins increases the possibility to meet desired levels of accommodation.

6.2 Validity and accommodation level accuracy

Both the validity of the research presented in the thesis and the proposed methods can be discussed. The lack of real user trials in the research can be considered to reduce the validity of the research as well as the fact that only one DHM tool, Jack 7.1, have been used in simulation experiments and only one task have been simulated and analysed. The results from the research demonstrate that the proposed process and methods is advantageous compared to approaches common in industry today but an important question still remains: *How accurate are the proposed methods at predicting the final accommodation level?* It is important to realise that the common target for the accommodation level of 90% should not be decided without respect to the source of the anthropometric data, i.e. evaluations based on anthropometric data taken from fully functional people ought to have higher accommodation levels. Another difficulty is that in reality there is no exact accommodation, a motion is not completely right or wrong, but somewhere on a scale. For example, what does non-accommodation for a certain test case and simulation mean? Will a real person performing the motion just feel discomfort or experience more serious problems? Therefore it is easier and often better to compare different concepts of solutions than to decide if the ergonomics is acceptable for a product or workplace. It will never be possible to fully secure the accommodation level accuracy because it is not possible to consider all the factors that will affect the interaction between the human, the product or workplace and the environment. When more factors are added to get a better accuracy, such as a more advanced biomechanical model, other problems occur with the increased time that each simulation needs. The goal should be, despite this, to improve current methods and tools to increase the usefulness in virtual product and production development

The proposed methods in this thesis are based on a number of assumptions, e.g. that simulations with boundary manikins are sufficient to assess the whole population inside the defined confidence region. The validity of this assumption is however depending on what is being evaluated and sought. In the examples in Paper A and Paper C the result parameters were design dimensions to define an adjustment range. That setup is more likely to find max and min values at the edges of the confidence region. The validity of the boundary case theory is likely to be more uncertain if instead a value for risk of musculoskeletal disorder was sought. This is also indicated by Mårdberg et al. (2012) who found manikins within the confidence region that had a higher ergonomics evaluation value calculated by torques on the joints and joints positions.

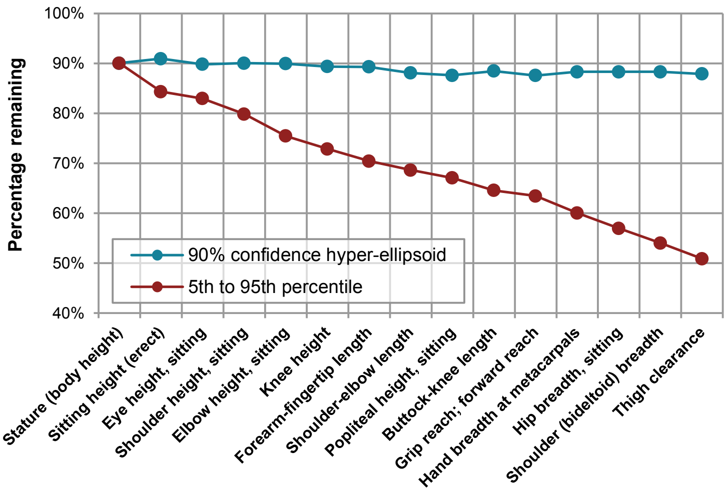

Figure 29 Illustration of decline in accommodation when comparing the confidence hyper-ellipsoid method and the 5th to 95th percentile method for men, data from ANSUR (Gordon et al., 1989) (Figure inspired by Roebuck et al. (1975))

The method presented in this thesis is based on mathematical and statistical assumptions such as that a confidence region surrounds the chosen accommodation level. Analysis shows that this is not exactly correct, which may be due to the data not being completely normal distributed or that the chi-square distribution does not fully predict the necessary size for the confidence region. However, the confidence hyper-ellipsoid method is far better than the percentile method used today for including the chosen accommodation, Figure 29.

PCA is useful when the design of a product or workplace will be influenced by many anthropometric measurements and there is a need to reduce the number of dimensions and the total number of manikins. However, when using PCA it is necessary to decide how many PC that should be used when defining the confidence region and thus how much of the total variation that will be considered. Within considerations of anthropometric diversity in design, a common approach is that 3-4 PCs are enough because the amount of the variability of the data that each PC describes tends to level off after 3-4 PCs, Figure 30. However, the discarded PCs will still add to the total percentage of variation and another way to look at this problem could be to assess the cumulative percentage of the variation that is described by the spared PCs, Figure 31 (Jolliffe, 2002). The variation that the first PCs describe depends on how many original measurements that are analysed and the correlation between these measurements. When analysing 39 measurements from female ANSUR data (Gordon et al., 1989) it can be discussed if using only 3-4 PCs, which explains not more than 69-75% of the total variation is enough. Instead maybe at least 12 PCs should be included to achieve a cumulative percentage of variation above 90%. Anyway, some part of the total variation will be discarded and what that does to the final resulting accommodation is uncertain and should be further studied.

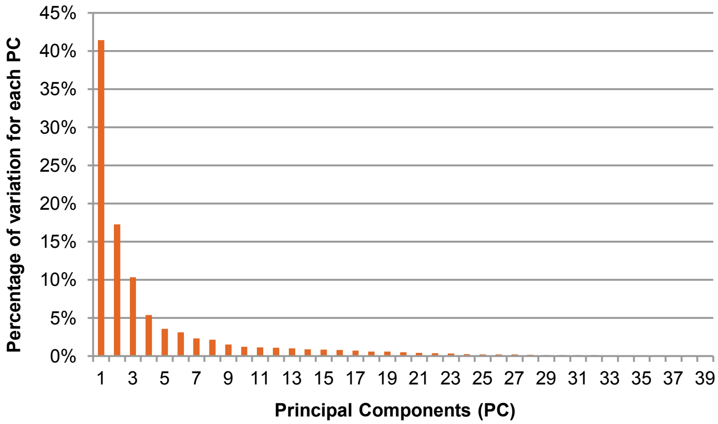

Figure 30 Description level for each PC, 39 analysed measurements for women, data from ANSUR (Gordon et al., 1989) (See Appendix 1 for list of measurements)

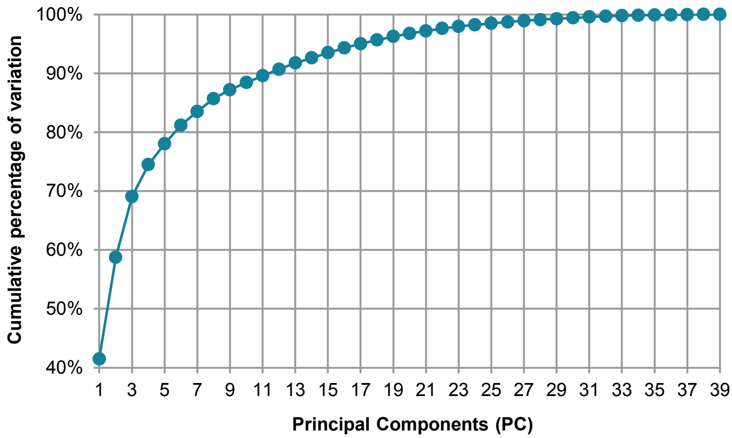

Figure 31 Cumulative percentage of the variation, 39 analysed measurements for women, data from ANSUR (Gordon et al., 1989) (See Appendix 1 for list of measurements)

PCA and its analysis of eigenvalues and eigenvectors can also be used to make predictions of missing measurements based on a few predictors such as stature and body mass index (Parkinson and Reed, 2010). This also makes it possible to go back and forth between PC space and real measurement space. A few real measurements can be used to predict all the PCs and vice versa (Shu et al., 2011). More defined measurements or PCs will give a better prediction and this technique could be used instead of the hierarchical regression equations. Using PCA also gives the possibility to include any human capability that can be measured and approximated with a normal distribution in this PCA based regression system. For example, body strength and range-of-motion, which certainly have some correlation to other body dimensions, could be measured and then be used to define manikins in a DHM tool. By using this procedure it will not be necessary to make a big study to evaluate the correlation between different measurements. Instead, several smaller tests with specific focus might give a good understanding of the diversity, e.g. one study could focus on building up the exterior and interior biomechanical model and another study for evaluating muscle strength in comparison with anthropometric measurements. Behavioural diversity would also be of interest to include and advanced methods have been developed for the consideration of posture variation among users, e.g. for vehicle interior design purposes, where both anthropometric and behavioural variation are factors in the model (Garneau and Parkinson, 2009). Also the matter if more cognitive capabilities could be measured and included in simulations and analysis should be further studied (Thorvald et al., 2012). The method of user characters to describe specific users would also gain if more human capabilities can be included, such as variation in muscle strength and vision, through better coherence between the manikin and the user character it tries to simulate.

6.3 Final thoughts

During this research a number of areas or factors have been identified which need to be considered to achieve the goal of increased consideration of anthropometric diversity and high accuracy in that the sought accommodation level is achieved. The goal is to get valid simulation results that predict the real results, e.g. the risk of injury or disorder when using the final product or workplace. One major factor that needs to be considered is the quality of DHM tools such as accuracy of algorithms for motion creation, accuracy of biomechanical model and the resolution of the human model which all affect the coherence between the simulation and real results. The simulations can predict wrong results and in that case it might be better to use physical prototypes and user trials to assess the design. An increased knowledge and improved processes in building prototypes and performing user trials could maybe be more useful and value adding than doing simulations for which the accuracy of the results can be discussed. Another factor is the efficiency capability of DHM tools or the time to do simulations. With more advanced biomechanical models and bigger consideration of human capabilities the simulation times increases rapidly. The problem may not be how consideration of anthropometric diversity should be done, but to what degree? Being certain that the chosen accommodation level really is reached might be unrealistic. The goal should maybe not be to define percentages that are accommodated but rather to identify which type of persons will have trouble using the product or workplace and then improve the design to meet these people's demands. It is important that these persons are not discarded as being too extreme but instead included into the design. It is evident that there are many factors that needs to be considered and trade-offs must be made as these factors to some degree contradict each other. The usability of DHM tools is therefore of great importance to support the user when doing these trade-offs.

7 Conclusions

In this thesis, the matter of anthropometric diversity consideration has been approached through an evaluation of existing methods for anthropometric diversity consideration and, based on this review, new and improved methods have been developed and implemented. Aspects that need to be considered to be certain that a high accommodation level accuracy is achieved and possibilities to include more physical characteristics and in turn consider more aspects of human diversity have been identified. A number of conclusions can be drawn from the results of the research presented in this thesis.

- The proposed boundary case method is advantageous compared to approaches based on the use of univariate percentile data, as often used in industry today.
- Because of the difficulty to simplify the mathematical procedure it is important that the methods and processes are implemented in a usable tool.
- Automated batch simulations with groups of manikins will decrease simulation time and gain accuracy of anthropometric diversity consideration when using DHM tools for the design of products and workplaces.
- Anthropometric data is well suited for statistical and mathematical analysis but some simplifying assumptions need to be done.
- It is favourable to incorporate all identified key measurements rather than just a few as this will have an impact on the simulations and analyses. If there still is a need to limit the number of manikins, PCA is adequate to use to reduce the number of dimensions.
- Still it is important to choose key variables with care because choosing too many key measurements will lead to an overwhelming number of manikins, and in many evaluations the variance of certain key measurements will not be of interest.
- Using PCA also gives the possibility to include any human capability that can be measured and approximated with a normal distribution in a PCA based regression framework.

- It is possible to adapt the methodology of experimental design when creating group of manikins and by using experimental design methods the effect of the axes of the confidence region can be measured. It is not certain that the major axis or first principal component always have the greatest effect on the resulting variable being analysed.
- Using the more advanced Central Composite Design gives additional possibilities to study the effect each axis have on the resulting variable. As the response surface can be rotated a direct connection can be analysed between the anthropometric measurements and the design dimensions.
- It will never be possible to fully secure the accommodation level accuracy because it is not possible to consider all the factors that will affect the interaction between the human, the product or workplace and the environment.
- An increased accommodation level accuracy is achieved if more boundary manikins are included in the simulation.
- When more factors are added to get a better accuracy, such as a more advanced biomechanical model, other problems occur with the increased time that each simulation needs.
- The aim of getting a high accommodation level accuracy must be done with consideration of the quality and efficiency capability of DHM tools.

8 Future work

There are a number of areas that can be addressed to further improve the consideration of anthropometric diversity when working with DHM tools.

One important area is to implement the framework for combining data of human capabilities, Figure 32. The implementation of this framework will include a number of studies and analyses.

- Parameterisation of the external model and prediction of joint centre positions connected to anthropometric measurements and motion data.
- Description of behavioural variation connected to physical capabilities.

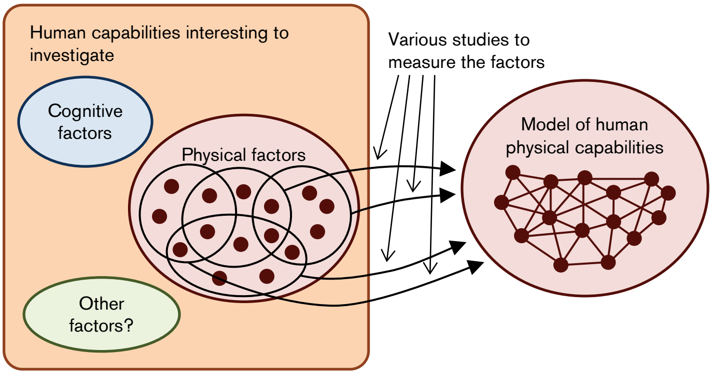

Figure 32 Imaginary illustration of the suggested PCA based regression system

Another area is the usability of DHM tools that needs to be improved with better user interfaces that support and guides the user.

- The user interface should include features that support the user to define appropriate key measurements, e.g. by suggesting key measurements depending on the design problem at hand or by highlighting key measurements with low correlation with previously selected key measurements.

In addition, the methods for multidimensional diversity consideration need to be further improved to increase the accommodation level accuracy.

- A broader search of existing methods with attention on the clothing industry.
- Further examination of the validity of the boundary case theory through simulations and evaluations targeted to specific design situations where different types of resulting variables are sought.

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Appendix

Appendix 1: 39 anthropometric measurements used in the PCA for Figure 30 and Figure 31.

#	Number and name in IS0 7250
1	4.1.1 Body mass (weight)
2	4.1.2 Stature (body height)
3	4.1.4 Shoulder height
4	4.1.7 Crotch height
5	4.1.9 Chest depth, standing
6	4.1.11 Chest breadth, standing
7	4.1.12 Hip breadth, standing
8	4.2.1 Sitting height (erect)
9	4.2.2 Eye height, sitting
10	4.2.3 Cervicale height, sitting
11	4.2.4 Shoulder height, sitting
12	4.2.5 Elbow height, sitting
13	4.2.6 Shoulder-elbow length
14	4.2.8 Shoulder (biacromial) breadth
15	4.2.9 Shoulder (bideltoid) breadth
16	4.2.11 Hip breadth, sitting
17	4.2.12 Lower leg length (popliteal height)
18	4.2.13 Thigh clearance
19	4.2.14 Knee height
20	4.2.15 Abdominal depth, sitting
21	4.2.17 Buttock-abdomen depth sitting
22	4.3.1 Hand length
23	4.3.3 Hand breadth at metacarpals
24	4.3.7 Foot length
25	4.3.8 Foot breadth
26	4.3.9 Head length
27	4.3.10 Head breadth
28	4.3.12 Head circumference
29	4.3.14 Bitragion arc
30	4.4.2 Grip reach; forward reach
31	4.4.5 Forearm-fingertip length
32	4.4.6 Buttock-popliteal length (seat depth)
33	4.4.7 Buttock-knee length
34	4.4.8 Neck circumference
35	4.4.9 Chest circumference
36	4.4.10 Waist circumference
37	4.4.11 Wrist circumference
38	4.4.12 Thigh circumference
39	4.4.13 Calf circumference

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