THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Anthropometric diversity and consideration of human capabilities

– Methods for virtual product and production development

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Cover illustration by Erik Brolin
The user interface of the anthropometric module, confidence ellipsoids with identified boundary cases as well as a female and male manikin family

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ABSTRACT

Contemporary product and production development is typically carried out with the support of computer tools where the design of products and workstations are originated and evaluated within virtual environments. Ergonomics addresses factors important to consider in the product and production development process to ensure a good fit between humans and the items being designed. Digital human modelling (DHM) tools enable simulations and analyses of ergonomics in virtual environments. Anthropometry is central when using DHM tools for product and production development to ensure that the design fits the intended proportion of the targeted population from a physical perspective. Several methods have been prescribed to consider the anthropometric diversity that exists within human populations. Still many DHM based simulations in product and production development processes are done with approaches that are poor in representing anthropometric diversity. Hence, there is a need for better tools and methods that would support DHM tool users to more effectively and efficiently consider anthropometric diversity in the design process.

In this thesis current methods for anthropometric diversity considerations have been reviewed and new methods and functionality have been developed and implemented in a DHM tool. Mathematical models have been developed to consider three specific parts important to the consideration of anthropometric diversity: generation of suitable test cases, prediction of missing anthropometric data and implementation of more diverse anthropometric variables such as strength and flexibility. Results show that the proposed methods are accurate and advantageous compared to approaches often used in industry today. The mathematical models for generation of suitable test cases and prediction of missing anthropometric data have been implemented in an anthropometric software module. The module has undergone usability testing with industry DHM tools users. The developed anthropometric module is shown to answer to relevant needs of DHM tool users and fit into the work processes related to DHM simulations and ergonomics analyses utilised in industry today.

Keywords: Ergonomics, Human Factors, Anthropometry, Multi-Dimensional, Diversity, Digital Human Modelling, Simulation, Visualisation, Workplace Design, Product Design, Accommodation.

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Erik Brolin
Skövde, March 2016

APPENDED PAPERS

Paper A

Use of digital human modelling and consideration of anthropometric diversity in Swedish industry

Bertilsson[1], E., Svensson, E., Högberg, D. and Hanson, L. (2010).

Proceedings of the 42nd annual Nordic Ergonomic Society Conference: Proactive Ergonomics - implementation of ergonomics in planning of jobs, tasks, systems and environments, Stavanger, Norway, September 2010.

Brolin performed and analysed the interviews together with Svensson and wrote the paper with Svensson, Högberg and Hanson. Brolin was the corresponding author and presented the work.

Paper B

Description of boundary case methodology for anthropometric diversity consideration

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

Published in *International Journal of Human Factors Modelling and Simulation (IJHFMS)*, Vol. 3, No. 2, 2012.

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

Paper C

Adaptive regression model for prediction of anthropometric data

Brolin, E., Högberg, D., Hanson, L. and Örtengren, R. (2016).

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

Brolin developed the model and performed the analysis and wrote the paper with Högberg, Hanson and Örtengren. Brolin is the corresponding author.

[1] Erik Brolin changed his last name from Bertilsson to Brolin in 2012.

Paper D Adaptive regression model for synthesizing of anthropometric population data

Brolin, E., Högberg, D., Hanson, L. and Örtengren, R. (2016).

Under review for publication in the *International Journal of Industrial Ergonomics*.

Brolin developed the model and performed the analysis and wrote the paper with Högberg, Hanson and Örtengren. Brolin is the corresponding author.

Paper E Generation and Evaluation of Distributed Cases by Clustering of Diverse Anthropometric Data

Brolin, E., Högberg, D., Hanson, L. and Örtengren, R. (2016).

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

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

Paper F Development and Evaluation of an Anthropometric Module for Digital Human Modelling Systems

Brolin, E., Högberg, D., Hanson, L. and Örtengren, R. (2016).

Submitted for publication in the *International Journal of Industrial Ergonomics*.

Brolin planned the module together with co-authors and then did part of the programming of the module. Brolin did the user evaluation and wrote the paper with Högberg, Hanson and Örtengren. Brolin is the corresponding author.

ADDITIONAL PUBLICATIONS

2015

Högberg, D., Brolin, E. and Hanson, L. (2015). Accommodation levels for ellipsoid versus cuboid defined boundary cases. *Procedia Manufacturing*, Volume 3, 2015, pp. 3702-3708.

Högberg, D., Brolin, E. and Hanson, L. (2015). Identification of redundant boundary cases. *Proceedings of the 19th Triennial Congress of the International Ergonomics Association. Lindgaard, G. and Moore, D. (Eds.)*, Australia, 9-14 August, 2015.

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Högberg, D., Brolin, E. and Hanson, L. (2014). Basic Method for Handling Trivariate Normal Distributions in Case Definition for Design and Human Simulation. *Advances in Applied Digital Human Modeling. Duffy, V.G. (Ed.)*. AHFE Conference, pp. 27-40, ISBN 978-1-4951-2094-7.

Brolin, E., Högberg, L. and Hanson, L. (2014). Design of a Digital Human Modelling Module for Consideration of Anthropometric Diversity. *Advances in Applied Digital Human Modeling. Duffy, V.G. (Ed.)*. AHFE Conference, pp. 114-120, ISBN 978-1-4951-2094-7.

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[3] Erik Brolin changed his last name from Bertilsson to Brolin in 2012.

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. It also includes the starting point of the research in the form of research questions derived from the background and identified research needs.

1.1 Background

Computer-aided design (CAD) have had a significant influence on design methods, organisational structures and the division of work by supporting designers in the process of analysing, optimising and combining design solutions (Pahl et al., 2007). However, the decision-making abilities of designers are still important, especially with the amount of concept solutions that can be produced using CAD tools. In today's complex development processes there is high volume of information that needs to be processed to make better-informed decisions. 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 in studying how a product, tool, workplace or task[4] will affect a potential user and vice versa, employing a systems view (Bridger, 2009). Using a Human Centred Design approach, attention is put on developing a product or workplace that matches the capabilities and diversity of humans (Norman, 2013). Studies to evaluate the interaction between users and products, workplaces or tasks have typically been done relatively late in the development phase (Porter et al., 1993; Duffy, 2012) and based on making expensive and time demanding physical mock-ups (Helander, 1999;

[4] 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.

Duffy, 2012). Obstacles towards more proactive ergonomics measures are found to be lack of knowledge, methods and tools for consideration of ergonomic issues together with a lack of cooperation and communication between project stakeholders (Falck and Rosenqvist, 2012).

To support the consideration of ergonomics and human factors in virtual environments, Digital human modelling (DHM) software can be used. DHM tools are computer based tools that provide and facilitate 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 digital human models, also called computer manikins, i.e. changeable digital versions of humans. DHM tools can be used to create, modify, present and analyse human-machine interactions in virtual environments. 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.

Existing anthropometric data can be acquired from a number of sources such as books, articles, software and web sources (Pheasant and Haslegrave, 2006; PeopleSize, 2008; Hanson et al., 2009b; 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. An issue with existing anthropometric data is that surveys sometimes include few subjects or that all necessary measurements are not included. Collecting new anthropometric data is expensive and time-consuming even if an increasing number of measurement studies are carried out using digital laser scanning techniques in order to get faster measuring processes, more data and data that can be reused for subsequent analyses (Robinette et al., 2002; Godil and Ressler, 2009; Hanson et al., 2009b; Robinette, 2012). Regardless whether anthropometric data is applied directly in design tasks or utilised within a DHM system there is a need for methods to predict and synthesize new anthropometric data that better represents the target population.

The variation of an anthropometric measurement within a population can most often be approximated with a normal distribution (Pheasant and Haslegrave, 2006). There are also variations between measurements, which can be approximated with correlation coefficients. Such variations 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 including only one or two measurements in the analysis and setting them to a specific percentile value, also called the univariate approach (Daniels, 1952; Roebuck et al., 1975; Ziolek and Wawrow, 2004; Robinette, 2012). Successful design of products and workplaces does however often need to consider variation in several body dimensions. Because of the fact that humans vary a lot in sizes and shapes, there is considerable uncertainty, for a range of design tasks, 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, 2012). 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 may not be 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 between different simulations done by a single user (Lämkull et al., 2008). This adds to the uncertainty of the simulation results. Methods and functionality in DHM tools that support the multidimensional consideration of anthropometric diversity are sometimes hidden or containing variables that are difficult to specify (Ziolek and Nebel, 2003). Furthermore, current DHM tools more or less forces the users to always specify overall body measurements such as stature when creating digital manikins, even if these measurements may not have a close connection to the anthropometric dimensions that are to be considered within a certain design task. DHM systems aimed at product and workstation design consider in most cases only physical user characteristics and with focus on consideration of body size related anthropometric diversity (Bubb and Fritzsche, 2009). However, the human-machine interaction is not only affected by the size and proportions of a user but also other user characteristics, e.g. muscle strength and joint range of motion (ROM) (Frey Law et al., 2009). And, as DHM systems become more advanced with sophisticated strength and motion prediction functionality, variables such as joint torque profiles and joint mobility need to be included when establishing the capabilities of computer manikins (Abdel-Malek and Arora, 2009; Hanson et al., 2009a). Hence, there is a need for methods and tools that facilitate an improved way of working with DHM tools for ergonomics design and that are able to consider the diversity within a range of different human characteristics when creating manikins in DHM tools. This would give computer manikins with enhanced ability to represent the variability of the targeted population and in turn produce more realistic and accurate simulations and evaluations when using DHM tools for the design of products and workplaces. Hence, the overall objective is that DHM simulations should assist decision making in the development process so that the final designs truly accommodate the intended target populations.

1.2 Purpose of research and thesis

The general purpose of the research presented in this thesis is to explore how increased consideration of anthropometric diversity can be achieved in virtual product and production development processes. Existing methods and how they are currently used in industry are to be evaluated. Based on this review new and improved methods and tools should be developed and implemented utilizing a holistic approach. Necessary functions to reach good consideration of anthropometric diversity and how they fit into the use process of a DHM system needs to be clarified. An additional purpose is to propose new methods for including additional user characteristics, for example muscle strength, range of motion and motion behaviour, when defining test manikins used in DHM simulations.

1.3 Research questions

The research is done in the context of DHM tool usage and takes its point of origin in identified needs. The research should benefit designers, ergonomists, engineers and product and production developers who need to include consideration of user characteristics in their development processes. By taking these aspects into consideration the following research questions have been formulated:

Research question 1 *How are DHM tools used in product and production development processes and what methods exists for consideration of anthropometric variation?*

Research question 2 *How can mathematical models and methods increase the accommodation accuracy of a design for a defined target group?*

Sub research question 2.1 *How can measurement combinations of anthropometric variables connected to the dimensions of a product or workplace be determined to identify suitable test cases?*

Sub research question 2.2 *How can valid and reliable predictions of unknown anthropometric variables be achieved when generating virtual human models?*

Sub research question 2.3 *How can additional anthropometric variables beside body size be included in the process of defining test cases?*

Research question 3 *How could the implementation of mathematical models be adapted to meet the needs of DHM tool users?*

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

- review current and develop new methods for prediction and consideration of anthropometric diversity and analyse the differences in evaluation results when utilising different approaches and models,
- propose methods to include more user characteristics and in turn consider more aspects of human diversity, and
- implement new methods and functionality in DHM tools.

1.4 Delimitations

Although a number of different user characteristics are of interest to measure and include in simulations and analyses, the remainder of this thesis will focus on fundamental anthropometric data and additional capability variables such as strength and joint range of motion. Thus, this work does not cover other aspects of human biomechanics such as material properties of skin and bones. Nor does the thesis consider data from body scanning (Godil and Ressler, 2009; Godil and Ressler, 2011; Park and Reed, 2015) which would give information of the three dimensional shapes of humans and could be included to get an increased realism and better simulations and evaluations when using DHM tools. This delimitation is made in order to narrow the field during the research process even though the research is done with the intention that additional type of data such as body scanning data should be possible to include in the process of defining test manikins used in DHM simulations.

2 FRAME OF REFERENCE

This chapter provides concepts and theory that are essential to the field of research: Ergonomics, Anthropometry and Digital Human Modelling.

2.1 Ergonomics

As a research field, ergonomics emerged from the problems and needs of humans to efficiently interact with the ever more advanced and demanding technology and industry in the mid-20th century (Pheasant and Haslegrave, 2006). Ergonomics can be called Human Factors, or Human Factors and Ergonomics, but should be viewed as one and the same research field[5] (Hendrick, 2008). 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' interaction with the closest surrounding and these two fields are also called *Micro-Ergonomics*. These two fields are accompanied with the field of 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*

[5] The term Ergonomics will be used, throughout the remainder of the thesis.

the profession that applies theoretical principles, data and methods to design in order to optimise human well-being and overall system performance.

(IEA, 2000)

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, systems, tools, products and public spaces. An interaction depends on factors connected to the demands of the technological system and the capability of the operator/user (Figure 1) (Czaja and Nair, 2012). The aim is to consider the factors that affect the interaction and to improve the performance of the 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 (Chapanis, 1996).

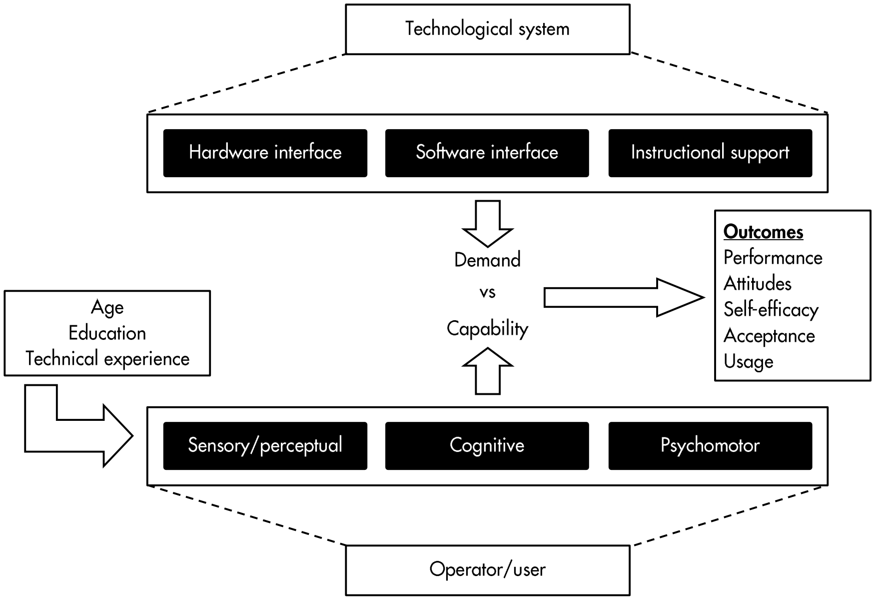

Figure 1 Example of human-machine system, adapted from Czaja and Nair (2012)

Good ergonomics is achieved when capabilities of humans match the demands given by the machine or task. Meeting this objective can be achieved through a human and user centred design process which aims at making systems more usable by focusing on the use of the system and applying ergonomics and usability knowledge and techniques (ISO, 2009). The concept of inclusive design is an example of a human centred design approach that aims to offer good ergonomics to a wide range of users (Waller et al., 2015). Within the inclusive design approach user characteristics can be categorised into seven capability categories: Vision, Hearing, Thinking, Communication, Locomotion, Reach & stretch and Dexterity (University of Cambridge, 2011). The capability levels can be assessed for each category to identify mismatches between the diversity of user's capabilities and the demands that would be caused by a specific machine or product design (Figure 2).

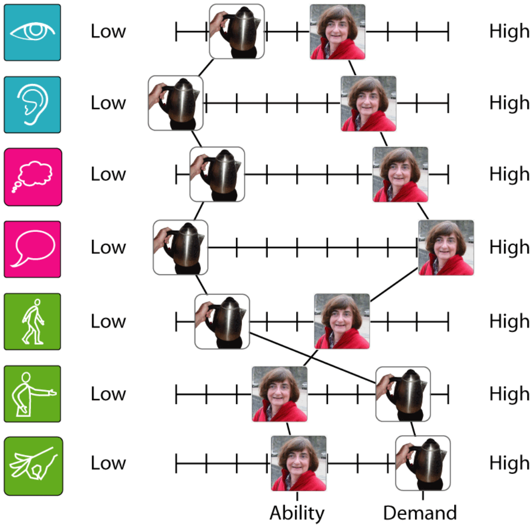

Figure 2 Seven capability categories used to measure a person's capability levels in relation to the level that a product would demand for a successful use, courtesy of University of Cambridge (2011)

In order to achieve a design that successfully can be used by the whole target group an inclusive design approach can be adopted, 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 (Waller et al., 2015). This can be done by focusing on users who have special capabilities, in turn leading to special needs for a successful interaction, e.g. persons with impairments. Another approach to recognise how user needs put requirements on the design 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 valuable input to the design process in form of new ideas and product concepts. Using the approach of lead users or users with special needs both have 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. Nevertheless, a user can have special needs while being an extreme user, e.g. a professional craftsman with a shoulder injury. What these concepts, 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 depend on capabilities of the user. Many of these needs can be connected to physical user characteristics such as vision, hearing, strength, range of motion and body size. Needs can also be connected to cognitive user characteristics such as attention and perception. Cognitive user characteristics can be difficult to measure in a consistent manner but most physical user characteristics 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.

2.1.1 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. To support the use of anthropometric data in product and production development Dainoff et al. (2004) introduced an ergonomic design process consisting of six states:

State 0: *Initial state of the design process*
State 1: *Statement of design problem*
State 2: *Defining target population*
State 3: *Anthropometric databases*
State 4: *Representing body size variability using cases*
State 5: *Transitioning cases to products*

The suggested process is front heavy and requires much analysis work before critical anthropometric cases to the design can be identified. However, for each state of the process, information is distilled and the number of possible test cases is reduced (Figure 3). In State 0 all body dimensions on anyone could be of interest to study while State 4 results in a few selected representative cases with measurement values for the critical body dimensions. One important part of the ergonomic design process is State 3 which deals with collecting useful and representative anthropometric data from databases.

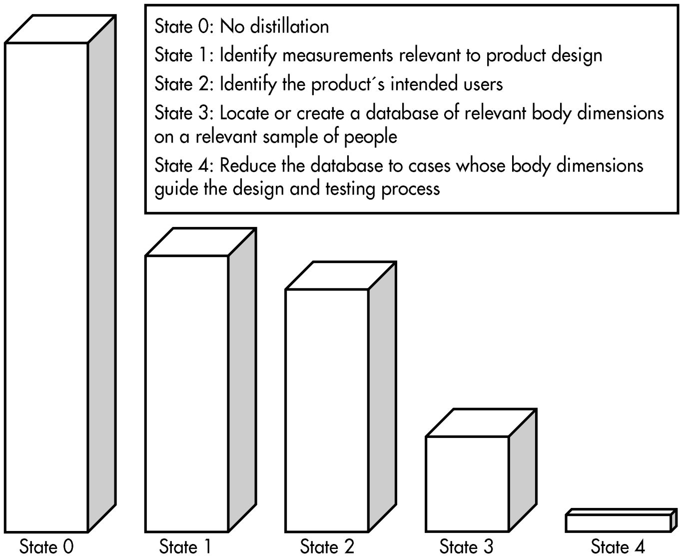

Figure 3 The information distillation process when using anthropometric data in design, adapted from Dainoff et al. (2004)

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 4). These measurements are generally for special situations and can be difficult to measure but are often valuable in the design of products and workplaces.

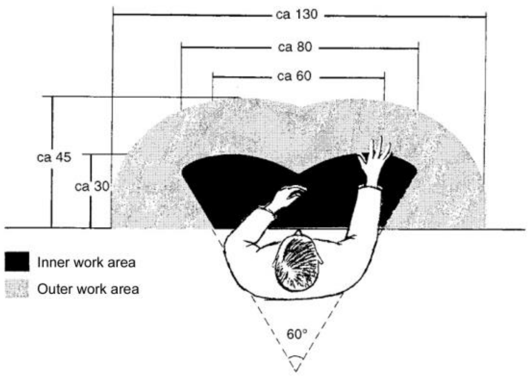

Figure 4 Functional dimensions of horizontal arc of grasp and normal working area, measurements in centimetres (Swedish Work Environment Authority, 1998)

Structural dimensions are measurements between anatomical landmarks defined for standardised postures at rest (Figure 5). 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).

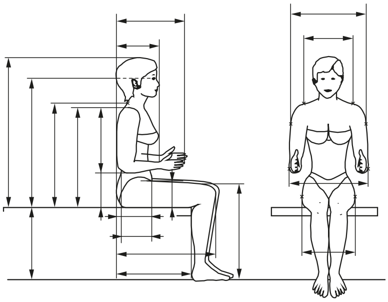

Figure 5 Structural dimensions in predefined static postures (University of Skövde, 2011)

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; PeopleSize, 2008; Hanson et al., 2009b; 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).

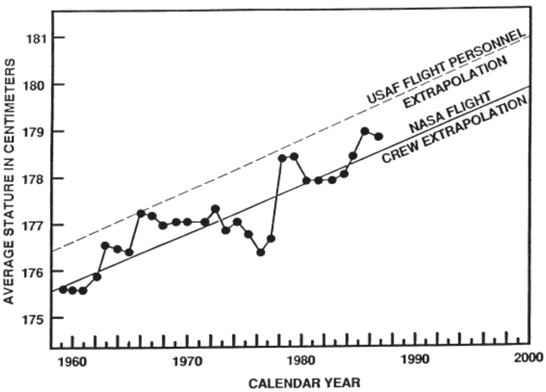

Figure 6 The secular trend here illustrated with increase in average stature for USAF flying personnel and NASA flight crews over a number of years (Chapanis, 1996)

However, data that is more up to date and for civilian populations is often not free of charge. An example of an extensive and relatively recent study is the Civilian American and European Surface Anthropometry Resource (CAESAR) (Robinette et al., 2002). An issue with existing anthropometric data is that surveys sometimes include few subjects or that all necessary measurements are not included, e.g. Hanson et al. (2009b) presents Swedish data on only 39 male subjects for some measurements and no circumference measurements are included. 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 7) (Godil and Ressler, 2009; Hanson et al., 2009b; Robinette, 2012). Still, collecting new anthropometric data is expensive and time-consuming even if such body scanning techniques are used.

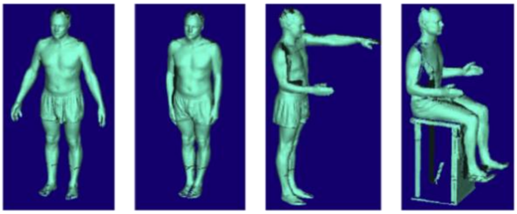

Figure 7 Results of body scanning in four different body postures (Hanson et al., 2009b)

In large ethnic, age and gender separated populations most body measurements can be considered normally distributed (Figure 9). However, body weight and muscular strength often show a positively skewed distribution curve (Figure 9) (Pheasant and Haslegrave, 2006).

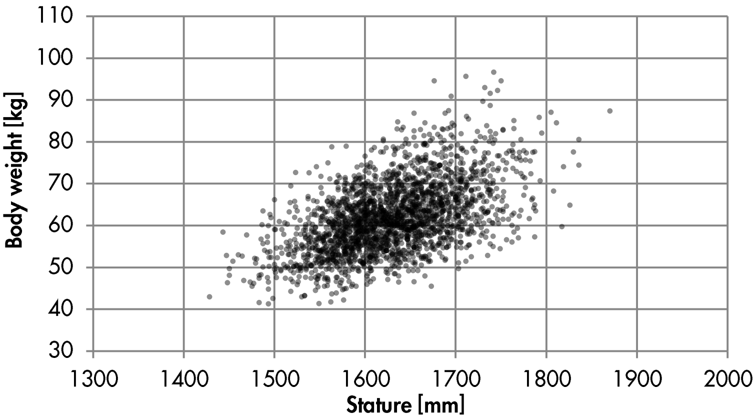

Figure 8 Scatterplot for stature and body weight for women, data from ANSUR (Gordon et al., 1989)

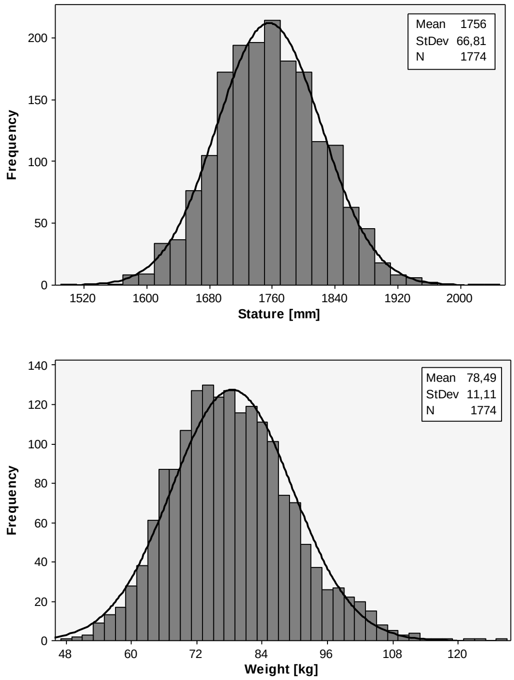

Figure 9 Histogram of stature and body weight for men, data from ANSUR (Gordon et al., 1989)

An additional fact is that the proportions of the human body vary from person to person, e.g. people of average stature are unlikely to 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 plotted and analysed to see how strongly they are connected (Figure 8). Length measurements usually have high mutual correlation and the same can be seen when analysing weight, 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 ergonomics evaluation and analysis (Figure 10) (Moroney and Smith, 1972; Roebuck et al., 1975).

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

	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

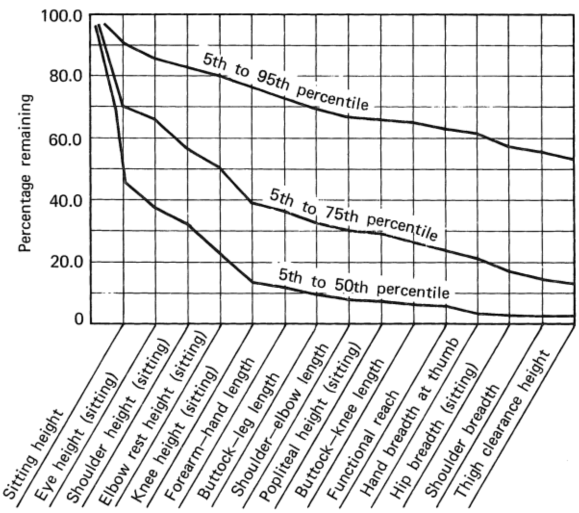

Figure 10 Illustration of decline in accommodation when a serial univariate approach is used in a multidimensional design case (Roebuck et al., 1975)

2.1.2 Multidimensional consideration of anthropometric diversity

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 aspired accommodation level, i.e. the proportion of the population that the design aims to include. The general 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 to accommodate. 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 (Waller et al., 2015). The use of boundary cases is based on the same principle as the identification of extreme users in the approach of inclusive design, i.e. that tests 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 also be used to decrease the risk of missing key areas when using boundary cases. Additionally, the distributed cases approach is more relevant to apply for certain design tasks, e.g. design of clothes (Dainoff et al., 2004; Robinette, 2012).

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 11). 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 12).

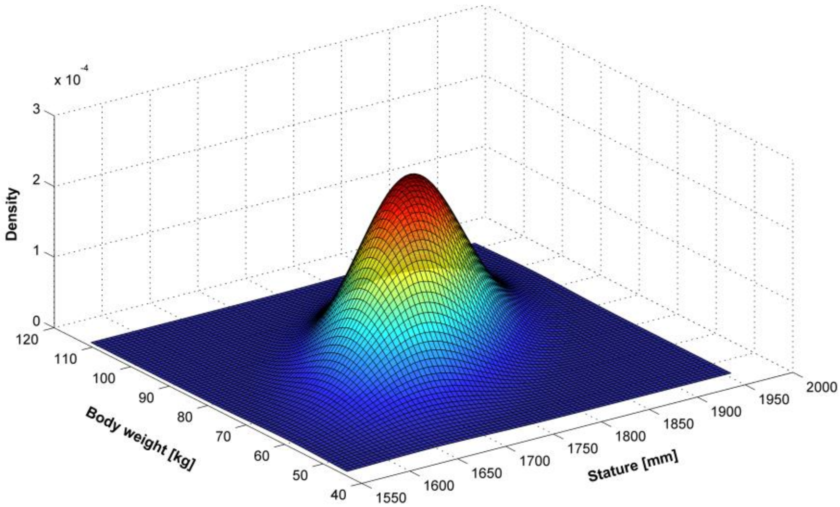

Figure 11 Two dimensional normal distribution for stature and body weight for men, data from ANSUR (Gordon et al., 1989)

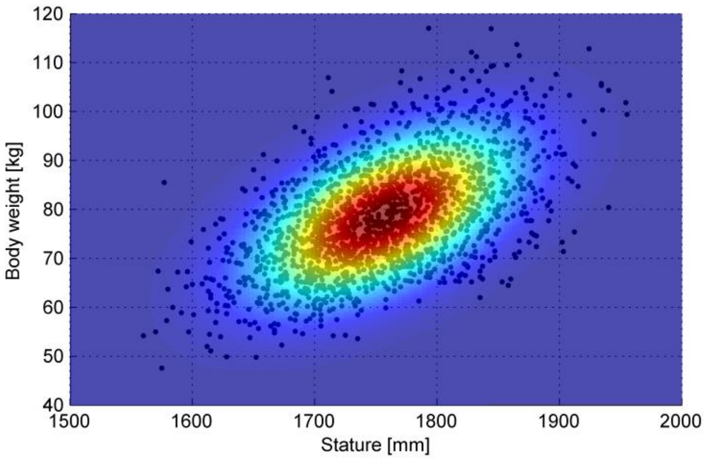

Figure 12 Two dimensional normal distribution for stature and body weight for men seen from above, data from ANSUR (Gordon et al., 1989)

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 confidence region, while retaining as much as possible of the variation in 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 body 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.

2.1.3 Prediction and synthesizing of anthropometric data

Whether anthropometric data is applied directly to design or utilised within a DHM system there is a need for methods to predict and synthesize new anthropometric data that better represents the target population. However, the goals of predictive models vary depending on whether the expected value of an anthropometric measurement is sought or if the need is to predict and synthesize the variance of the anthropometric measurement within the target population. Predicting the expected value of dependent measurements using regression models is an essential part of DHM systems which gives the functionality of creating human models based on a few predictive anthropometric measurements. The number of independent key variables varies from case to case and should be chosen based on relevance to the design problem (Dainoff et al., 2004). Regression models can be seen as black boxes that use input, i.e. predictive anthropometric measurements, to produce output, i.e. a complete set of anthropometric measurements (Figure 13).

Figure 13 The regression model seen as a black box that uses input to produce output

The accuracy of a regression model should therefore be measured by how good the model predicts the unknown measurements, i.e. dependent variables, based on the known predictive anthropometric measurements, i.e. independent variables. A synthesizing procedure can be explained by using data from a detailed sample population to generate regression equations used to predict missing anthropometric population data for a target group (Figure 14).

Detailed sample population

Subject	Stature	Weight	Leg length	Arm length	Hip breadth
1	1652	72	842	340	827
2	1767	84	940	350	844
3	1738	67	950	380	890
⋮	⋮	⋮	⋮	⋮	⋮
n	1760	66	934	395	810

Generation of regression equations

Target population with missing population data

Subject	Stature	Weight	Leg length	Arm length	Hip breadth
1	1796	65	Missing	Missing	Missing
2	1836	74	Missing	Missing	Missing
3	1845	78	Missing	Missing	Missing
⋮	⋮	⋮	⋮	⋮	⋮
n	1787	70	Missing	Missing	Missing

Prediction of missing population data

Synthesized population data

Subject	Stature	Weight	Leg length	Arm length	Hip breadth
1	1796	65	926	399	827
2	1836	74	971	360	887
3	1845	78	976	415	860
⋮	⋮	⋮	⋮	⋮	⋮
n	1787	70	929	380	830

Figure 14 Synthesizing procedure for missing anthropometric population data

Existing methods for predicting missing anthropometric data has previously used either proportionality constants (Drillis et al., 1966) or linear regression with stature and/or body weight as independent variables. However, these so-called flat regression models can make estimations with large errors when there are low correlations between the independent and dependent variables (Gannon et al., 1998; You and Ryu, 2005). You and Ryu (2005) present an alternative hierarchical regression model that uses geometric and statistical relationships between body measurements to create specific linear regression equations in a hierarchical structure. Their results show that using a hierarchical regression model gives better estimates of predicted measurements if more measurements are known and used as input. The hierarchical regression model requires data on measurements highest up in the hierarchy, i.e. stature and body weight to always be included even if these measurements may not have a close connection to the anthropometric dimensions that are to be considered within a certain design task (Bertilsson et al., 2011). In addition, it is not certain that both stature and body weight are included in all anthropometric sources of interest, even if it is the case in most situations. Another issue with the hierarchical regression model is that regression equations need to be constructed manually if a new anthropometric source is to be used, other than the ANSUR data that the regression equations presented by You and Ryu (2005) are based on.

Measurements predicted by using flat or hierarchical regression models will always be the same. This is not the case in human populations, e.g. persons of a specific stature will have different body weights and proportions (Daniels, 1952). Incorporating a stochastic component to retain residual variance of the anthropometric data increases the accuracy of regression models, especially at percentiles in the tails of the distribution (Nadadur and Parkinson, 2010; Poirson and Parkinson, 2014). The hierarchical regression model presented by You and Ryu (2005) has also been further developed to include a stochastic component. This is achieved by using the corresponding sampling distribution for each regression equation (Jung et al., 2009). Combinations of principal component analysis (PCA) and linear regression to synthesize virtual user populations have been shown to further improve accuracy (Parkinson and Reed, 2010). Incorporation of residual variance has also been shown to give accurate results when predicting preferred design dimensions and behavioural diversity of products (Flannagan et al., 1998; Parkinson and Reed, 2006; Garneau and Parkinson, 2011).

2.1.4 Variation of strength and joint range of motion variables

The human-machine interaction is not only affected by the size and proportions of a user but also other user characteristics, e.g. muscle strength and joint range of motion (ROM) (Frey Law et al., 2009). And, as DHM systems become more advanced with sophisticated strength and motion prediction functionality, variables such as joint torque profiles and joint mobility need to be included when establishing the capabilities of computer manikins (Abdel-Malek and Arora, 2009; Hanson et al., 2009a). Several studies has connected variance in strength (Mathiowetz et al., 1985; Frontera et al., 1991; Skelton et al., 1994; Shklar and Dvir, 1995; Lindle et al., 1997; Lynch et al., 1999; Peolsson et al., 2001; Dey et al., 2009; Roy et al., 2009; Dewangan et al., 2010; Aadahl et al., 2011; D'Souza et al., 2012) and flexibility (Walker et al., 1984; Roach and Miles, 1991; Roy et al., 2009; Soucie et al., 2011) to age and sex. The conclusion from these studies is that men and younger people are in general stronger than women and older people. Age has a similar effect on flexibility, with lower flexibility in older populations, but women are in general more flexible than men. However, the differences in flexibility are generally small in both comparisons. Viitasalo et al. (1985); Andrews et al. (1996); Dey et al. (2009) also connected muscle strength to overall body size variables like stature and body weight. Different regression equations for predicting strength variables have been proposed where Andrews et al. (1996) present equations for a number of different arm muscle actions with age, sex and body weight as predictive variables. Hughes et al. (1999) use the same predictive variables to generate regression equations for shoulder strength in eight different shoulder positions. Aadahl et al. (2011) present equations for lower limb extension power and grip strength using sex and age as predictive variables. Both

Lynch et al. (1999) and D'Souza et al. (2012) present equations for elbow and knee peak torque where Lynch et al. (1999) use age and sex as predictive variables and D'Souza et al. (2012) use the respective segment mass in addition to age and sex. The National Isometric Muscle Strength Database (1996) presents equations for 10 different muscle groups on both left and right body size using age, sex and body mass index (BMI) as predictive variables. However, a literature study showed that there is little correlation between body size, strength and ROM (Table 2) (Brolin et al., 2014a). The study also showed that there are few published studies where body size, strength and ROM have been tested all at the same time. An exception is Steenbekkers and Van Beijsterveldt (1998) where data of body size, strength and ROM is connected to age but where the correlations between these groups of variables are also presented. Because the correlation coefficients might be influenced by a common influence of age, the partial correlation coefficients are also presented (Steenbekkers and Van Beijsterveldt, 1998). Melzer et al. (2009) study the association between ankle muscle strength and limits of stability in older adults and present correlation coefficient for the dorsiflexion and plantarflexion isometric strength. Hupprich and Sigerseth (1950) study the specificity of flexibility in girls and present correlation coefficients between measurements of flexibility.

Table 2 Average of correlation coefficients within and between groups of anthropometric variables from studies of body size, strength and range of motion

Source	Body size and strength	Body size and ROM	Strength and strength	Strength and ROM	ROM and ROM
Steenbekkers and Van Beijsterveldt (1998)	0.551 (6)	0.018 (8)	0.742 (1)	0.175 (8)	0.217 (1)
Roy et al. (2009)	N.D.	N.D.	N.D.	-0.123 (24)	N.D.
Andrews et al. (1996)	0.655 (52)	N.D.	N.D.	N.D.	N.D.
Shklar and Dvir (1995)	N.D.	N.D.	0.425/0.653[a] (30)	N.D.	N.D.
Melzer et al. (2009)	N.D.	N.D.	0.520 (1),	N.D.	N.D.
Mathiowetz et al. (1985)	N.D.	N.D.	0.611/0.613[a] (56)	N.D.	N.D.
Viitasalo et al. (1985)	0.341 (10)	N.D.	0.586 (10)	N.D.	N.D.
Hupprich and Sigerseth (1950)	N.D.	N.D.	N.D.	N.D.	0.185 (66)

N.D. = No data available.
In parenthesis: Number of correlation coefficients used for calculating average correlation coefficient
[a] Correlation coefficients for both sexes (female/male)

2.2 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 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 (Siemens, 2011), DELMIA HUMAN (Dassault Systèmes, 2015), RAMSIS (Human Solutions, 2010) and SAMMIE (Marshall and Case, 2009). More recent DHM software are ANYBODY (Rasmussen et al., 2003) and SANTOS (Abdel-Malek et al., 2007), which has been developed during the last decade (Bubb and Fritzsche, 2009). In 2010 research was commenced to develop the DHM tool IMMA (Intelligently Moving Manikins) (Högberg et al., 2016). IMMA uses advanced path planning techniques to generate collision free and biomechanically acceptable motions for digital human models in complex assembly situations, e.g. vehicle assembly. A central ambition in the IMMA development is to make a DHM tool with high usability. This for example means that the tool shall support the tool user to consider human diversity. It shall also be easy to instruct the manikin to perform certain tasks, and there shall be relevant functionality to perform time-dependent ergonomics evaluations to control and assess complete manikin motions (Hanson et al., 2012).

In general, 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. These digital human models, also called computer manikins or just manikins, are changeable and controllable virtual versions of humans (Figure 15). The human models in the DHM tools typically consist of an interior model and an exterior model. The interior model aims to represent the human skeleton and is built up with rigid links connected by joints. The exterior model aims to represent the human 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 muscle models that are included in the simulations and analyses (Rasmussen et al., 2003; Bubb and Fritzsche, 2009). Still, currently only four of the seven capabilities presented in Figure 2 can credibly be evaluated through DHM simulations, i.e. vision, locomotion, reach & stretch and dexterity. Capabilities related to cognitive ergonomics such as hearing, thinking and communication are hard to assess using DHM tools (Thorvald et al., 2012).

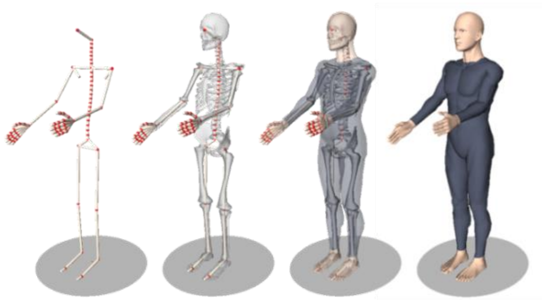

Figure 15 The human model in IMMA consists of an interior and an exterior model

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 (Lämkull et al., 2008; Abdel-Malek and Arora, 2009). Methods for predicting 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 the human body. Physics-based 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, being a mix of both data-based and physics-based methods, do also exist using both data of captured motions and data on joint constraints to predict motions.

Anthropometry is central in DHM systems to meet intended accommodation levels in simulations and analyses, eventually to be offered by the final product or workplace. In DHM tools, human models can typically be created by quickly defining just stature and body 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 consideration of multidimensional anthropometric diversity when performing simulations and evaluations (Bubb et al., 2006). It is often necessary in commercial DHM tools to define measurement or percentile values for specific overall body size variables like stature and body weight to be able to create manikins, even if these measurements may not have a close connection to the anthropometric dimensions that are to be considered within a certain design task. 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, 2012). 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 17) (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 tool focuses on providing anthropometrics and more diverse user data that is accessible, valid and applicable, but also means of utilising the data to assess the accessibility and inclusiveness of design solutions. The method and data in HADRIAN is implemented to work together with 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 16) (Marshall et al., 2010). 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 (a.k.a. personas) to create manikins. To more accurately simulate elderly people the joint flexibility of the manikins are adjusted based on range of motion data.

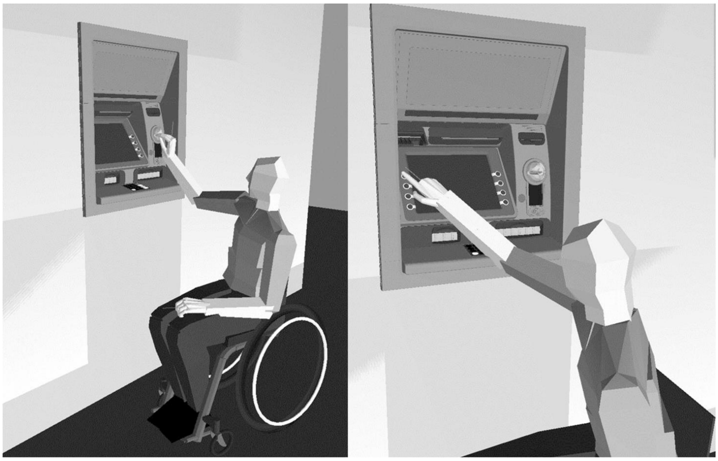

Figure 16 Validation of an ATM being performed in the SAMMIE system in HADRIAN (Marshall et al., 2010)

There are also other areas within the field of DHM development that need further improvement to be able to produce simulations that correctly predict an evaluated task. In simulations of assembly work, 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). Future technological and organizational trends and demands of DHM tools is presented in Wischniewski (2013) through the results of a survey using the Delphi technique. In the survey, 44 experts answered questions and assessed statements regarding upcoming trends in "Digital Ergonomics". Results from the survey show that, among other things, functionality connected to *providing sufficient mapping of anthropometric and biomechanical variance*, and *increased software usability to support software use for novices*, was deemed important and state-of-the-art between 2015 and 2020. Software support for *virtually designing and evaluating products and processes for different regions of the world* was deemed important and state-of-the-art between 2020 and 2025. Important and state-of-the-art after 2025 was considered to be *holistic tools that allows for cognitive, anthropometric and biomechanical evaluation of products and work processes*. Challenges and deficits using DHM tools was, among other things, considered to be *high software complexity, in some cases unknown validity* and *a lack of standard for models and file formats* (Wischniewski, 2013).

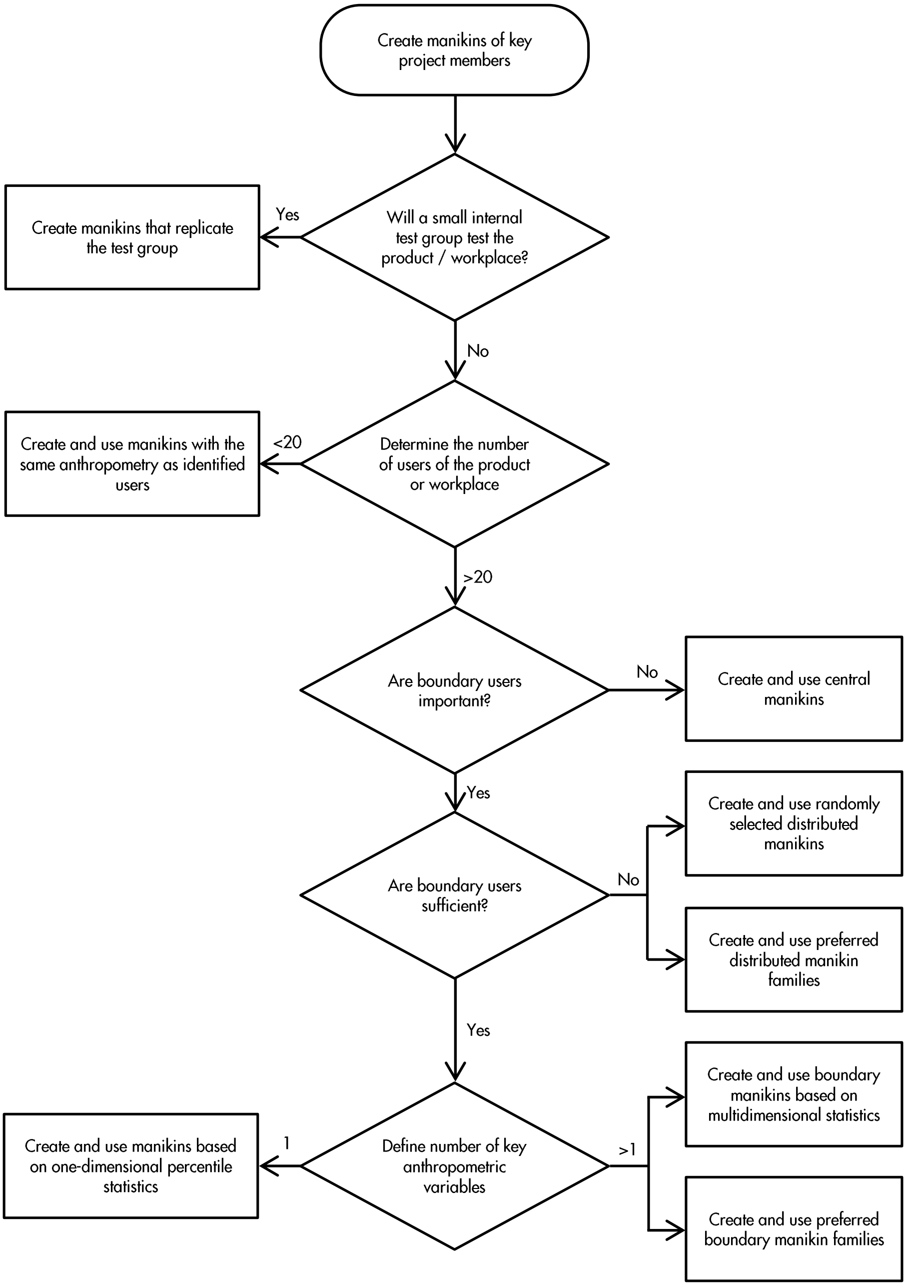

Figure 17 Flowchart as a guide to select user representation method: replicas of identified users, central, distributed or boundary manikins (modified from Dainoff et al., 2004; Hanson and Högberg, 2012)

3 RESEARCH METHODS AND PROCEDURE

This chapter presents definitions of design and design research as well as existing design research frameworks. The research approach of the work in the thesis is described in relation to existing frameworks.

3.1 Design and Design research

As the goal of the work presented in this thesis is to develop methods and tools for anthropometric diversity consideration to assist designers in virtual product and production development projects it is necessary to discuss what differs this work from regular design and development. Blessing and Chakrabarti (2009) make a distinction between design and design research by describing design as *"the process through which one identifies a need, and develops a solution – a product – to fulfil the need"* and design research as *"a process with overall aim to make design more effective and efficient, in order to enable design practice to develop more successful products"*. Horvath (2001) describes design as *"a distinguished discipline since it (i) synthesizes new information for product realization, (ii) establishes quality through defining functionality, materialization and appearance of artefacts, and (iii) influences the technological, economic and marketing aspects of production"* and design research as *"generating knowledge about design and for design"*. Eckert et al. (2003) describe design research as *"inherently multi-disciplinary and driven by the twin goals of understanding designing and improving it – two goals that require very different research methods"*. It seems that design research can be described as having a twofold objective by providing understanding about design regarding methods and procedures but also to suggest improvements by introducing new methods and tools to support the design process. To provide structure and help to achieve more rigour in design research Blessing and Chakrabarti (2009) propose a design research methodology called DRM. Two of the objectives of DRM are to provide a framework for design research and guidelines for systematic planning of research. The DRM framework consists of four stages (Figure 18):

- Research Clarification (RC) which helps clarify the current understanding and the overall research aim,
- Descriptive Study I (DS-I) which aims at increasing the understanding of design and the factors that influence its success by investigating the phenomenon of design, to inform the development of support,
- Prescriptive Study (PS) which aims at developing support in a systematic way, taking into account the results of DS-I and
- Descriptive Study II (DS-II) which focuses on evaluating the usability and applicability of the developed support.

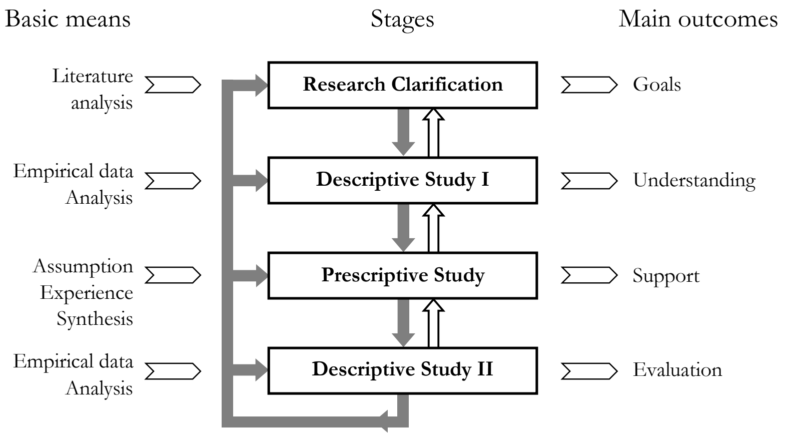

Figure 18 The DRM framework, adapted from Blessing and Chakrabarti (2009)

DRM should not be seen as a set of stages and supporting methods to be executed rigidly and linearly. Multiple iterations within each stage and between stages are possible. Important factors throughout DRM are criteria which are preliminary set in the RC stage and further identified and defined in the DS-I stage. Usually two different types of criteria are identified, *success criteria* and *measurable success criteria*. The success criteria relate to the ultimate goal to which the research project intends to contribute and measurable success criteria serve as reliable indicators of the success criteria when it cannot be used to judge the outcome of the research, given the resources available in the project.

Eckert et al. (2003) propose another design research framework called the *Spiral of Applied Research* (SAR) (Figure 19). This framework argues that applied design research should cover eight distinct types of research objectives (Eckert et al., 2004). The intention of SAR and its eightfold path is to provide a research strategy for a large group of researchers that carries out research over many years. Individual researchers or projects may only cover a few of these eight objectives and can begin with any of these four activities:

- Empirical studies of design behaviour,
- Development of theory and integrated understanding,
- Development of tools and procedures, or
- Introduction of tools and procedures.

During and after each of these four activities, evaluations are supposed to take place to assess important findings which in turn can lead to new research proposals.

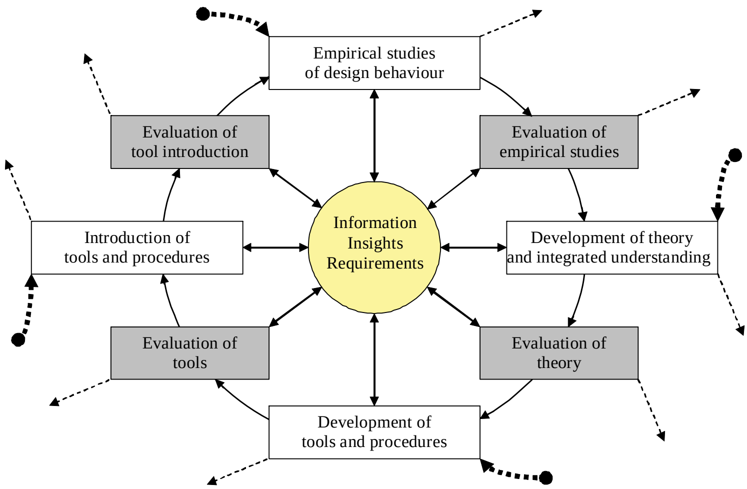

Figure 19 The Spiral of Applied Research (SAR): the eight types of research objectives (Eckert et al., 2004)

Jørgensen (1992) describes a model for how applied research is conducted and is based on a basic system theoretical point of departure. He argues that research can take its origin from either a more problem based approach or a more theory based approach (Figure 20). The approach depends on the order in which the two fundamental and complementary system operations, *analysis* and *synthesis* are performed. However, these approaches are often mixed and combined during a research project (Figure 21). In the procedure suggested by Jørgensen (1992) the two approaches are conducted intertwined and followed by a development activity. This procedure will anchor the research in a practical reality as well as process the resulting research findings into practical applications. The primary research effort is in the synthesis, the formation of a new theory, model structure, a new concept etc.

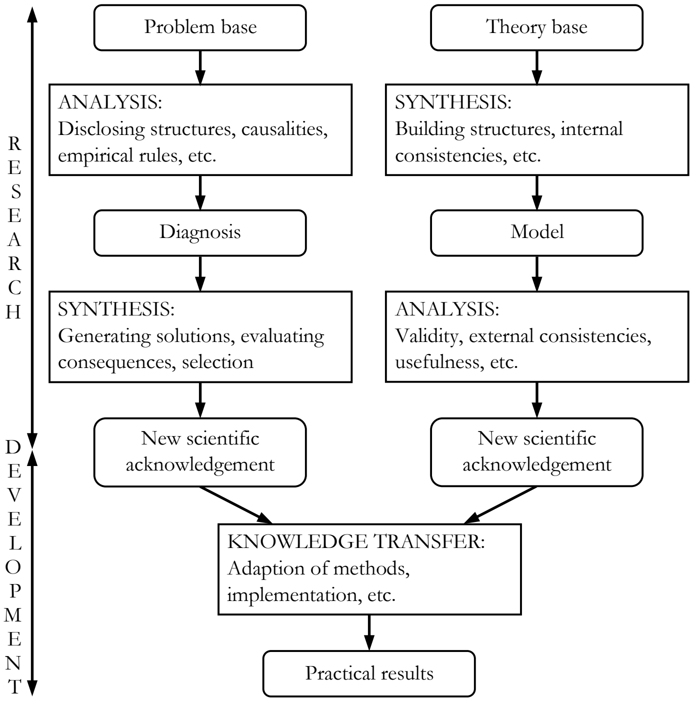

Figure 20 Basic work paradigms for research and development activities, translated and adapted from Jørgensen (1992)

Similar approaches and research frameworks can be found in other areas than engineering such as information systems and information and communication technology (Peffers et al., 2007; Vaishnavi and Kuechler, 2015). It is possible to identify a number of similarities between the design research frameworks suggested by Jørgensen (1992); Eckert et al. (2003); Eckert et al. (2004); Blessing and Chakrabarti (2009). In all of these research frameworks initial research studies are conducted to provide understanding of the research area and subsequent research activities are done to develop theory and models. In addition to these more research intense activities, actual development of tools and procedures are included as a second phase and the introduction of these tools and procedures are the subject of additional research studies. Notable is that the processes of these research frameworks are quite similar and not that different from common product development processes (Pahl et al., 2007; Cross, 2008; Ulrich and Eppinger, 2012). The simple product development process presented by Cross (2008), including the phases: Explore, Generate, Evaluate, Communicate, could for example easily be overlaid on any of the presented research frameworks. The fact that many of the researchers come from the engineering design area has probably affected the research procedures and frameworks. Oates (2006) defines the difference between "normal" design and what she calls design and creation research. Research projects based on design and creation should demonstrate, besides technical skills, academic qualities and must also create some new knowledge. Oates (2006) also presents an evaluation guide for assessing design and creation research which will be reflected on in the discussion chapter. All of the mentioned design research frameworks were considered, modified and used as inspiration to structure the research methodology of the work presented in this thesis.

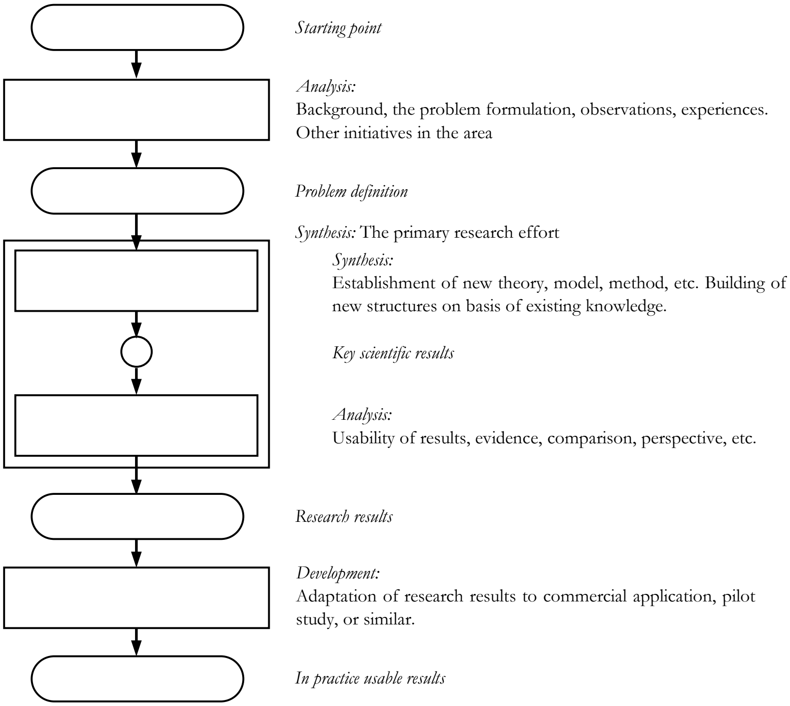

Figure 21 Widely applicable scientific work paradigm, translated and adapted from Jørgensen (1992)

3.2 Research approach

The work presented in this thesis has been done within bigger research projects including close collaboration with industry partners, both developers and users of DHM tools. The research started jointly with the commencement of the development of the IMMA DHM tool (Hanson et al., 2010). Within this project a specific work package considered anthropometric diversity with the purpose:

> *To review anthropometric diversity methods available and modify one method to also include other physical characteristics, such as diversity in range of joint motion, which also effects motion behaviour. A user friendly graphical interface, for the specification*

of the characteristics of the target population, is developed as well as a method that proposes a set of manikins that consider human diversity

Project plan for the Pro Viking project IMMA (2009)

Additional projects have followed upon the IMMA project which ended in 2013. The subsequent projects have increased the focus on additional diversity such as within strength and joint-range of motion (CROMM, 2014) and also on human diversity in the field of occupant packaging (Virtual Driver, 2015). Figure 22 shows the utilized research methodology, inspired by the procedure suggested by Jørgensen (1992), and how it relates to the research questions and appended papers.

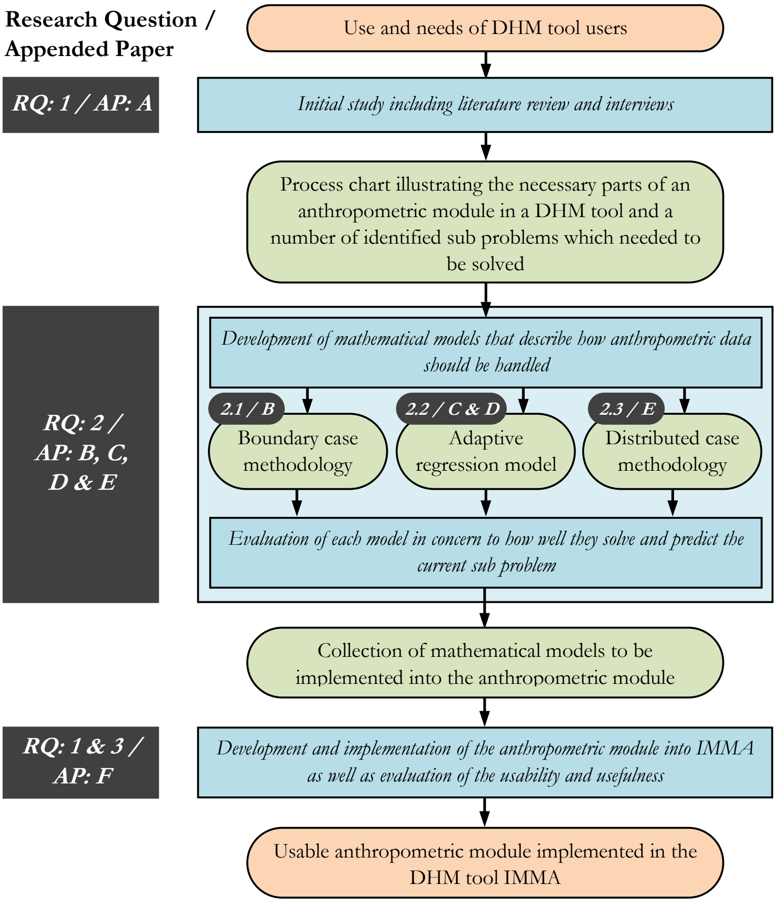

Figure 22 The applied research methodology and how it relates to the research questions (RQ) and appended papers (AP)

To fulfil the purpose of the research project the research process has taken its point of departure in the state of current methods and DHM tools and the use and needs of DHM users. To get a better understanding of the field an introductory empirical study was performed similar to the *Descriptive Study I* (Figure 18) in Blessing and Chakrabarti (2009), *Empirical studies of design behaviour* in Eckert et al. (2003) and the initial analysis activity in Jørgensen (1992). 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. This initial study answered the first research question about the current use of DHM tools and existing methods for consideration of anthropometric variation. A result from the initial study was a plan and process chart illustrating the necessary parts that needs to be included in an anthropometric module in a DHM system (Figure 23).

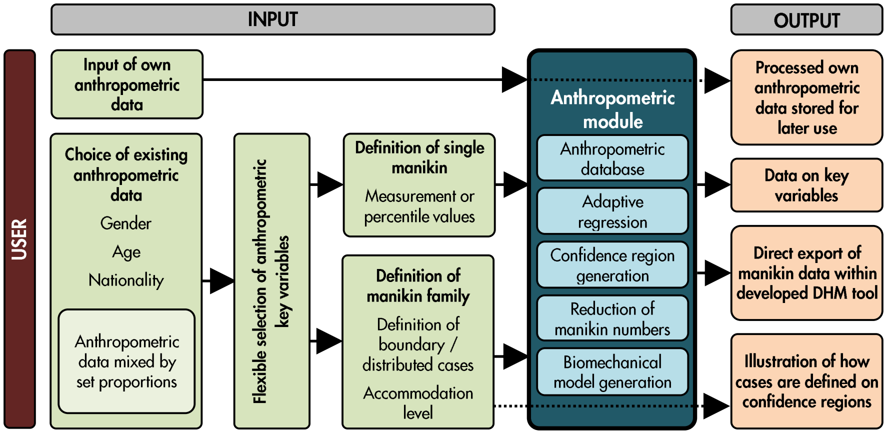

Figure 23 Process chart illustrating the necessary parts of an anthropometric module in a DHM tool

From this plan and process chart a number of sub problems could be identified which needed to be solved in order to get a complete functioning anthropometric module and also to be able to answer the second research question about how mathematical models and methods can increase the accommodation accuracy for a design and a defined target group. Each sub problem was connected to one of the sub research questions 2.1-2.3 and was dealt with in similar manners including literature studies, collection of anthropometric data, evaluation of existing mathematical and statistical methods, and application of these methods to anthropometric data. For each sub problem mathematical models that describe how anthropometric data should be handled were constructed and evaluated in concern to how well they solved the current sub problem. This phase matches with the *Prescriptive Study* in the DRM framework (Figure 18), the objective *Development of theory and integrated understanding* in the SAR framework (Figure 19) and the synthesis activity in the applied research framework (Figure 20 and Figure 21).

The mathematical models for most sub problems were combined into a complete system which corresponds to the initial plan and process chart of the anthropometric module (Figure 23). The interface as well as the content of the complete system was evaluated in regard to usability and accuracy in predictions, and deficient mathematical models were improved based on the results from the analysis of the complete system. When the functioning complete system was achieved an overarching evaluation could be done answering the last and third research question regarding how the implementation of mathematical models can be done to meet the needs of DHM tool users similar to the *Descriptive Study II* in the DRM framework (Figure 18), the objectives *Development of tools and procedures* and *Evaluation of tools* in the SAR framework (Figure 19) and the development and knowledge transfer activities in the applied research framework (Figure 20 and Figure 21).

3.2.1 Presentation and dissemination of research

Throughout the research process results from the initial study as well as mathematical models and implementation concepts have been presented to other researchers at several scientific conferences (Table 3). These assessments of the research, regarding both aim and methodology, have been done to provide valuable input to the process and verify its quality.

Table 3 Presentation of the different studies at scientific conferences

Conference	Year	Research question & type of study
AHFE *(Applied Human Factors and Ergonomics)*	2010	**RQ 1:** Initial literature study
NES *(Nordic Ergonomics Society)*	2010	**RQ 1:** Initial interview study
DHM *(Digital Human Modeling Symposium)*	2011	**RQ 2.1:** Boundary case methodology
ICPR *(International Conference on Production Research)*	2011	**RQ 3:** Development and implementation
NES *(Nordic Ergonomics Society)*	2012	**RQ 2.1:** Boundary case methodology
DHM *(Digital Human Modeling Symposium)*	2013	**RQ 2.2:** Adaptive regression model
DHM *(Digital Human Modeling Symposium)*	2014	**RQ 2.3:** Distributed case methodology
AHFE *(Applied Human Factors and Ergonomics)*	2014	**RQ 3:** Development and implementation

3.3 Methods and procedures of contributing papers

The research process includes a number of different methods and procedures to gather and analyse data (Table 4). The results of Paper A are based on a literature and interview study. Paper B, C, D and E include literature studies, mathematical modelling, and statistical evaluations. Paper B also includes DHM simulations to evaluate the suggested method. Paper F bases its results on the implementation activities of the previously created mathematical models as well as an interview study and usability tests.

Table 4 Methods and procedures of contributing papers

Paper	Interviews	Mathematical modelling	DHM simulation	Statistical evaluation	Implementation	Usability test
A	X					
B		X	X			
C		X		X		
D		X		X		
E		X		X		
F	X				X	X

3.3.1 Interviews

In Paper A, nine qualitative, semi-structured interviews (Howitt and Cramer, 2011) were conducted to get an understanding of different methods and approaches when working with anthropometric diversity in today's automotive industry in Sweden. In total sixteen participants, who worked with either product or production development, were interviewed. Their work positions varied from machine operators to simulation engineers with an up to date expertise of DHM system and also people with more overall responsibility for virtual manufacturing and simulation. The interview questions covered topics such as the use of DHM tools, anthropometric databases and creation of manikins, key anthropometric variables, pros and cons of current DHM tools as well as suggestions for improvements. The interviews were audio recorded and notes were taken. The result from the interviews was analysed and a comparison between product development and production development was done.

In Paper F, the developed anthropometric module and its interface was evaluated to assess if it matches the needs and if it would fit into the work process used by DHM tool users. Focus group interviews (Howitt and Cramer, 2011) were done at three product development departments within the Swedish automotive industry to verify the results found in Paper A and to gain a deeper understanding of the manikin creation process currently used in industry. In total eight persons participated in the focus group interviews which consisted of discussion and identification of current work procedures and wanted functionality of DHM tool users. The focus group interviews were documented through audio recordings and notes.

Because the interviewed companies in Paper F also were interviewed in Paper A, it was possible to do a comparative longitudinal analysis across these studies. The interviewed participants were not the same at two of the three companies but it was still possible to do a comparison of the work procedure and utilized methods.

3.3.2 Mathematical modelling

A significant part of Paper B, C, D and E consists of development of mathematical models to handle anthropometric data. These developments were similar including literature studies where possible models were evaluated in terms of functionality and applicability for implementation into DHM tools. Based on these evaluations new mathematical models that describe how anthropometric data should be handled were constructed, evaluated and improved. The method for calculating confidence regions in Paper B was adopted from literature regarding linear algebra (Lay, 2006) and multivariate statistical analysis (Johnson and Wichern, 1992; Sokal and Rohlf, 1995; Brandt, 1999; Myers et al., 2009) as well as PCA (Jolliffe, 2002).

Paper C and D together describe the development of an adaptive linear regression model for prediction of missing anthropometric data. This model is based on a conditional linear regression model using multivariate statistical analysis (Johnson and Wichern, 1992) but also includes use of PCA (Jolliffe, 2002) to consider issues of multicollinearity between selected independent measurements. The difference between Paper C and D is that Paper C describes a model that predicts the most expected values for unknown variables while Paper D describes an extended model for synthesizing of anthropometric population data including incorporation of a stochastic component to retain residual variance of the anthropometric data.

Paper E describes a study where the synthesizing process in Paper D is applied to more diverse anthropometric variables such as strength and flexibility (Steenbekkers and Van Beijsterveldt, 1998). A synthesized population of 10000 individuals with values for 14 variables, in addition to sex and age, was subsequently used in cluster analyses (Everitt et al., 2011) where identified cluster centres determined unique distributed cases.

3.3.3 DHM simulation

In Paper B different manikin test groups were defined based on four different approaches which compared the so called percentile approach to confidence regions in two and three dimensions as well as the use of PCA to reduce the dimensionality of confidence regions (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 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 (Figure 24) (Siemens, 2011).

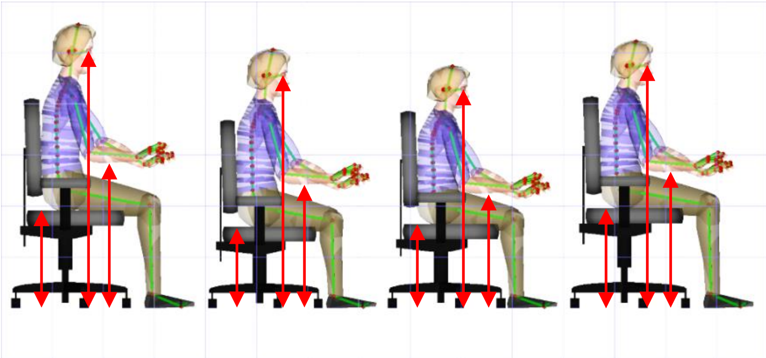

Figure 24 Manikins in seated posture with distances measured for the design dimensions seat height, table height and eye height

3.3.4 Statistical evaluation

To quantify the accuracy and usefulness of the different mathematical models, statistical evaluations were done where different measures were quantified. Paper C and D used a similar setup for the evaluations which were performed using the ANSUR anthropometric data (Gordon et al., 1989). In the analyses sex was treated separately by creating specific regression equations for each sex. 56 anthropometric measurements (Appendix 1) were included in the analyses and four comparative scenarios were created where the number of independent variables varied for each scenario.

In Paper C two evaluation tests were performed where the accuracy of the regression models were evaluated by assessing the coefficient of determination, R^2 and the root-mean-square deviation (RMSD). In the first test the adaptive regression model, including conditional regression and principal component regression, was compared with a flat regression model based on stature and body weight (Drillis et al., 1966) and a hierarchical regression model that uses geometric and statistical relationships between body measurements to create specific linear regression equations in a hierarchical structure (You and Ryu, 2005). The second evaluation test was constructed to evaluate the impact of sample size on the accuracy of the predicted values and the equations' accuracy in predicting values for individuals that are not within the test sample. This test was evaluated using only the adaptive regression model including conditional regression and principal component regression because the flat and hierarchical regression models were not applicable in the assessment procedure of the second evaluation and also due to the results from the first evaluation.

Paper D, which assessed the regression model's accuracy in synthesizing anthropometric population data, used an evaluation test similar to the second test of Paper C. However, it was not possible to use the same measures as in Paper C, for assessing the accuracy of the regression model. Instead, as the incorporation of a stochastic component is done to retain residual variance of the anthropometric data, the accuracy was evaluated by calculating the root-mean-square deviation (RMSD) of the 5th, 50th and 95th percentiles of the synthesized populations compared to the percentiles of the control group.

In Paper E three clustering algorithms were evaluated by assessing the test cases they suggested and how well these test cases represented the diversity of the synthesized population. The evaluation, which consisted of calculating and comparing a number of quantitative measures, was repeated for 1000 runs to get an average result for different synthesized populations and more sound conclusions. Some of these quantitative measures were also assessed visually for a number of the synthesized populations in the 1000 runs. Additionally, visual assessments were done where the suggested cases and the synthesized individuals were plotted together for some of the synthesized populations.

3.3.5 Implementation

The development of the anthropometric module took its departure from methods, guidelines and suggested work procedures presented in literature (Meindl et al., 1993; Speyer, 1996; Dainoff et al., 2004; Hanson et al., 2006) as well as findings from studies of current use of DHM tools presented in Paper A and the identified gap in between these two. This initial study had led to the generation of the previously presented process chart of an anthropometric module in a DHM tool (Figure 23). To support the structure given in existing guidelines the developed interface was based on the five states of the ergonomic design process presented by Dainoff et al. (2004). The module's user interface was divided into different sections where each section is intended to match a state in the ergonomic design process. To achieve the intended usability the different functions were structured throughout the interface in the same order as they would typically be used in an ergonomics design analysis. Most of the functionality of the interface was connected to either creating single manikins or manikin families. The divided parts for creating single manikins and manikin families were developed to have similar structure and also share some functional elements.

3.3.6 Usability tests

The second part of the evaluation in Paper F consisted of usability tests of the developed interface together with questionnaires regarding the user experience. To evaluate possible usability issues four scenarios were generated to facilitate usability testing by simulating realistic events. The first three scenarios were based on example cases of how DHM tools can be applied in different design settings and for different design undertakings, focusing on user variation in anthropometry presented by Hanson and Högberg (2012). The fourth scenario was based on additional needs presented in Paper A related to the possibilities to rescale a population to better fit the target group and to implement anthropometric data, measured on individuals in the target group of interest, into DHM systems. In total 10 participants performed the usability test but due to time limitations for the usability tests at the companies one participant was able to perform only the first two scenarios, whereas the other nine participants performed all four scenarios. Both quantitative (time to complete specific tasks, counts of actions and rate of errors) and qualitative data (subjective ratings, comments, thoughts and identified behaviour) were collected during the usability tests to provide a more complete understanding of possible issues (Creswell and Clark, 2007).

4 RESULTS

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

4.1 Paper A: Use of digital human modelling and consideration of anthropometric diversity in Swedish industry

The aim of the paper was to study the use of DHM tools and consideration of anthropometric diversity in the Swedish automotive industry. This was done through an interview study at five production development departments and four product development departments. Consequently, another objective was to compare the use of DHM systems in product development with the use in production development. Thus, the paper addresses the first research question of this thesis and the results can be summarized as follows:

- DHM tool users often employ rough approaches for considering anthropometric diversity.
- Product development departments have in general better work procedures when working with DHM tools and anthropometric diversity, compared to production development departments.

4.1.1 Use of digital human modelling and consideration of anthropometric diversity

Overall, most analyses done with DHM tools aim at situations where reach and clearance can be a problem. Interviews showed that used methods and work processes generally were in a development phase and not fully evolved. Several companies did not use DHM tools; instead they used anthropometric data directly from tables or analysed ergonomic problems with video recordings. The video analyses were done with one person randomly selected from the work personnel or at best two persons; one long and one short person. According to the interviews, a DHM tool needs to be fast and easy to use. It should be possible to rapidly scale a manikin in order to see how a work position will affect a person with other body dimensions. A wanted function is the possibility to rescale a population to better fit the target group. Using a simulation system should lead to better quality with the same work effort and the results need to be trustworthy. The interviewed persons believe that using DHM tools give the opportunity to work with "active" development where it is possible to redefine a product or workplace based on simulation results. The possibility to early evaluate solutions without creating a physical mock-up reduces costs and development time.

The analyses done in the DHM systems are currently often combined with guesswork based on simulation results and self-knowledge to produce result for the rest of the population. This fact is due to the slow and difficult process when manually positioning manikins. To cover all intended users a large part of the departments use a very rough strategy involving one or two manikins based on stature percentiles. The goal can be that the biggest male (95th percentile in stature) and the smallest female (5th percentile in stature) should be able to do the task. Another approach is that a woman of the 50th percentile stature should be able to reach the work area. It is not unusual that even these objectives are not possible to fulfil and if that happens studies are done to expose what is possible to achieve depending on the workstation. The reason for these simplified solutions is the time-consuming processes when working with several manikins, even if good features exist to assist in the positioning of a manikin.

In contrast to this rough strategy with few manikins, there were also some departments that used a more refined approach on the problem and used manikin families. These manikin families were based on Speyer (1996), which contains twelve human models supposed to cover anthropometric diversity within the target population. Another solution was to define the population and target groups in the beginning of a project and based on that data five stature and body weight percentile manikins were created to cover the extremes of that population. These five manikins are then used during the whole project time.

4.1.2 Difference between production and product development departments

The use of DHM simulation systems varied a lot, both between different companies but also within the companies when comparing product development departments to production development departments. A common case was that the product development departments had come further in their work with DHM systems, particularly in respect to consideration of anthropometric diversity. Most production development departments had recently started to work with DHM systems or was about to do so soon. Product development departments had in contrast described work procedures for DHM tool use and had in some cases also done clinics to verify the results of DHM simulations with real persons doing the same tasks as the simulated manikins. Three of the interviewed product development departments had also taken measurements on individuals in specific target groups of interest.

4.2 Paper B: 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 principal component analysis (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. The paper provides answers to the second research question and specifically sub research question 2.1 and the contribution can be summarized as:

- The boundary case method which creates a confidence region for a number of selected variables and defines a number of manikins supposed to cover an intended accommodation level is clearly described and exemplified.
- If the design of a product or workplace will be influenced by many bodily dimensions it is suggested that all anthropometric measurements of interest are included in the study.
- If there is a need to reduce the number of manikins PCA can be used to reduce the dimensionality of the created confidence regions and thus the number of manikins.
- The proposed boundary case method is advantageous compared to approaches based on the use of univariate percentile data in design.

4.2.1 Description of mathematical procedure of the boundary case method

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 the 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.

4.2.2 Use of principal component analysis to generate boundary cases

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 discarding minor PC so that the remaining PC contributes to the desired degree of explanation of variation of the original data. A confidence region is then defined based on the remaining PC and values for the desired number of boundary manikins are calculated on the border. The PC values of each manikin are translated to actual body measurement values defined in standardised normal scores using the eigenvectors of the remaining PC. The standardised normal scores are converted to real measurement values by multiplication with the standard deviation and thereafter adding the mean value for the corresponding anthropometric measurement.

4.2.3 Comparison of proposed method and use of univariate percentile data

The evaluating simulation showed that the proposed confidence region approach is advantageous compared with the approach, here named *percentile approach,* where key dimensions are set to a specific percentile value. In the first example the evaluated manikins were defined from two key measurements, chosen as stature and sitting height. The confidence ellipse approach gives more extreme, but still realistic cases, than the percentile approach (Figure 25). The ellipse theoretically encloses 90% of the individuals, whereas the square area, formed by the 90% confidence intervals for each dimension separately, 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.

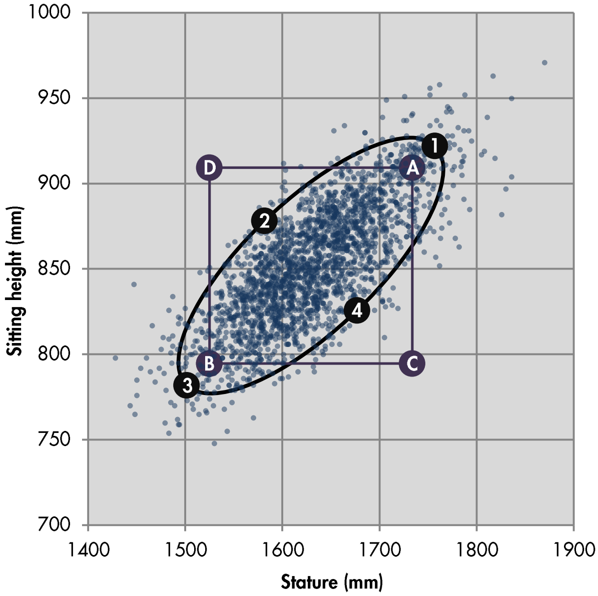

Figure 25 The bivariate 90% confidence ellipse as well as the square region shaped by the two univariate confidence intervals

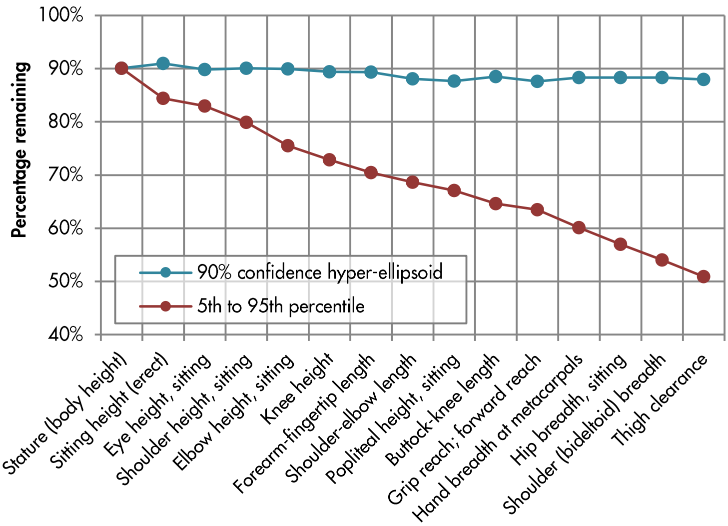

Figure 26 Illustration of decline in accommodation when comparing the confidence hyper-ellipsoid method and the 5th to 95th percentile method for men, data from ANSUR (Gordon et al., 1989) (Figure inspired by Roebuck et al. (1975))

The comparison can be extended to even more dimensions, using more key anthropometric variables, by calculating the number of measured individuals that are found inside, thus being considered accommodated, a generated multidimensional hyper ellipsoid as well inside a multidimensional hyper cuboid based on the 5th and 95th percentile value for the selected key variables. The percentile approach shows identical behaviour as presented by Roebuck et al. (1975) with a rapidly reduced percentage inside the hyper cuboid while the confidence region in the form of a hyper ellipsoid almost covers the intended accommodation level (Figure 26).

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. 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 27).

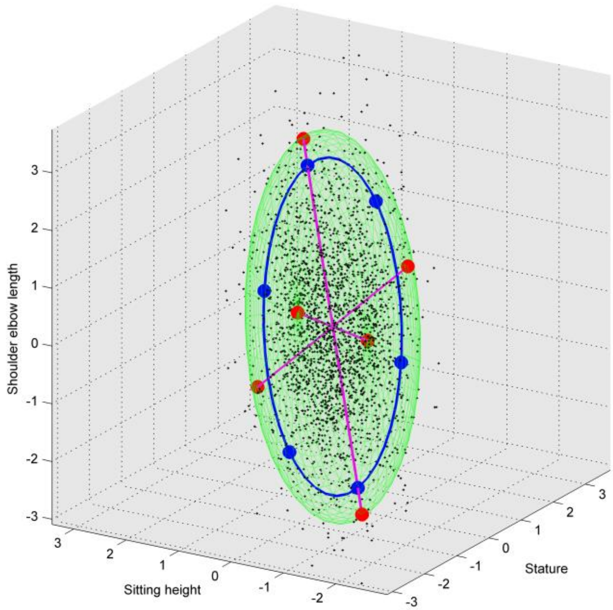

Figure 27 A three dimensional 90% confidence ellipsoid as well as boundary cases at the axial end points of the ellipsoid and in the direction of the first and second principal component (scales in standardised z-score)

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 28. 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.

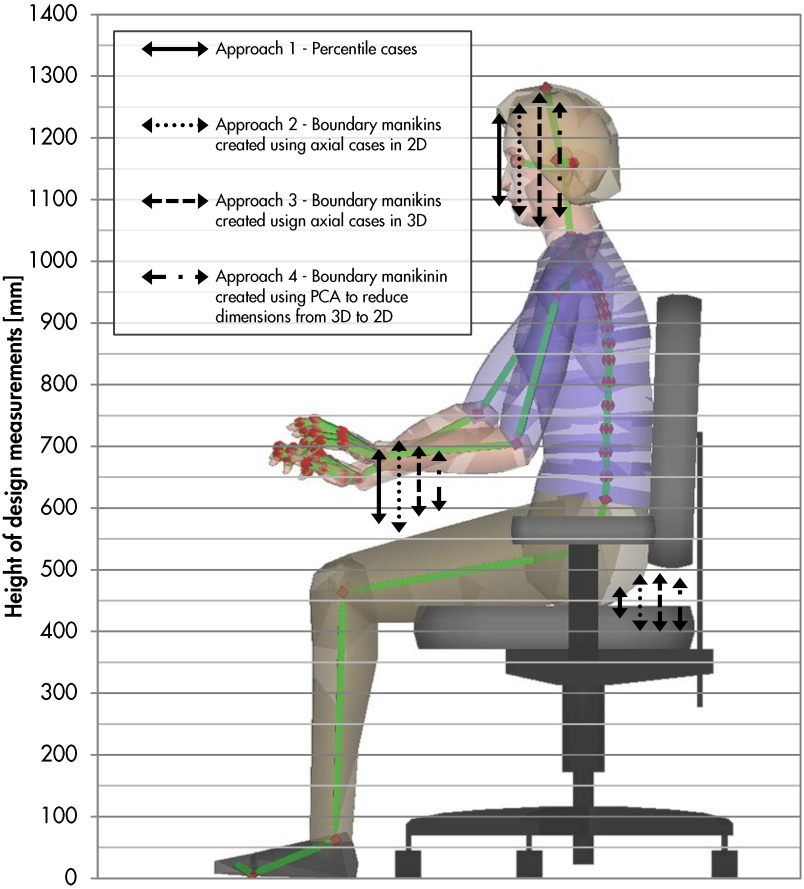

Figure 28 Results from simulation in the DHM tool Jack 7.1 for the four test groups

4.3 Paper C: Adaptive regression model for prediction of anthropometric data

Paper C presents and evaluates an adaptive linear regression model for prediction of anthropometric data. The developed model was evaluated by assessing the accuracy of the predicted values for the dependent measurements and compared to a flat regression model (Drillis et al., 1966) and a hierarchical regression model (You and Ryu, 2005). An additional evaluation test was carried out to observe how the regression model performs depending on sample size and the equations' accuracy in predicting values for individuals that are not within the test sample. The paper provides answers to the second research question and specifically sub research question 2.2 and resulted in the following:

- Using an adaptive regression model that makes use of all known variables to predict the values of unknown measurements is advantageous compared to the flat and hierarchical regression models
- The accuracy of the regression model due to the sample size increases logarithmically.
- Apart from the sample size, the accuracy of the regression model is affected by the number of, and which, measurements that are selected as independent variables.
- Principal component regression should be used when there is a risk of multicollinearity between the independent variables, i.e. when the sample size is small and several measurements are selected as independent variables.

4.3.1 Adaptive regression compared to flat and hierarchical regression

The results where the predicted results were assessed for the same individuals that were used to generate the regression equations show that the adaptive regression model achieved higher accuracy than the flat and hierarchical regression models (Figure 29).

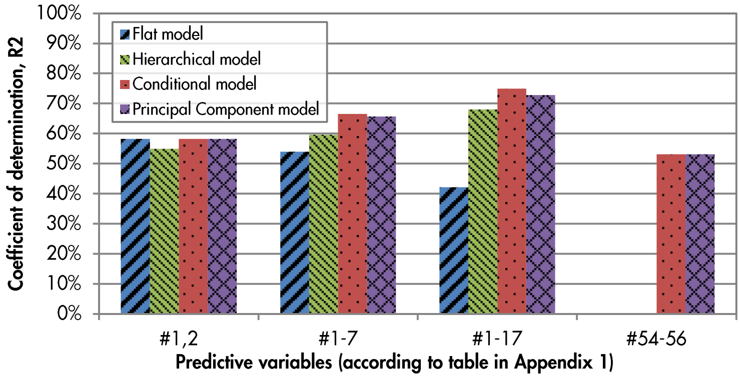

Figure 29 Graph illustrating the evaluation of the R^2 value for the dependent variables based on the results from the four different scenarios *(Higher value indicates higher accuracy)*

Both the hierarchical regression model and the adaptive regression model have the advantage that when more measurements are included the models will give a better prediction of the unknown measurements compared to the flat regression model based on two variables, stature and body weight. An adaptive regression model has the additional advantage that any measurement can be used as an independent variable which is shown in scenario 4 where the flat and hierarchical regression models were unable to produce any predictions.

4.3.2 External accuracy and effect of sample size

The results where the sample size used to construct the regression equations varied, show that the regression models accuracy depended both on how many measurements that were used as independent variables but also on the sample size that the regression equations were based on (Figure 30 and Figure 31). Higher accuracy was always achieved when the sample size was increased. Higher accuracy was also achieved in most cases when the number of measurements used as independent variables was increased. However, scenario 4, with three independent variables showed lower accuracy compared to scenario 1 with only stature and body weight used as independent variables. This shows that it is possible to gain higher overall accuracy if measurements that better explain the total body size are selected.

Conditional regression have, compared to principal component regression, troubles handling issues with multicollinearity when the number of independent variables is higher and the sample size is small. Nevertheless, when the sample size increases conditional regression performs slightly better than principal component regression. The intersection points between the two regression methods when assessing the coefficient of determination seems to be around 100 individuals (Figure 30 and Figure 31). This indicates that if the regression equations were to be based on fewer than 100 individuals, principal component regression should be used. It can also be argued that principal component regression should always be used as there is no significant difference between the two regression methods when the sample size is larger. The prediction of female data has an overall lower accuracy compared to the prediction of male data if the coefficient of determination is assessed. This indicates that there is lower correlation between measurements in the female data. However, if the root-mean-square deviation is assessed there is little difference as the lower correlation in the female data is offset by the greater variance in the male data.

Another result from the study is that the increase in accuracy based on the sample size increases logarithmically with an initial rapid increase flattening out after 256 individuals (Figure 30 and Figure 31). This suggests that an anthropometric database should contain at least 250 individuals of each sex if regression equations will be based on the data. However this number might vary if the source data is significantly different from the target population in terms of age, ethnicity and other variables.

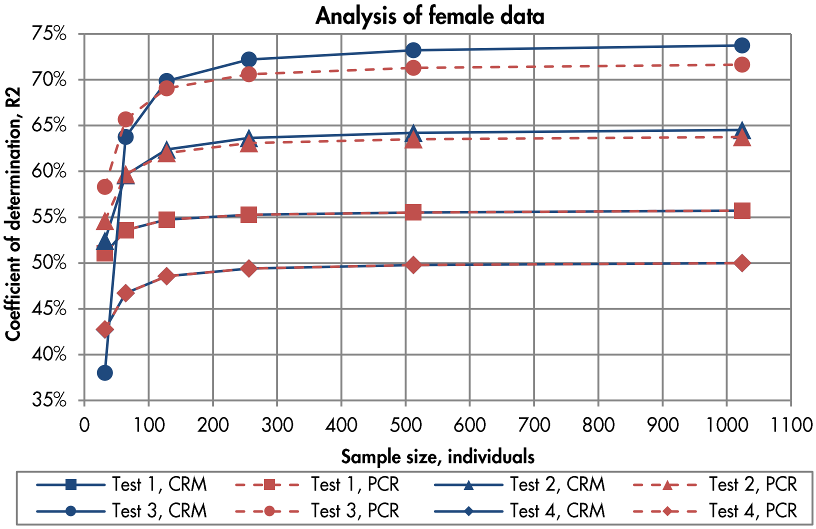

Figure 30 Graph illustrating the evaluation of the R^2 value for the dependent variables based on the results from the four different tests for female data (Higher value indicates higher accuracy) *CRM = Conditional regression, PCR = Principal component regression*

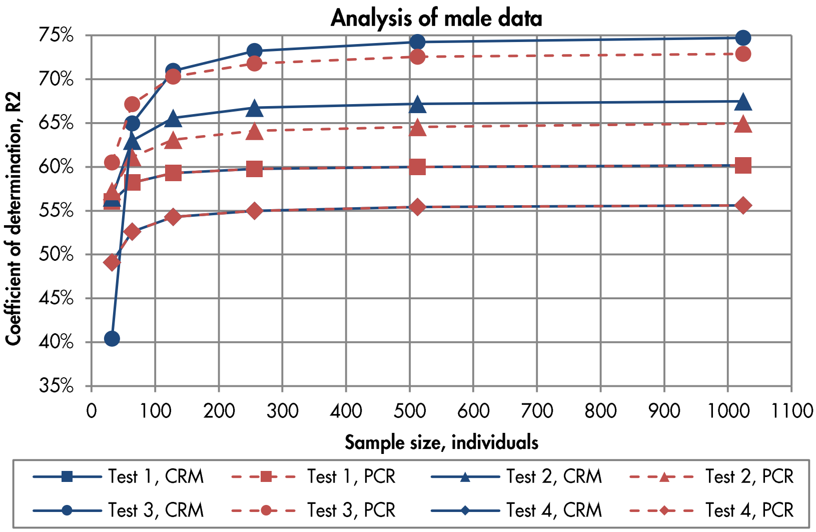

Figure 31 Graph illustrating the evaluation of the R^2 value for the dependent variables based on the results from the four different tests for male data (Higher value indicates higher accuracy) *CRM = Conditional regression, PCR = Principal component regression*

4.4 Paper D: Adaptive regression model for synthesizing anthropometric population data

Paper D presents and evaluates an extension of the adaptive linear regression model in Paper C which in Paper D is extended to also synthesize anthropometric population data by incorporating a stochastic component. As Paper C the paper provides answers to the second research question and specifically sub research question 2.2 and resulted in similar results which can be summarized as:

- The proposed adaptive regression model for synthesizing population data gives valid results with small errors of the compared percentile values if the sample size is high.
- The proposed adaptive regression model gives the possibility to utilize anthropometric data sources even if measurements are missing as they can be predicted and synthesized.
- Principal component regression is preferable to use as there often is a risk of multicollinearity between the independent variables, especially when the sample size is small. Conditional regression can be used on data based on sample sizes larger than 128 subjects.
- Descriptive statistics such as mean and standard deviation values together with correlation coefficients is enough to perform the conditional regression procedure. However, principal component regression that includes incorporation of a stochastic component requires raw data on an individual level.

4.4.1 Accuracy for synthesizing anthropometric data

The study showed similar results as the results from test 2 in Paper C where the accuracy of the adaptive regression model depends both on the sample size and the number of independent variables. As in Paper C the conditional regression showed lower accuracy when the number of independent variables is higher and the sample size is small. Nevertheless, the performance of conditional regression increased when the sample size increased. The performance of the conditional regression is about equal to the principal component regression model for samples containing 128 or more subjects. As in Paper C, the increase in accuracy based on the sample size increases rapidly in the beginning but tends to flatten out after 256 individuals (Figure 32-Figure 35).

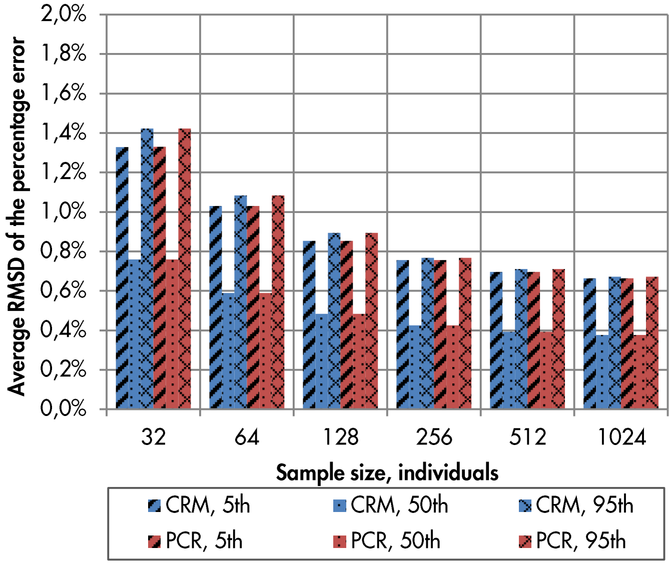

Figure 32 Graph illustrating the evaluation of the average RMSD of the percentage error for the prediction of percentiles for the dependent variables in scenario 1 (Lower value indicates higher accuracy) *CRM = Conditional regression, PCR = Principal component regression*

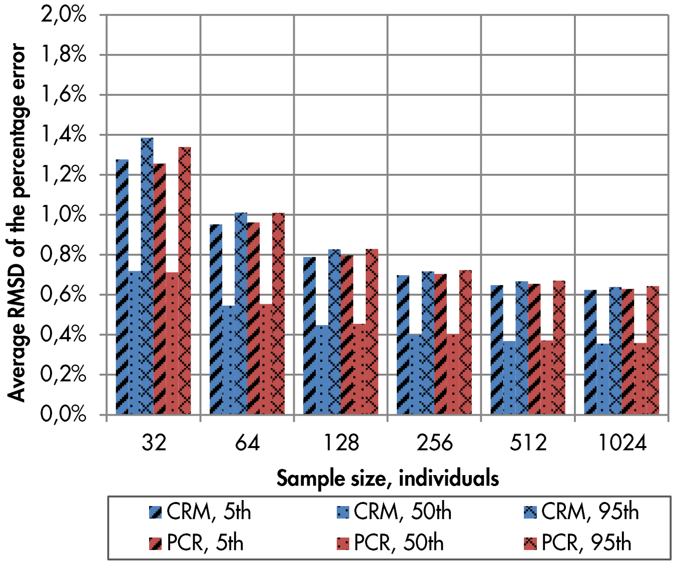

Figure 33 Graph illustrating the evaluation of the average RMSD of the percentage error for the prediction of percentiles for the dependent variables in scenario 2 (Lower value indicates higher accuracy) *CRM = Conditional regression, PCR = Principal component regression*

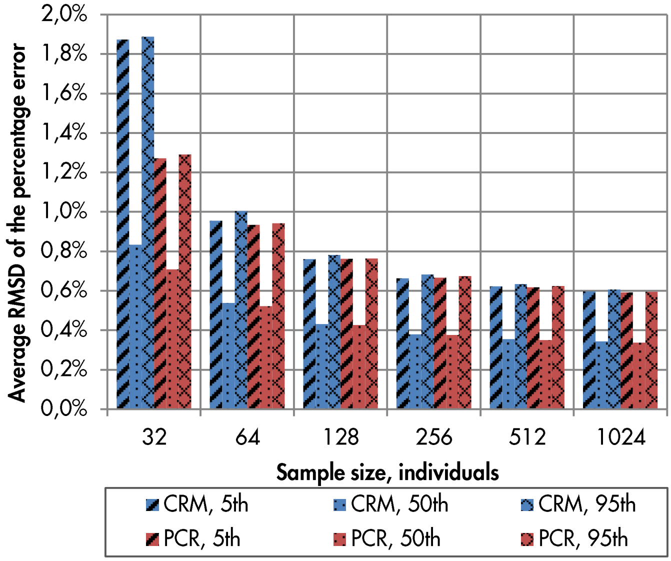

Figure 34 Graph illustrating the evaluation of the average RMSD of the percentage error for the prediction of percentiles for the dependent variables in scenario 3 (Lower value indicates higher accuracy) *CRM = Conditional regression, PCR = Principal component regression*

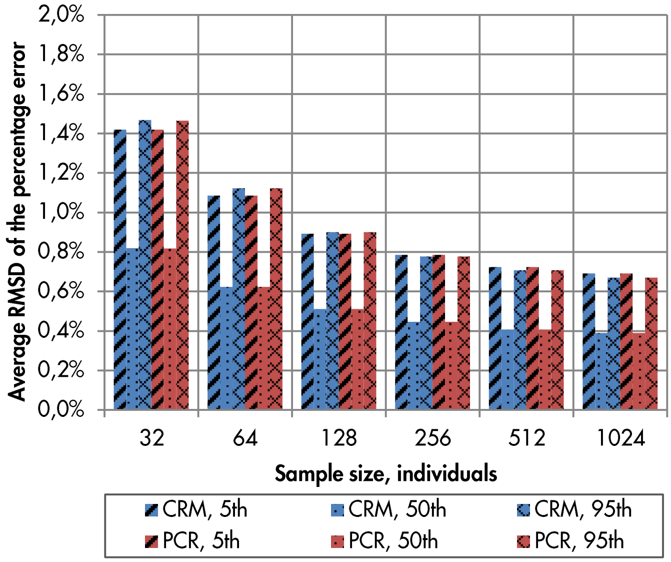

Figure 35 Graph illustrating the evaluation of the average RMSD of the percentage error for the prediction of percentiles for the dependent variables in scenario 4 (Lower value indicates higher accuracy) *CRM = Conditional regression, PCR = Principal component regression*

When the sample size is small some measurements stood out as having higher errors connected to them. If these measurements are evaluated more closely they are found to have low correlation to other measurements and/or relative high coefficient of variation which can explain the predictions with higher errors when the sample size is small. On the other hand, when the sample size was high the accuracy of both regression methods was high with small errors for all four scenarios. This shows that synthesizing populations using the presented regression model, which incorporates a stochastic component and simultaneously consider skewness, gives valid results if based on sound data gathered on a suitable sample similar to the target population.

4.5 Paper E: Generation and Evaluation of Distributed Cases by Clustering of Diverse Anthropometric Data

Paper E presents and evaluates a method where diversity in body size, strength and ROM, together with diversity in other capability measurements, is included in the process of generating data for a group of test cases using cluster analysis. The three clustering algorithms were evaluated by assessing the test cases they suggested and how well these test cases represented the diversity of the synthesized population. The paper provides answers to the second research question and specifically sub research question 2.3 and resulted in the following:

- It is possible to use cluster analysis on data that represents a range of user characteristics to generate test cases argued to be valuable test cases at evaluations of design concepts.
- However, using cluster generated cases following the methodology presented in this study does not facilitate ensuring that a certain percentage of the targeted population is accommodated.
- The most promising of the three algorithms, based on the results from the study, is the Gaussian mixture distribution algorithm which generates cases that are concentrated towards the centre of the distribution but more diverse than them generated by the k-means algorithm and at the same time evenly spread out throughout the distribution.

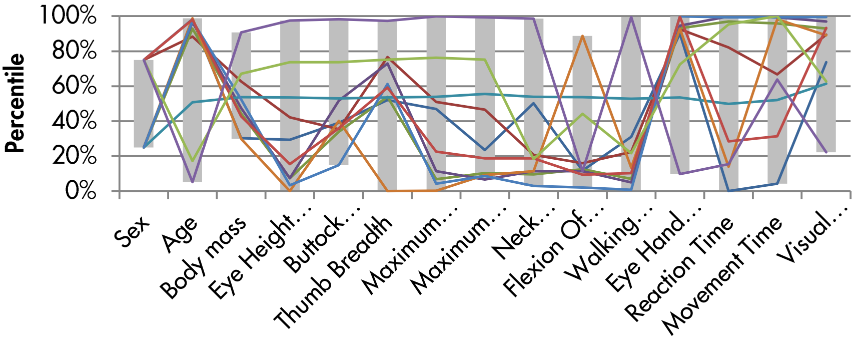

Figure 36 Visualisation of percentile values and percentile range for each variable and each case generated by the hierarchical clustering algorithm *(For percentile values of the variable sex: 25% is a female individual and 75% is a male individual)*

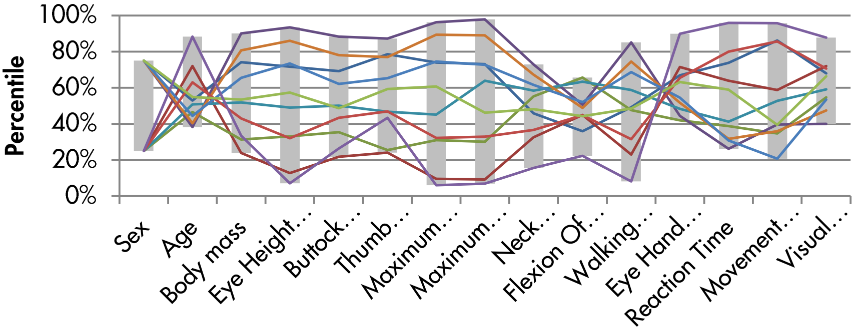

Figure 37 Visualisation of percentile values and percentile range for each variable and each case generated by the k-means algorithm *(For percentile values of the variable sex: 25% is a female individual and 75% is a male individual)*

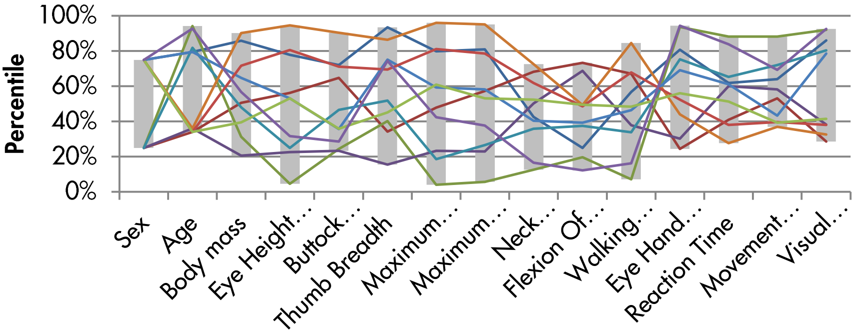

Figure 38 Visualisation of percentile values and percentile range for each variable and each case generated by the Gaussian mixture distribution algorithm *(For percentile values of the variable sex: 25% is a female individual and 75% is a male individual)*

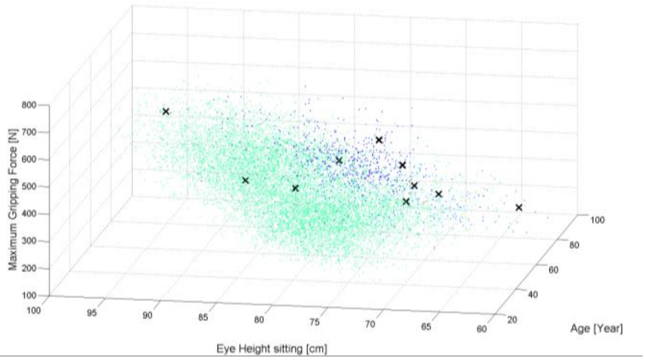

Figure 39 Scatterplot of clusters and suggested cases generated by the hierarchical clustering algorithm for the three variables Age, Eye height, sitting, and Maximum gripping force

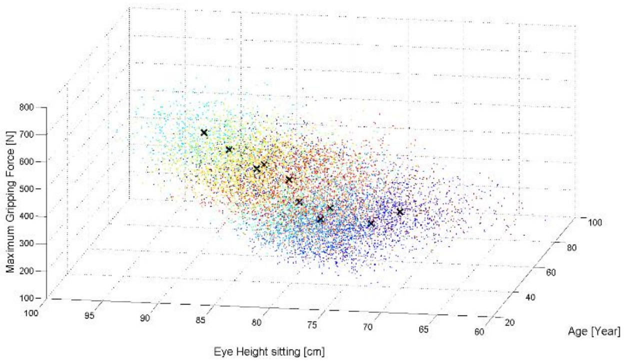

Figure 40 Scatterplot of clusters and suggested cases generated by the k-means clustering algorithm for the three variables Age, Eye height, sitting, and Maximum gripping force

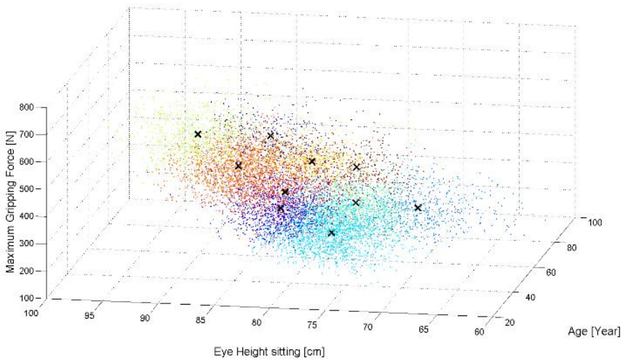

Figure 41 Scatterplot of clusters and suggested cases generated by the Gaussian mixture distribution algorithm for the three variables Age, Eye height, sitting, and Maximum gripping force

4.5.1 Evaluation of cluster generated distributed cases

From the quantitative measures (Table 5) and visualisations (Figure 36-Figure 41) it is possible to see different results for the three clustering algorithms. It can be concluded that all three have their positive and negative sides where the hierarchical and k-means algorithm give the most diverse results and where the Gaussian mixture distribution gives results that are in between and in some sense is a good compromise of the first two. It is also possible to see similarities between the results from all three algorithms where the male cases, in general, are younger, stronger and bigger. The older cases tend to be slower, having a longer reaction and moving time and needing text with high visual contrast to be able to read.

Table 5 Comparison of the three clustering algorithms by five quantitative measures

Clustering algorithm:	Hierarchical	K-Means	Gaussian mixture distribution
Average percentile range	79	65	69
Average percentile distance	145	116	126
Minimum percentile distance	34	30	41
Average minimum percentile distance	75	53	67
Variance of the minimum percentile	13	3	2

4.6 Paper F: Development and Evaluation of an Anthropometric Module for Digital Human Modelling Systems

Paper F presents the development of the anthropometric module and its interface in the IMMA DHM tool. The paper also includes an evaluating interview and usability study to assess if the developed anthropometric module and its interface matches the needs and if it would fit into the work process used by DHM tool users. Thus, the paper aims at providing answers to the first and third research question and the results can be summarized as:

- The proposed interface has functionality for creating both single manikins and manikin families and the content and structure of the interface follows guidelines for using anthropometric data in design.
- The developed anthropometric module and its interface is generally considered easy to use and navigate within.
- The biggest usability issues with the interface are lack of response and lack of explanation of more complex functionality.

- All participants thought that the interface and its feature would help them in their daily work and that it would fit into the work processes related to DHM simulations and ergonomics analyses followed at their departments today.
- In currently used DHM tools the manikin creation functionality is seldom used and all studied companies used some version of percentile manikins.
- As it is problematic to include additional anthropometric data into currently used DHM tools the users are forced to use special solutions.

4.6.1 Anthropometric module

The resulting user interface has two main parts made up of a big tab area and a row of buttons below the tab area (Figure 42 and Figure 43). The tab area has two tabs, one for manikin family creation and one for single manikin creation. The row of buttons includes functionality to add new population data to the anthropometric data base (Figure 44), possibility to save and load manikins, and to create manikins within a DHM tool as well as closing the complete window. Both tabs in the tab area are divided into three sections that match state 2, 3 and 4 in the ergonomic design process (Section 2.1.1). Thus, the main sections of the two manikin family and single manikin tabs in the tab area are:

- *Defining target population*
- *Measurement selection*
- *Measurement settings (only single manikin)*
- *Options (only family manikins)*

Defining target population is done differently for the manikin family tab compared to the single manikin tab. For the single manikin tab, a name for the manikin can be set as well as selecting the sex of the manikin and which population or nationality the manikin should be based on. Defining the target population in the manikin family tab has a different goal as different populations can be selected at the same time and also chosen to be combined into a new mixed population based on proportion values of each selected population. It is also possible to save and load specific target population setups. The section for body measurement selection is identical for the two tabs. It can be used in two ways, either by selecting check boxes via a graphical illustration of the measurements or directly from a list of measurement names. The two check boxes connected to a specific measurement are checked regardless if the graphical illustration or the list is used. The available measurements are based on ISO 7250 (ISO, 2008) which deals with basic human body measurements for technological design. It is possible to save and load a list of the selected measurements for a specific DHM evaluation. The third section deals with specific settings and options and is fundamentally different for the two tabs. For the single manikin tab, measurement or percentile values can be set for each selected measurement. Depending on if the measurement or percentile value is set by the user the other value is calculated automatically. For the manikin family tab the third section is concerned with additional options such as case selection, size of confidence region and use of techniques to reduce the number of manikins using principal component analysis (PCA) or by discarding redundant manikins found within a collective confidence region. The user gets immediate feedback on how many manikins that will be created at the bottom of this section, depending on selected choices.

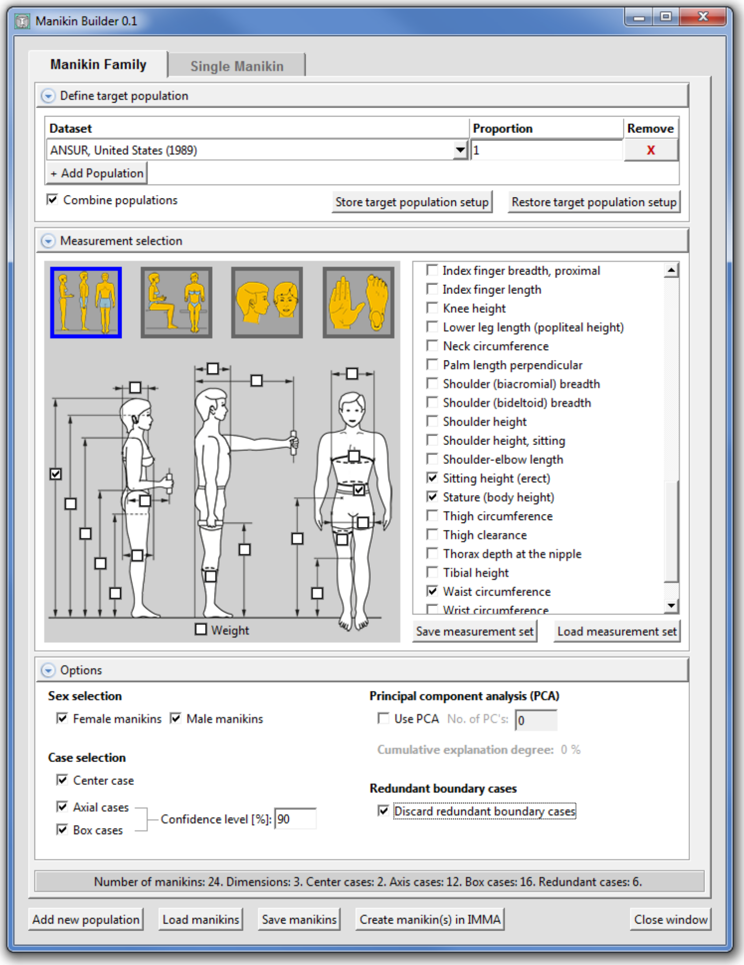

Figure 42 Interface of the anthropometric module showing the manikin family tab

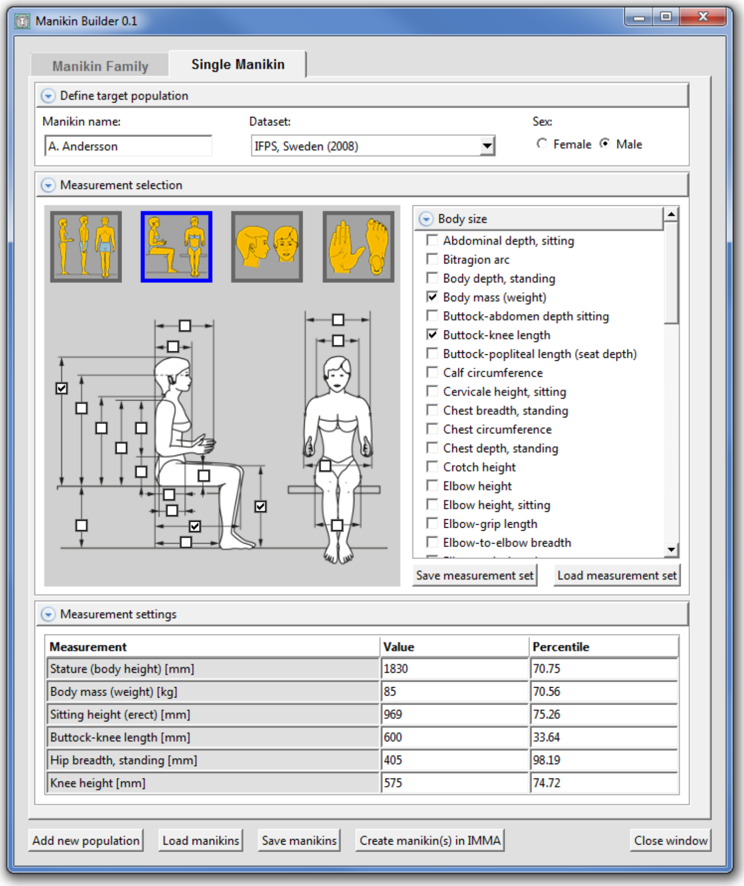

Figure 43 Interface of the anthropometric module showing the single manikin tab

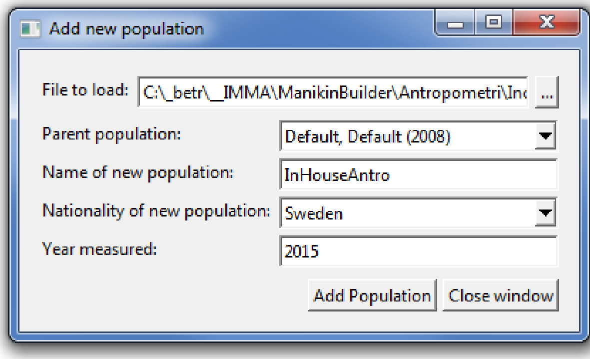

Figure 44 Interface window showing functionality to add new population data

4.6.2 Current work procedures and consideration of anthropometric diversity

The focus group interviews gave insight into the current situation regarding methods used today and knowledge of the participants but also issues with currently used DHM tools. All three companies created manikins at the start of each development project, or with some regular time intervals, and seldom used the manikin creation functionality of their current DHM tools. This indicates that they do not often perform State 1 in the ergonomic design process concerning constraints on the design connected to human capabilities, or at least not when working with DHM tools. All interviewed companies use some version of percentile manikins, often focusing on the smallest and largest manikins, based on stature and/or body weight. As a large part of the simulations are done for automotive occupant packaging and reach analyses within vehicle interiors it could be discussed if it is suitable to use only a few measurements such as stature and body weight as key anthropometric measurements. Reasons for this rough approach can be explained by lack of methods or knowledge, but can also be connected to the functionality and usability of current DHM tools which often requires stature and body weight to be defined to be able to create human models. The currently used DHM tool at two of the companies also includes more advanced functionality for considering multi-dimensional design problems. However, due to problems of including additional anthropometric data this functionality can only be used for a subset of the target population for which population data is included in the DHM tool. As it is costly and time consuming to include additional anthropometric data into the DHM tools the users are forced to use special solutions which lead to anthropometric data being found on different places and a process difficult to understand for new team members and people outside the department.

4.6.3 Usability test results

The usability tests showed that some specific tasks took longer time to perform due to functionalities that were more difficult to use. The tasks were often not performed in the intended order. Instead the participant often skipped more difficult tasks and focused on completing simple tasks that could easily be done. This sometimes led to that the participants forgot to perform the more difficult tasks. It was also possible to see a learning effect, both considering the time for some tasks but also based on the behaviour of the participants when they were more accustomed to the interface during the third and fourth scenario. The usability tests helped to identify a number of issues with the developed interface. One thing that took relatively long time and was connected to a high number of unnecessary actions was selecting measurements. An issue with this task was that all users were not familiar with the naming of specific measurements, which is based on ISO 7250 (ISO, 2008), and had trouble finding wanted measurements in the list or graphical illustrations. Other functionalities that was found difficult to use was connected to defining the target population and using functionality to reduce the number of manikins. Corresponding functionalities had not been seen in any other DHM tool and were considered somewhat complex. An issue found regarding the definition of target population is that users need to know or be informed in some way that it is possible to combine and work with several populations at the same time. Issues with functionalities to reduce the number of manikins were that several participants did not understand the concepts of these functionalities.

Despite several issues with the tested interface the subjective ratings showed an overall positive opinion (Figure 45). Both novice and expert DHM tool users considered the interface easy to use and navigate within. All participants thought that the interface and its features would help them in their daily work and that it would fit into the work processes related to DHM simulations and ergonomics analyses followed at their departments today. This result is supported by the focus group interviews that showed no major disagreement between the tested interface and the current work process employed by the companies.

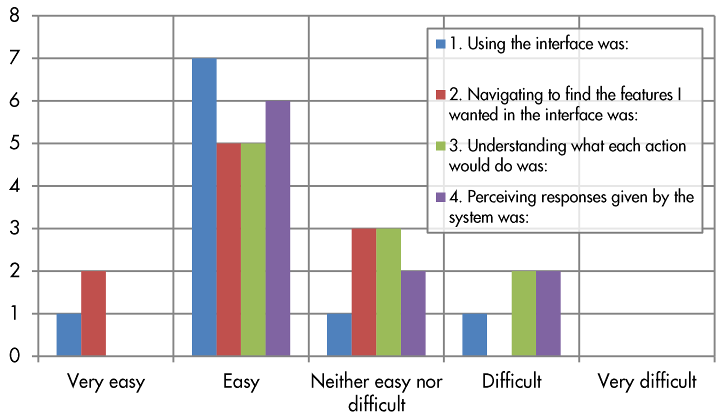

Figure 45 Subjective ratings of the overall user experience of the 10 participants

5 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 research methods, theoretical and practical contributions and validity of research.

5.1 Answers to research questions

The following sections discuss how the results of the appended papers relates to the three research questions and to what extent these questions could be answered.

5.1.1 How are DHM tools used in product and production development processes and what methods exist for consideration of anthropometric variation?

The results from Paper A show that DHM tools users often employ rough approaches for considering anthropometric diversity. It is assumed good enough to do analyses with only a few human models as virtual test persons when designing workstations or evaluating manual work. Typically a small female and a large male, according to stature, are considered as sufficient when performing ergonomics evaluations using DHM tools. The use of DHM simulation systems varies when comparing product development and production development departments where product development departments generally have more developed methods and work processes for the consideration of anthropometric diversity. Results from Paper F verify the results from Paper A while also highlighting issues that DHM tool users often have to do some special solutions for solving problems because their current DHM tools do not always work as they would want them to. Because the studied product development departments in Paper F (studied in December 2015) were studied also in Paper A (studied in February-April 2010), it was possible to do a comparative longitudinal analysis across these studies. The interviewed participants were not the same at two of the three companies but it was still possible to do a comparison of the work procedures and utilized methods. Comparing the results of Paper A and Paper F shows that two of three companies have improved their working procedure or are about to implement new procedures. One possible reason for this improvement is because of the increased attention consideration of anthropometric diversity has received through the research projects mentioned in Section 3.2. By studying and questioning their working procedures an improvement process might have started. This change could be described as a "Hawthorne effect" (Bridger, 2009), but on a bigger scale affecting the whole work process.

Results from the literature study of existing methods for consideration of anthropometric variation are presented in Section 2.1.2. A number of published methods for an improved consideration of anthropometric diversity have been analysed. Three themes have been identified during the analysis of published methods:

- generation of suitable test cases,
- prediction of missing anthropometric data and
- implementation of more diverse anthropometric variables such as strength and joint flexibility.

An additional theme, dealing with methods for how to utilize 3D body scan data when creating human models, has also been identified. However, due to set delimitations this theme was not considered further in this thesis. Only a few of the methods presented in literature, regarding generation of suitable test cases, have been implemented in commercial DHM tools. This has resulted in low usability and tools that sometimes forces the users to implement special solutions and workarounds when dealing with anthropometric diversity. There is an evident gap between methods proposed in literature and the rough approaches often used by industry today. This gap needs to be closed in order to achieve efficient DHM tool use and good consideration of anthropometric diversity, and to eventually have design of products and workstations that truly accommodate the intended portions of the target populations.

5.1.2 How can mathematical models and methods increase the accommodation accuracy of a design for a defined target group?

New, as well as improved versions of the mathematical models and methods, that were deemed necessary in order to close the identified gap found in the initial study, were presented in Paper B, C, D and E.

RQ 2.1: How can measurement combinations of anthropometric variables connected to the dimensions of a product or workplace be determined to identify suitable test cases?

The results from Paper B show that the common boundary case methodology can be generalised and extended to any number of dimensions using linear and matrix algebra. This makes it possible to generate suitable test cases for the specific anthropometric key variables that are of interest to include in the ergonomics evaluation. The simulation results from Paper B also demonstrate that the proposed boundary case methodology is advantageous compared to approaches based on the use of univariate percentile data, as often used in industry today. However, the proposed method is still based on the assumption 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 example in Paper B the result parameters were design dimensions to define adjustment ranges. That setup is likely to find max and min values at the edges of the confidence region. This is an example of a design task where the boundary case methodology is argued to work well. The validity of the boundary case methodology is likely to be more uncertain if instead a value for risk of musculoskeletal disorders was sought. This is also indicated by Mårdberg et al. (2012) who found manikins within a confidence region that were considered to have higher biomechanical loads, if joint torques and extreme joint positions were assessed, than tested boundary manikins. The method presented in Paper B 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 when studying anthropometric data, which is due to the data not being entirely normal distributed. However, the confidence hyper-ellipsoid method is far better than the percentile method used today for including the chosen accommodation level, as shown in Figure 26.

According to the results it is favourable to incorporate all identified key measurements rather than just a few as this will have positive 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. When using PCA it is necessary to decide how many PCs 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 46). However, the discarded PCs would still add to the total percentage of variation explained 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 47) (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 (see Appendix 2 for list of 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, at least 12 PCs should be included to achieve a cumulative percentage of variation above 90%.

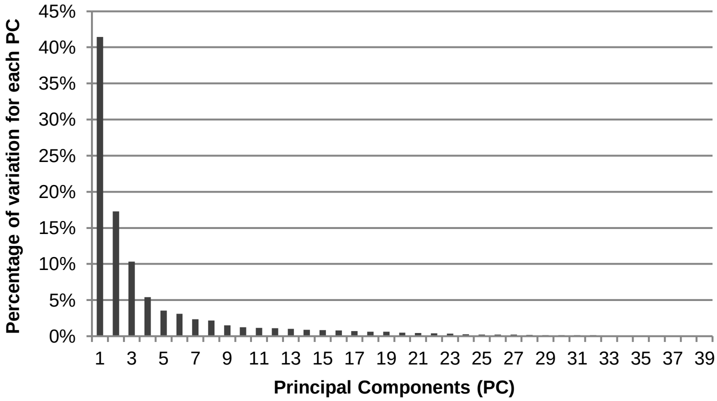

Figure 46 Description level for each PC, 39 analysed measurements for women, data from ANSUR (Gordon et al., 1989) (See Appendix 2 for list of measurements)

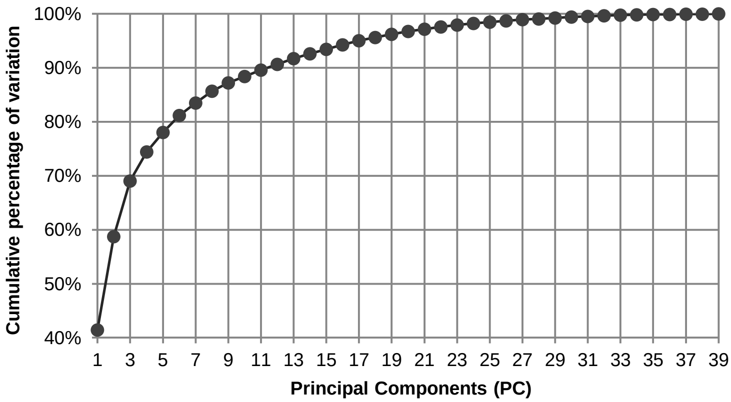

Figure 47 Cumulative percentage of the variation, 39 analysed measurements for women, data from ANSUR (Gordon et al., 1989) (See Appendix 2 for list of measurements)

RQ 2.2: How can valid and reliable predictions of unknown anthropometric variables be achieved when generating virtual human models?

The results from Paper C and D show that using an adaptive regression model for predicting and synthesizing anthropometric population data generates valid predictions. The proposed regression model has a twofold purpose and can be used for predictions of the expected value as well as synthesizing of a complete population distribution. The proposed regression model can be considered adaptive as it can quickly be applied to new anthropometric population data and any measurement can be used as independent variables. Results from the studies also show that the accuracy is dependent on the number of independent variables as well as the sample size. Accuracy based on sample size increases rapidly in the beginning but tends to flatten out after 256 individuals. This indicates that it is possible to have a relatively small sample size of 256 individuals of each sex and still have a relative high percentage of accuracy.

RQ 2.3: How can additional anthropometric variables beside body size be included in the process of defining test cases?

The proposed boundary case methodology was shown to be suitable when generating test cases for anthropometric body size data. However, if other user characteristics are introduced that have low correlations also within themselves, e.g. flexibility measures of different joints, the boundary case methodology is less useful (Brolin et al., 2014a) To solve this issue a method for generating distributed cases by clustering diverse anthropometric data was presented and evaluated in Paper C. Results from the study show that it is possible to use cluster analysis on data that represents a range of user characteristics to generate valuable test cases for evaluations of design concepts. The most promising of the three algorithms, based on the results from the study, is the Gaussian mixture distribution algorithm which generates cases that are concentrated towards the centre of the entire distribution but more diverse than them generated by the k-means algorithm and at the same time evenly spread out throughout the entire distribution.

5.1.3 How could the implementation of mathematical models be adapted to meet the needs of DHM tool users?

The results of Paper F show the development and evaluation of an anthropometric module and its interface. The resulting anthropometric module includes functionality appropriate for consideration of anthropometric diversity in a DHM tool with a user interface that supports a structured work process. The resulting user interface was achieved by basing the development on anthropometric design guidelines and known methods found in literature as well as findings from the initial interview study presented in Paper A. The development used an iterative process where concepts of the interface have been continually communicated to and evaluated by the research group and participating companies. An important activity to be able to answer the third research question was the final evaluation of the anthropometric module and its interface where a mixed method approach was used (Creswell and Clark, 2007). This was done through combined focus group interviews and usability test sessions where both qualitative and quantitative data were collected. The combination of qualitative and quantitative evaluation provides a more complete understanding of possible issues where the focus group interviews gave an understanding of the context the participants worked within and with what procedures they used to work. The subsequent usability tests revealed some usability issues and improvement potentials for the design of the interface.

5.2 Discussion of research methods

The research presented in this thesis was done to investigate how increased consideration of anthropometric diversity can be achieved in virtual development processes. During the research process which is consistent with processes in identified design research frameworks (Section 3.1), progress has continually been made in terms of both knowledge and results. The research quality of the different methods and procedures to gather and analyse data are discussed in the following sections.

5.2.1 Interviews

Interviews were used both during the initial study and in the later focus group study. The results were obtained through audio recording and by taking notes but might have been improved with more rigorous methods including transcription and coding of the interview results. However, the used approach is considered enough as all interviews pointed to similar conclusions and the results can be considered sound particularly within automotive companies being the focus of the studies.

5.2.2 Mathematical modelling

When creating mathematical models focus was put on the nature of anthropometric data and the possibility of statistical and mathematical analysis of such data. Much of the statistical and mathematical analysis of the data is based on the assumption that anthropometric data can be approximated with a normal distribution. The validity of this assumption can be discussed and a solution that considers skewed distributions was utilized and evaluated in the synthesizing process described in Paper D. The method used gave satisfactory results but should be evaluated more in further research together with other distribution fitting methods such as using the log-normal distribution. This or an alternative solution needs to be implemented throughout the anthropometric module, e.g. skewed distributions should also be considered when generating confidence regions.

5.2.3 DHM simulation

The boundary case methodology in Paper B was evaluated by DHM simulation. However, only one DHM tool, Jack 7.1, have been used in simulation experiments and only one task have been simulated and analysed. Additional and more thorough simulations and evaluations should be done to evaluate the results of different design approaches.

5.2.4 Statistical evaluation

The statistical evaluations were created for each specific paper, especially for Paper D and Paper E. In Paper D, the accuracy in the tails of the distribution was used as a measure of the accuracy of the synthesizing process. However, this measure does not reflect the accuracy in predicting the correlation coefficients between variables. That is an important factor to explain the relationship between measurements and something that the proposed regression model is created to do accurately. In Paper E, all the quantitative measures were defined in order to assess if the generated cluster centres were evenly spread out and covering as big part of the multidimensional distribution as possible. Additional measures that better assess this objective could be considered. The statistical evaluations were also to some degree affected by the space limitations that scientific publication allows. Predictions and generation of missing data were done for a high number of variables. To reduce the length of the analysis the average accuracy was used instead of the accuracy for each variable and only visualisation examples of graphs were shown.

5.2.5 Implementation

The implementation of the developed models into a functional user interface has been performed during a long period of time with a number of iterations. The implementation process could have been shortened and improved if interface usability experts and designers had been more included in the process. Still, a usability expert gave input to the design process, especially in the late phases of the development.

5.2.6 Usability test

The developed anthropometric module and its interface was evaluated through usability test with personnel at product development departments at automotive companies. The reason for focusing on personnel at product development departments was that, based on previous research findings, they were deemed to have enough insight into existing issues when considering anthropometric diversity in DHM tools to give valuable feedback at this initial evaluation phase. Nevertheless, additional testing needs to be done with personnel at production development departments, as well as other industries and university students. Additional testing could also evaluate if previous training and instructions would help to improve the use of the interface and its features. As manikins may be created infrequently for specific projects or products, evaluation of the interface for infrequent use should also be performed.

5.3 Theoretical and practical contributions

The thesis and the appended papers have not been focused on extensive theoretical contributions. However, the mathematical models presented in this thesis can be seen as theoretical contributions as they expand the knowledge of how to work with data to achieve an increased consideration of anthropometric diversity. The major theoretical contribution is argued to be the flowchart and overarching model that describes components and functionality that are necessary to achieve a useful anthropometric module in a DHM tool. Instead of generating a theoretical framework the research has been based on theories, e.g. boundary cases being sufficient to consider a complete population for many design problems, which have been generalized and made available in a usable tool. The result is a tool that is based on guidelines in literature, while the development has its starting point in current use of DHM tools. To achieve this, knowledge have been gathered from different areas, such as mathematics and statistics, analysed and then combined into new models in the field of ergonomics and anthropometry.

5.4 Validity of research

This thesis and its appended papers can be viewed as a description of a process for working with anthropometric data in an enhanced way. The validity of the developed models have been evaluated in Paper B, C, D, E and F using DHM simulations, statistical evaluations and usability tests. The empirical results from the interview study in Paper A were verified through the focus group interviews in Paper F. However, it is necessary to also evaluate the overall research process in terms of scientific rigour, validity and communication. Oates (2006) suggests an evaluation guide to assess research based on design and creation of IT artefacts which is what this research can be seen as having finally resulted in. In this research the resulting anthropometric module and its interface is the main focus and is in itself a contribution to knowledge. What distinguishes this work from normal design and development is the scientific rigour in which the included mathematical models have been created and the new knowledge that have been generated from evaluations of these models. The overall development process of the actual user interface has been described but not in detail. However, results of this process have been published and presented at scientific conferences (Bertilsson et al., 2011; Brolin et al., 2014b). In addition, all included functionality in the anthropometric module and its interface is based on methods that have been published in scientific papers. The anthropometric module and its interface have gone through evaluation in the form of usability tests with a limited number of actual end-users. No proper statistical analyses were done on the results from the usability tests. However, the goal of the usability tests were to uncover issues with the user interface and not to statistically determine the usefulness of the interface compared to some other solution (Dumas and Redish, 1999). A limitation of the research is that only the automotive industry in Sweden is studied and the needs of solely these companies have been the input to the synthesis process. However, these methods and models are most likely generic enough to be applied within any development process where physical user interaction needs to be considered. The developed methods and models could 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. For example the study in Paper D is specifically aimed to be used both within but also outside DHM tools to synthesize anthropometric data where such is missing. During the research process, additional research themes have been identified but not considered within the scope of the thesis, e.g. methods for how to utilize 3D body scan data when creating human models, which can limit the validity of the argued holistic approach of the thesis. The delimitations were deemed necessary in regard to the time frame and scope of this thesis but these additional areas are considered to be implemented in future research.

6 CONCLUSIONS

In this thesis, the matter of anthropometric diversity consideration has been approached through an evaluation of existing methods for anthropometric diversity consideration and the use of these methods in virtual product and production development processes. Based on this review, new and improved methods have been developed and implemented into an anthropometric software module to be used within the DHM tool IMMA (IMMA, 2009; Hanson et al., 2014; Högberg et al., 2016). Aspects that need to be considered to be certain that a high accommodation level accuracy is achieved, and possibilities to include more user 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.

- DHM tools users often employ rough approaches for considering anthropometric diversity and there is an identified gap between industry and existing DHM tools on one side and guidelines and methods found in literature on the other side.
- The common boundary case methodology has in this research been generalized to use any number of anthropometric key variables and also utilise principal component analysis to reduce the dimensionality of confidence regions.
- The proposed multivariate boundary case methodology is advantageous compared to approaches based on the use of univariate percentile data, as often used in industry today.
- A new adaptive regression model has been created that produce accurate predictions for both expected values as well as synthesized population distributions.
- The proposed regression model can quickly be applied to any anthropometric data and use any measurement as independent variables, but also use principal component regression to reduce risks of multicollinearity between independent variables.

- It is shown that cluster analysis can be used on data that represents a range of user characteristics, e.g. strength and joint flexibility besides body size, to generate valuable test cases for evaluations of design concepts.
- The boundary case methodology and adaptive regression model have been implemented in an interface for an anthropometric module in the IMMA DHM tool.
- The developed anthropometric module and its interface is based on relevant needs of DHM tool users and known guidelines for consideration of anthropometric diversity in design.
- Usability tests of the developed anthropometric module and its interface showed unanimously positive opinions regarding usefulness and suitability of implementation into current work processes related to DHM simulations and ergonomics analyses utilised in industry today.

7 FUTURE WORK

During the research for this thesis and its appended papers a number of themes have been identified that are important for consideration of anthropometric diversity when working with DHM tools. Most of these themes have been considered within the research but some have not. Nevertheless, all themes have been areas that need further work regarding both development and evaluation.

Proposed mathematical models could be improved to achieve even higher accuracy and more support for additional types of user characteristics. Strength and flexibility data should be included in the creation of digital human models but also body scan data to better explain the shape and size of the body. Methods for considering non-normal distributions could be evaluated and implemented throughout the anthropometric module, e.g. skewed distributions should also be considered when generating confidence regions. The method of generating test cases using cluster analysis should be further studied and improved, e.g. the way that the representative cases for each cluster are calculated could be improved as well as the statistical evaluation method. Cluster analysis could also be useful to have when identifying redundant boundary cases in multidimensional space by combining cases that lies close to each other.

Both the proposed mathematical models and the developed anthropometric module would benefit from being additionally evaluated. The validity of the boundary case theory could be further examined through simulations and evaluations targeted to specific design situations where different types of resulting variables are sought. The adaptive regression model should be evaluated with source and target data from different populations. The developed anthropometric module and its interface is desired to go through additional usability testing with different types of users. Additional testing could also evaluate if preceding training and instructions would help to improve the use of the interface and its features.

Performing simulations with a number of manikins, as suggested in this thesis, will require fast and accurate positioning and motion algorithms. It will also require appropriate and easy to use ergonomics evaluation methods which could identify manikin cases that would have issues interacting with the designed product or workplace. Such evaluation methods do not exist in current DHM tools but are important to develop to achieve a system that both considers anthropometric diversity but also evaluates ergonomics conditions and suggest design improvements based on this diversity.

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APPENDIX

Appendix 1 The 56 anthropometric measurements included in the evaluation of regression models (the columns Scnr 1, Scnr 2, Scnr 3 and Scnr 4 indicates which measurements were independent variables varied for each of the four scenarios)

#	Anthropometric measurement	Unit	Scnr 1	Scnr 2	Scnr 3	Scnr 4
1	Stature	mm	X	X	X	
2	Weight	kg	X	X	X	
3	Acromial height	mm		X	X	
4	Knee height at midpatella	mm		X	X	
5	Trochanterion height	mm		X	X	
6	Thumb-tip reach	mm		X	X	
7	Waist circumference at omphalion	mm		X	X	
8	Buttock circumference	mm			X	
9	Chest circumference	mm			X	
10	Elbow circumference	mm			X	
11	Forearm-hand length	mm			X	
12	Functional leg length	mm			X	
13	Hand circumference at metacarpale	mm			X	
14	Hand length	mm			X	
15	Head circumference	mm			X	
16	Thigh circumference, proximal	mm			X	
17	Wrist circumference, stylion	mm			X	
18	Ankle circumference	mm				
19	Axilla height	mm				
20	Arm circumference at axillar	mm				
21	Foot circumference	mm				
22	Biacromial breadth	mm				
23	Bideltoid breadth	mm				
24	Buttock depth	mm				
25	Buttock-knee length	mm				
26	Buttock-popliteal length	mm				
27	Calf circumference	mm				
28	Cervicale height	mm				
29	Chest breadth	mm				
30	Chest depth	mm				
31	Crotch height	mm				
32	Eye height (sitting)	mm				
33	Foot breadth	mm				
34	Foot length	mm				
35	Forearm circumference, flexed	mm				
36	Gluteal furrow height	mm				
37	Hand breadth at metacarpale	mm				
38	Head breadth	mm				
39	Head length	mm				
40	Heel breadth	mm				
41	Hip breadth	mm				
42	Interpupillary distance	mm				
43	Knee circumference	mm				
44	Knee height (sitting)	mm				
45	Lateral malleolus height	mm				
46	Neck circumference over larynx	mm				
47	Shoulder-elbow length	mm				
48	Sitting height	mm				
49	Thigh clearance	mm				
50	Waist breadth at omphalion	mm				
51	Waist depth at omphalion	mm				
52	Waist height at omphalion	mm				
53	Wrist to centre-of-grip length	mm				
54	Hip breadth (sitting)	mm				X
55	Popliteal height	mm				X
56	Radiale-Stylion length	mm				X

Appendix 2 39 anthropometric measurements used in the PCA for Figure 46 and Figure 47.

#	Number and name in ISO 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