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## Accommodation levels for ellipsoid versus cuboid defined boundary cases

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### Abstract

The definition and use of boundary cases is a common approach when aiming to anthropometrically accommodate a desired percentage of the targeted population by a design. The cases are defined based on anthropometric data that represents the targeted population. Approaches that define cases based on the variation within just one body measurement are poor for most design problems in representing anthropometric diversity. Hence, the consideration of variation within several body measurements is preferred. However, an approach that is based on performing several separate studies of the variation within a number of measurements leads to undesired reduction of accommodation due to the lack of consideration of the effects of correlations between measurements. This paper compares theoretical accommodation levels when using an ellipsoid versus a cuboid based approach for defining boundary cases to represent anthropometric variation within three body measurements. The ellipsoid approach considers correlations between body measurements whereas the cuboid approach does not consider correlations between body measurements. The paper suggests the application of the ellipsoid method for defining boundary cases for better reaching desired accommodation levels in boundary case based design problems. These cases can be used to define computer manikins when using digital human modelling tools. The method is also applicable when wishing to select extreme but representative real people to be involved in physical fitting trials.

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## 1. Introduction

The boundary cases approach aims to assist design tasks in that it offers a method to represent anthropometric variation among targeted users of products, vehicles, workstations or systems. The method is based on the concept of handling anthropometric diversity by the definition of *cases* where each case represents an extreme but likely anthropometric combination [1]. The rationale behind the boundary case method is that, if the design is adapted to accommodate the boundary cases, people with less extreme body measurement combinations will also be anthropometrically accommodated by the design [1,2]. The definition of boundary cases when it is enough to consider the variation within one body measurement is rather straightforward, and is typically done by the definition of one small case (e.g. 5th percentile) and one large case (e.g. 95th percentile). However, very few design tasks are that simple and often it is needed to consider variation within several body measurements in order to meet desired accommodation levels. Consequently, methods for how to simultaneously consider variation within several body measurements have been developed, e.g. the multidimensional boundary case method [1,2,3,4].

In contemporary product development processes, design is typically performed by the assistance of computers, where products, vehicles, workstations or systems are designed in virtual worlds using computer aided design and engineering (CAD/CAE) tools. In line with this, digital human modelling (DHM) tools have been developed to assist designers to consider human factors in virtual design processes [5]. In an anthropometry context, the DHM tools typically facilitate the creation of human models of almost any combination of size and measurement, but the determination of the anthropometry of the digital human models to be used when doing the design work remains as a task for the designer.

Using methods such as the multidimensional boundary case method for the consideration of anthropometric diversity when using DHM tools gain in the ergonomic qualities of the objects being designed, be they products, vehicles, workstations or systems. A study of Swedish vehicle manufacturing companies found however that it was common to use only a few human models as virtual test persons when designing workstations or evaluating manual work [6]. Typically, a small female and a large male, according to stature, were considered as sufficient when performing ergonomics evaluations using DHM tools. Such an approach means that a single key measurement is used (i.e. *stature*) and that two boundary cases are used (i.e. *small female* and *large male*). Similar findings have been reported in other studies [1,2,7,8,9]. There may be many reasons for this failure in best practice, but traditions of how to perform DHM based simulations, and lack of DHM tool functionality and usability, are believed to be important causes. So, the question arises of how to support improved practice when using DHM tools in virtual design processes to consider anthropometric diversity. One step in the right direction in better assisting designers and engineers in considering anthropometric diversity is the approach taken by the IMMA (Intelligently Moving Manikins) DHM software [10]. In IMMA, the default procedure when performing an ergonomics simulation and evaluation includes the definition of a family of boundary cases followed by an automatic batch simulation and presentation of the results from ergonomic assessments for all cases.

More generally, e.g. as shown in [11], one can consider the simultaneous variation in three human body dimensions by relatively basic mathematical treatment of the anthropometric data representing the targeted user group. In using the trivariate (three-dimensional) boundary case approach one can define a number of boundary cases that concurrently represent variation within three body measurements that are important to the design task at hand. These measurements are here called *key measurements*, and can for example be *stature*, *sitting height* and *waist circumference*, or *shoulder-elbow length*, *forearm-hand length* and *forearm circumference, flexed*. When plotting each individuals' measurement combination in a three dimensional space, the three dimensional scatter plots have different shapes depending on the correlations between the measurements. Typically the scatter plot has the shape of an ellipsoid as the overall shape is built up from three distributions that resemble normal distributions. The approach presented in [11] defines an ellipsoid that aims to encapsulate the desired percentage of the scatter plot, in turn aiming to be a representation of a theoretical level of accommodation of targeted users. An alternative approach would be to define cases for each dimension separately (e.g. 5th percentile and 95th percentile), thus representing a disconnected methodology. 'Disconnected' is used here to mean a methodology that does not take correlations between measurements into consideration, and that the method rather is based on using a series of separate univariate confidence intervals. Such an approach would give a cuboid shape aiming to encapsulate the desired percentage (90% in this case) of the scatter plot. However, it is well known that this approach leads to reduced

accommodation levels for each dimension that is added [8]. This is due to the fact that the methodology does not consider the influence of the correlation between the measurements. Still this method is sometimes used in practise. One reason for that may be that the method seems reasonable at first impression. Another reason may be due to the fact that most anthropometric data is presented as separated data without giving information of correlations between measurements.

To assess the performance of the ellipsoid and cuboid approach further, this paper compares theoretical accommodation levels when using the ellipsoid versus the cuboid based approach for defining boundary cases to represent simultaneous anthropometric variation within three body measurements.

## 2. Method

The study is performed by counting the number of individuals that are encapsulated by the ellipsoid and the cuboid respectively for three specific key measurements and a specific desired accommodation level. This gives an indication of the theoretical ability of the two approaches to meet the desired accommodation level. The data for 2208 females from the ANSUR database [12] is used as example population in the study since it is a large and acknowledged database. A synthesized trivariate normal distribution of 10000 individuals, created by randomizing values that fulfil the average, standard deviation and correlation matrix values, is used to compare results from using the ANSUR data. The results from the synthesized population are given by the average values from 10 randomizations. The combinations of three key measurements were altered to also study the influence of the correlation between the key measurements. A correlation above 0.7 was considered high (H) and correlation with absolute value below 0.3 as low (L). Table 1 shows the key measurements and the correlations for 4 selected test case combinations of high and low correlation, where each test case includes three specific key measurements.

Table 1. Key measurements and correlations of 4 test cases.

Test case	1	2	3	4
Key measurements	<i>Stature and Forearm-hand length</i>	<i>Stature and Forearm-hand length</i>	<i>Stature and Forearm-hand length</i>	<i>Stature and Elbow Rest Height</i>
Correlation	0.71 (H)	0.71 (H)	0.71 (H)	0.18 (L)
Key measurements	<i>Stature and Acromion Height</i>	<i>Stature and Eye height sitting</i>	<i>Stature and Elbow Rest Height</i>	<i>Stature and Abdominal-Extension Depth Sitting</i>
Correlation	0.97 (H)	0.75 (H)	0.18 (L)	0.14 (L)
Key measurements	<i>Forearm-hand length and Acromion Height</i>	<i>Forearm-hand length and Eye height sitting</i>	<i>Forearm-hand length and Elbow Rest Height</i>	<i>Elbow Rest Height and Abdominal-Extension Depth Sitting</i>
Correlation	0.73 (H)	0.25 (L)	-0.29 (L)	0.06 (L)

The targeted theoretical accommodation level was set to 90%. For the ellipsoid this means that the ellipsoid is scaled to encapsulate 90% of the scatter plot, as described in [3]. For the cuboid case this means that 5th percentile and 95th percentile values were set as confidence interval limits for each of the three dimensions separately.

### 3. Results

Table 2 shows the results from counting the percentage of the scatter plot that was encapsulated by the ellipsoid and the cuboid approach respectively, when using ANSUR data and synthesized data.

Table 2. Percentage of encapsulated scatter plot for the 4 test cases, for ellipsoid and cuboid approach and ANSUR and synthesized data.

Test case		1	2	3	4
Ellipsoid (% inside)	ANSUR	89.81	90.04	90.40	89.86
	Synthesized	89.91	90.06	89.85	89.92
Cuboid (% inside)	ANSUR	83.06	79.30	76.27	73.46
	Synthesized	82.67	78.57	76.16	73.16

### 4. Analysis and Discussion

Table 2 indicates how the ellipsoid approach is successful in meeting the objective to encapsulate 90% of the data building up the three dimensional scatter plot. Some variation around the targeted accommodation value, i.e. 90% in this case, is reasonable due to randomization effects in the synthesized data, and due to the fact that the ANSUR data is not exactly normal distributed, even though that approximation is a reasonable assumption for most body measurements [13]. The cuboid approach is less successful in meeting the 90% accommodation objective. The result also indicates how the method becomes even poorer for lower correlations, i.e. approximately 83% for test case 1 and approximately 73% for test case 4. In order to investigate this trend further the synthesized data was set to the two extreme situations with correlations of zero and one respectively between three dimensions, i.e. representing a scatter that resembles a sphere and a line. For a correlation of zero this gave that the cuboid approach theoretically accommodated 73.07% and the ellipsoid approach 89.99 %. At a correlation of one the cuboid approach gave 89.95% and the ellipsoid approach 89.96%, i.e. both approaches approximately met the theoretical accommodation objective of 90%. A conclusion is that the cuboid gets better for higher correlations, and is as good as the ellipsoid approach for correlations of approximately one. However, when selecting key measurements the general recommendation is to choose measurements that are critical in relation to the design task at hand, and to strive to select measurements with low correlations to avoid having redundant information [2], which is in favour of the ellipsoid approach.

To illustrate the outcomes of the two approaches, Table 3 shows percentile values for 8 selected cases for the ellipsoid and the cuboid approach respectively, here for test case 1. The cases for the cuboid approach are defined at the corners of the cuboid. For the ellipsoid approach the 8 cases are defined at the corners of the largest possible cuboid located within the ellipsoid (Figure 1). This is based on the assumption that the ellipsoid shape is represented well enough by these 8 cases. Indeed more cases could have been added to enhance the representation, such as cases at the ends of the axes, but to ease the comparison of the two approaches it was decided to have 8 cases for each approach.

Table 3. Percentile values of 8 boundary cases for test case 1, for ellipsoid and cuboid approach.

Approach	Measurement	Boundary cases (percentiles)							
		1	2	3	4	5	6	7	8
Ellipsoid	<i>Stature</i>	94	11	19	97	81	3	6	89
	<i>Forearm-hand length</i>	70	2	2	70	98	30	30	98
	<i>Acromion Height</i>	97	18	10	94	90	6	3	82
Cuboid	<i>Stature</i>	95	95	5	5	95	95	5	5
	<i>Forearm-hand length</i>	95	5	5	95	95	5	5	95
	<i>Acromion Height</i>	95	95	95	95	5	5	5	5

Table 3 shows how the ellipsoid approach renders cases that are systematically spread in order to represent the variation in the distribution, and where some percentile values go beyond 5th and 95th percentile in order to meet the overall 90% accommodation objective. The ellipsoid approach shows symmetry in the percentile values of the pairs of boundary cases: 1-7, 2-8, 3-5 and 4-6.

Figure 1 shows test case 1, i.e. the scatter plot of the three measurements *Stature*, *Forearm-hand length* and *Acromion Height*, viewed in the orthogonal projection of the first two measurements and plotted in standard score space. It can be seen how the cases calculated by the ellipsoid approach are measurement combinations that are located on the boundary of the distribution (Figure 1, red dots). It can also be seen how the cuboid approach renders boundary cases with some percentile combinations that are far out from the scatter plot and hence are unlikely measurement combinations in reality (Figure 1, blue dots). This is another drawback of the cuboid approach when correlations get higher and the scatter plot becomes a narrower ellipsoid shape. Hence, following the cuboid approach to define boundary cases when correlations are higher may eventually lead to poor design solutions, that for example are unnecessary large, cumbersome or expensive. Thus, as design is a complicated optimization task of finding the best overall solution that will meet a range of, often conflicting, requirements, the ellipsoid approach is argued to give the designer more precision than the cuboid approach when defining boundary cases to use in the design task.

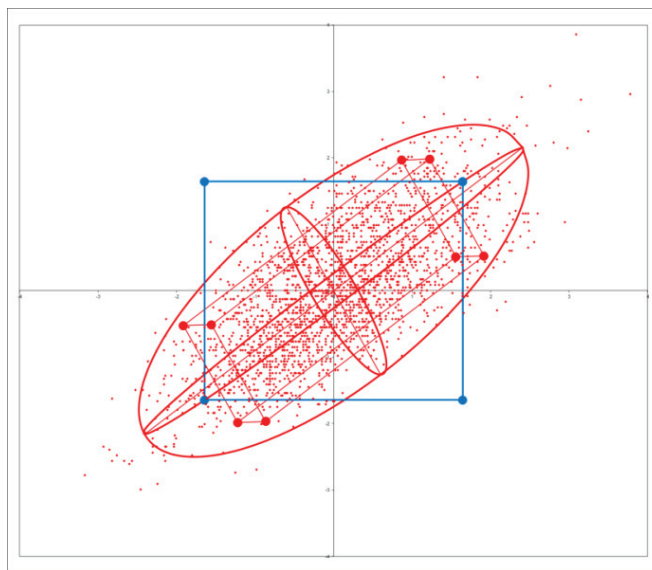


Figure 1. Scatter plot, and ellipsoid and cuboid approach and associated boundary cases.

This paper describes a more basic approach compared to multidimensional (4D and more) or Principal Component Analysis (PCA) based methods, e.g. as described in [3,14]. Indeed there are situations when more advanced methods are advantageous. However, the ability to view a scatter plot and the encapsulating shapes and boundary cases in 3D is beneficial for understanding and monitoring the results from the mathematical method. Indeed, PCA can be used to reduce the dimensionality to 2D or 3D, but still it is argued to be harder to interpret what the principal component based results represent than viewing the scatter plot in 3D where each dimension represents one of the chosen key measurements. Also, if the three dimensions are selected thoughtfully a good representation of anthropometric diversity can be achieved in many cases [15,16].

The ellipsoid based method suggested in this paper is mainly thought of as an aid to defining suitable boundary computer manikins, where then the DHM tool being used defines the other body measurements by the use of inbuilt regression methods. However, the method is also applicable when wishing to recruit extreme but representative real people to be involved in fitting trials. For example, choosing the three key measurements *stature*, *weight* and *sitting height*, which are quite straight forward to measure, and would mean a general representation of anthropometric variation, and an accommodation level of 90%, the ellipsoid method suggests following approximate measurement

combinations of female test users, here defined at the ends of the axes of the ellipsoid (Table 4). It is worth mentioning however that the percentile values are outcomes based on the ANSUR data which is somewhat dated (1988) and limited in terms of representing ‘average people’ in that it is based on army personnel measurements [12]. The percentile values are then translated into actual measurements for Swedish females 18-65 years old by using the software PeopleSize [17] and selecting anthropometric data from 2009 published in [18] (Table 4).

Table 4. Suggested approximate key measurements of female boundary test persons to recruit at general fitting trials.

Measurement		Boundary cases defined at ellipsoid axis ends					
		1	2	3	4	5	6
Stature	mm	1835	1516	1613	1738	1707	1644
	percentile	98.9	1.1	18.4	81.6	67.7	32.3
Weight	kg	83	53	65	61	54	81
	percentile	96.8	3.2	57.5	42.5	4.8	95.2
Sitting height	mm	970	811	918	863	924	857
	percentile	98.6	1.4	78.2	21.8	82.5	17.5

A main objective of this paper and the proposed ellipsoid based method is to show that it is advantageous compared to approaches based on the use of disconnected univariate percentile based anthropometric analyses, which are shown to be poor in representing anthropometric diversity among targeted users when two or more dimensions influence the design task, in line with [1,2,7,8,9]. Having the ellipsoid plotted together with a scatter plot based on data of real individuals, as in Figure 1, is argued to be important in order to illustrate how the ellipsoid encapsulates approximately the percentage of the dots set by the value of the accommodation objective. Also, the scatter plot is argued to be important to highlight that people that are located outside of the ellipsoid by the set accommodation objective are likely to be excluded by the final design. Hopefully this will trigger discussions within the design team, and with clients and managers, of appropriate accommodation levels. Setting an accommodation level of 90% is common, but still that means that 1 of 10 persons is not explicitly considered in the design. A 90% accommodation objective can indeed be seen as somewhat out-of-date given the concern for issues like inclusion, accessibility, quality of life, high productivity and safety [19]. Aiming for higher accommodation levels complies with the concept of *inclusive design*, which has positive implications both on life-quality for more people but also opens opportunities to expand markets by satisfying more users by the design [20]. The reasoning behind the inclusive design approach is that designers should try to include users rather than exclude them when designing products, systems and environments; it encourages an attitude of ‘what if we design like this, then we would include these user groups as well, rather than exclude them’. The issue of whether or not someone actually is accommodated by a design is however often not so precise, but rather a multifaceted ‘grey area issue’ [21]. Hence, accommodation when interacting with a product or workstation is often within a range that can be described as going from *works well - being frustrated - having difficulty to exclusion* (not able to use/perform task/interact). Indeed, the approach presented in this paper does not aim to ensure that someone with anthropometry that would be located within the ellipsoid would be accommodated and that someone outside the ellipsoid would be non-accommodated. Firstly, there may be other measurements than the three measurements, selected on the assumption that they would limit accommodation, which will cause exclusion. Secondly, there may be links between human anthropometry and accommodation of using an object that is not captured when using this method, which would rather be captured by observing digital human models or real people interacting with the object being designed. It may, of course, also be other issues than anthropometry that cause exclusion. Still the method is claimed to be a substantial improvement from the common univariate 5th percentile female to 95th percentile male approach. As argued in [22], if user groups are to be excluded of one reason or another, that outcome ought to be the result of a conscious design decision rather than for example an effect of poor information, knowledge or consideration within the design team, and that designers need support, e.g. tools and methods, to meet this objective. The method presented in this paper is a contribution towards that call.



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