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## Identification of redundant boundary cases

Dan Högberg<sup>a</sup>, Erik Brodin<sup>a,b</sup>, Lars Hanson<sup>a,b,c</sup>

<sup>a</sup>*School of Engineering Science, University of Skövde, Skövde, SWEDEN;* <sup>b</sup>*Department of Product and Production Development, Chalmers University of Technology, Gothenburg, SWEDEN;* <sup>c</sup>*Industrial Development, Scania CV, Södertälje, SWEDEN*

The boundary case method is established for the representation and consideration of anthropometric diversity in design tasks with certain characteristics. Sometime boundary cases are defined separately for two distributions, e.g. for females and males, which may lead to a situation where some boundary cases will be redundant in that they are located within the joint distribution rather than on the joint boundary. This paper describes and illustrates a method for automatic identification of redundant boundary cases that are located within two three-dimensional overlapping distributions.

**Practitioner Summary:** The paper describes a pragmatic way to focus the design work on users with specific limiting body measurement combinations that can be used to obtain design data or be used to describe appropriate test persons or digital human models for design problems where the boundary case method is suitable.

**Keywords:** boundary cases, digital human modelling, anthropometry, diversity, accommodation

### 1. Introduction

The boundary case method is established for the representation and consideration of anthropometric diversity in design tasks with certain characteristics (HFES 300 Committee, 2004). The method aids designers to identify limiting anthropometric data and then turn this into design data in order to better meet desired accommodation levels. The concept is based on the assumption that if the design accommodates these boundary cases the design will also accommodate humans with more common anthropometry (Robinette, 2012). The approach can be used to get direct design data, e.g. minimum and maximum values for height adjustment of a seat in order to accommodate a desired proportion of the targeted population. The approach can also be used to define anthropometric values for a number of key measurements when recruiting subjects to physical fitting trials. And the approach can be used to define anthropometric values for a number of key measurements when defining boundary digital human models (computer manikins) to be used in ergonomics simulations, where the digital human modelling (DHM) tool itself defines the values of the other measurements, based on the values of the key measurements. This paper is mainly composed in the context of DHM where the proposed method is used to define boundary case manikins.

Anthropometric data is commonly separated per gender, and digital human models are typically defined as representing either females or males. Hence it is common to define boundary cases that represent diversity within the female population, and boundary cases to represent diversity within the male population. Since females and males are relatively similar in sizes this often means that some boundary cases become redundant in that they are located within the overlap of the two distributions rather than on the joint boundary. Typically one wants to keep the number of boundary cases low and only use the ones that are assumed critical to the design problem at hand, since that is the basic idea of the boundary case method. So there are benefits of identifying and remove these redundant cases in order to only use the actual boundary cases. For univariate (one-dimensional) or bivariate (two-dimensional) circumstances, i.e. when variation of females and males within one or two anthropometric dimensions are considered simultaneously, this phenomena can easily be seen and resolved by visual inspection. For one-dimensional situations this is indeed common practise in that a small female and large male often are used as boundary cases, i.e. that the redundant large female and small male cases are removed. A similar approach but for two dimensions is shown in Högberg et al. (2012). For three dimensional situations this is harder to resolve by visual inspection, and for four and more dimensions it would be impossible or extremely hard to visually identify redundant boundary cases. As mentioned, it is desired to keep the number of boundary cases low, and in a DHM context a lower

number of cases also ease the ergonomics simulations and the evaluation of simulation results. Hence, for situations where anthropometric variation within several dimensions are simultaneously considered and the number of boundary manikins increases, it becomes particularly beneficial to remove redundant boundary manikins and rather use the actual boundary manikins in the ergonomics simulations. This paper describes and illustrates a method that uses mathematics for the automatic identification of redundant boundary cases that are located within two three-dimensional overlapping distributions.

## 2. Method

The triaxial ellipsoid that encapsulates the desired proportion of the trivariate normal distribution is defined by the eigenvalues and eigenvectors of the correlation matrix and by scaling the ellipsoid according to the chi-squared distribution, using the mathematical methodology described in Brolin et al. (2012). This is done separately for female and male data. The method is tested using the ANSUR anthropometric dataset for females and males (Gordon et al., 1989) in order to have data of a large number of anthropometric measurements for a large number of individuals. The number of individuals encapsulated by the ellipsoid is calculated in order to compare the desired percentage of individuals inside the ellipsoid with the actual percentage. Six boundary cases are defined at the ends of the axes of the ellipsoid and eight boundary cases at the corners of the maximum volume cuboid inside the ellipsoid. This gives in total 28 boundary cases for both female and male population. A mathematical method is developed that defines and position the two ellipsoids in the common 'real' space (i.e. in a non-standardised space) and then, by using the ellipsoid equation, automatically identifies those boundary cases that are located within the joint volume represented by the two ellipsoids rather than on the boundary of the joint volume.

## 3. Results

Results are described by an example where *Stature*, *Sitting Height* and *Hip Breadth* and an accommodation objective of 90% are selected. Input data and the counted percentage of individuals located within the two defined ellipsoids are given in Table 1. Data of the defined 28 boundary cases are given in Table 2.

Table 1. Input data and the counted percentage of individuals located within the two defined ellipsoids.

Measurement (mm)	Females			Males		
	Stature	Sitting Hgt	Hip Brth	Stature	Sitting Hgt	Hip Brth
Average ( $\mu$ )	1629	852	343	1756	914	342
Standard dev. ( $\sigma$ )	64	35	22	67	36	20
Corr. matrix ( $\rho$ )						
Stature	1	0.755	0.372	1	0.741	0.453
Sitting Height	0.755	1	0.438	0.741	1	0.464
Hip Breadth	0.372	0.438	1	0.453	0.464	1
Inside ellipsoid (%)		90.49			90.25	

Table 2. Data of the defined 28 boundary cases.

Case	ID#	Female						Male						
		Stature		Sitting Hgt		Hip Brth		Stature		Sitting Hgt		Hip Brth		
		mm	%-ile	mm	%-ile	mm	%-ile	mm	%-ile	mm	%-ile	mm	%-ile	
Axis	F1	1770	99	931	99	381	96	M1	1904	99	993	99	379	97
Axis	F2	1489	1	773	1	305	4	M2	1608	1	835	1	305	3
Axis	F3	1683	80	821	19	345	54	M3	1815	81	882	18	342	51
Axis	F4	1576	20	883	81	340	46	M4	1696	19	946	82	341	49
Axis	F5	1576	20	832	29	384	97	M5	1707	23	890	25	376	96
Axis	F6	1682	80	872	71	302	3	M6	1804	77	938	75	307	4
Cuboid	F7	1711	90	868	68	390	98	M7	1848	92	927	65	383	98
Cuboid	F8	1549	10	777	2	346	55	M8	1677	12	836	1	341	48
Cuboid	F9	1487	1	813	13	343	50	M9	1608	1	873	12	340	47
Cuboid	F10	1649	62	904	93	387	98	M10	1779	64	964	92	383	98
Cuboid	F11	1772	99	891	87	342	50	M11	1904	99	955	88	343	53
Cuboid	F12	1610	38	800	7	298	2	M12	1733	36	863	8	301	2
Cuboid	F13	1548	10	836	32	296	2	M13	1664	8	901	35	300	2
Cuboid	F14	1710	90	927	98	340	45	M14	1835	88	992	99	343	52

The developed method identifies following redundant boundary cases, i.e. cases that are located within the other ellipsoid: F1, F6, F11, M2, M5, M8 and M9. This reduces the number of boundary cases from 28 cases down to 21, i.e. a reduction of 25% in this case. Figure 1 shows the scatter plot of the two distributions where female data is in red and male data is in blue, viewed with Stature on the horizontal axis and Hip Breadth on the vertical axis. Figure 1 also shows all 28 boundary cases where the seven redundant boundary cases are marked with a green ring.

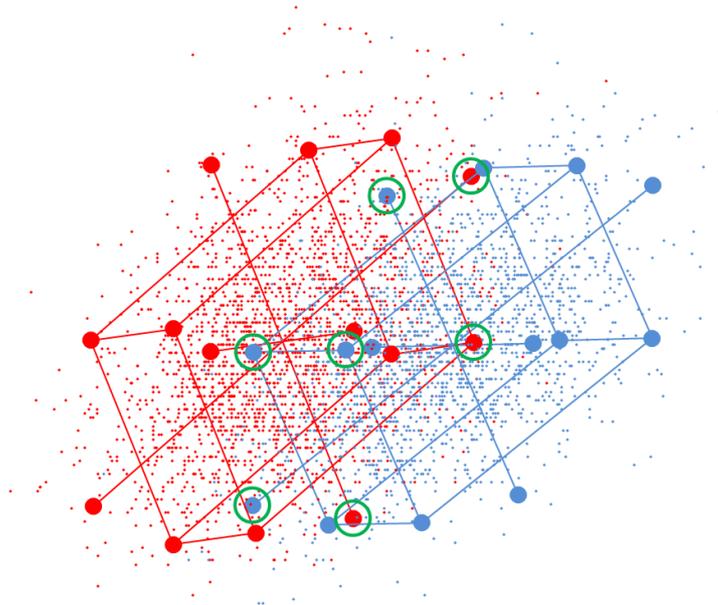


Figure 1. Scatter plot of female and male distribution together with the 28 boundary cases. The seven redundant boundary cases are marked with a green ring.

Figure 2 shows the 28 boundary cases when modelled in the DHM tool Jack 8.2 (Siemens, 2015), with the axis cases on the upper row and cuboid cases on the lower row. The seven redundant cases are marked with a green ring.

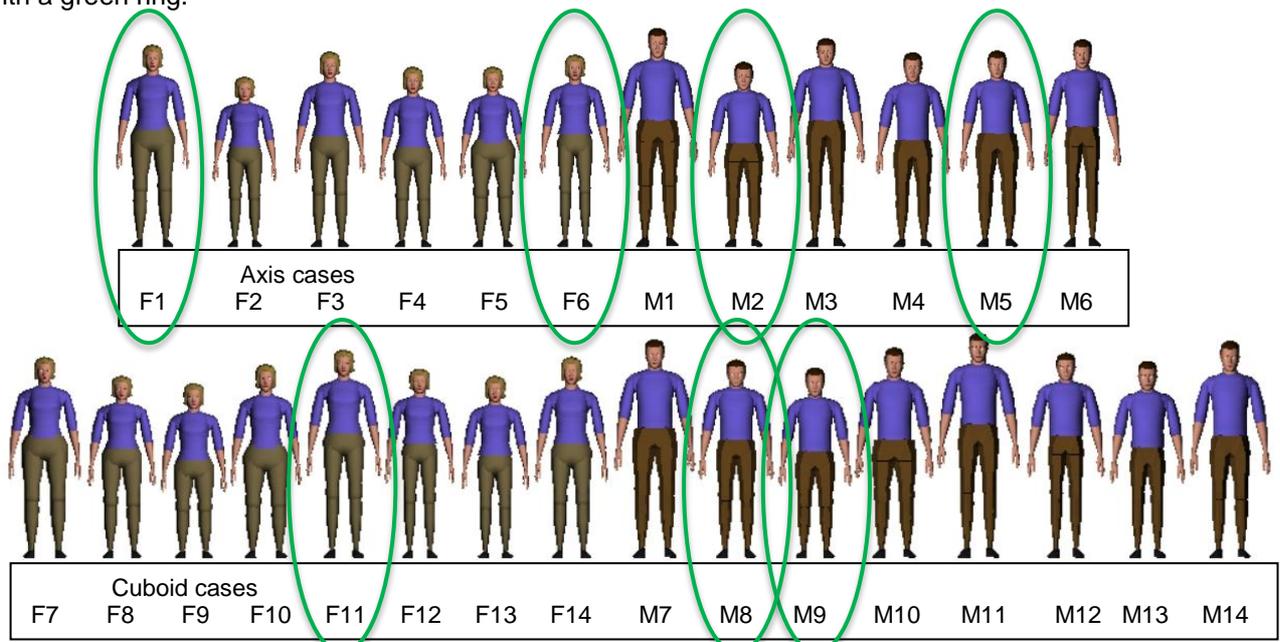


Figure 2. 28 boundary manikins modelled in DHM tool Jack. Seven redundant boundary manikins marked with green ring.

#### 4. Discussion

As the method removes cases it is worth highlighting that the purpose is not to remove people from being accommodated when designing things (products, workplaces, vehicles etc.) but rather the opposite. The method is a pragmatic way to focus the design work on those cases that are on the joint boundary when considering several distributions and when working on design problems suitable for the boundary case method. Hence, the objective is that the method will support the practise of designing for anthropometric diversity and lead to designs that better meet desired accommodation levels. Aiming to meet set accommodation levels, and especially aiming to increase accommodation levels, complies with the concept of *inclusive design*. Inclusive design has positive implications both on life-quality for more people but also opens opportunities to expand markets by satisfying more users by the design (Waller et al., 2015). 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 users or 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' (Clarkson et al., 2015). Hence, accommodation when interacting with a product or workstation etc. 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 joint boundary would be accommodated and that someone outside the joint boundary 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, e.g. related to preference as shown in Garneau and Parkinson (2009). It may, of course, also be other issues than associated with anthropometry that cause exclusion. Still the method is claimed to be a pragmatic way to identify suitable boundary cases to focus the design work on. As argued in Porter et al. (2002), if user groups are to be excluded by a design 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. Porter et al. (2002) also argues 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.

The methodology is illustrated using data from ANSUR (Gordon et al., 1989) in order to use large and acknowledged anthropometric database. However, since that data is somewhat aged (1988) and limited in terms of representing 'average people', as it is based on army personnel measurements, the detailed results of the presented methodology, e.g. cases' millimetre and percentile values, should be viewed with that consideration. However, the presented method is applicable using any well founded anthropometric dataset.

As noted, in practical design work there are benefits from keeping the number of boundary cases low, and someone may indeed find that it for certain design tasks is good enough to only use the axis cases or cuboid cases, and hence even further reduce the number of cases. In the example shown in this paper this would mean that 4 of the axis cases could be removed, i.e. going from 12 to 8 cases, or that 3 of the cuboid cases could be removed, i.e. going from 16 to 13 cases.

The methodology can be used for similar purposes, e.g. to identify redundant cases when separate boundary cases are defined for several nationality populations, as shown for two-dimensional situations in Högberg et al. (2012).

The methodology considers the variation within three measurements simultaneously and if these three dimensions are selected thoughtfully a good representation of anthropometric diversity can be achieved in many cases (Speyer, 1996; Bubb et al., 2006). Still for some design problems it is needed to consider simultaneous variation in more than three dimensions and hence the methodology can be developed to consider more dimensions than three. Principal component analysis (PCA) can be applied to reduce the dimensionality in multidimensional analyses while still represent most of the variance in the data (Meindl et al., 1993; Jolliffe, 2002). Mixing PCA with the approach presented in this paper is assumed to be problematic though since PCA will give the two (or more) distributions different spaces, making the identification of overlaps of the distributions challenging. This is an area for further investigation.

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