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Using experimental design to define boundary manikins

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Abstract. When evaluating human-machine interaction it is central to consider anthropometric diversity to ensure intended accommodation levels. A well-known method is the use of boundary cases where manikins with extreme but likely measurement combinations are derived by mathematical treatment of anthropometric data. The supposition by that method is that the use of these manikins will facilitate accommodation of the expected part of the total, less extreme, population. In literature sources there are differences in how many and in what way these manikins should be defined. A similar field to the boundary case method is the use of experimental design in where relationships between affecting factors of a process is studied by a systematic approach. This paper examines the possibilities to adopt methodology used in experimental design to define a group of manikins. Different experimental designs were adopted to be used together with a confidence region and its axes. The result from the study shows that it is possible to adapt the methodology of experimental design when creating groups of manikins. The size of these groups of manikins depends heavily on the number of key measurements but also on the type of chosen experimental design.

Keywords: Design of experiments, Confidence region, Ergonomics simulation, Digital human modelling

1. Introduction

Evaluation of physical human-machine interaction needs to include the consideration of anthropometric diversity, i.e. dimensional variation of human body measurements among targeted users. This is particularly central when using Digital Human Modelling (DHM) tools to proactively ensure intended accommodation levels by performing ergonomics simulations and analyses. When studying larger populations, most body measurements can be considered normally distributed. Still the proportions of the human body vary from person to person, e.g. people of average height do not necessarily have an average value for all body measurements [10]. There exist different approaches for the consideration of anthropometric diversity in design. A well-known method is the use of boundary cases where manikins with extreme but likely measurement combinations are derived by mathematical treatment of anthropometric data [3, 6, 9, 12]. The supposition by that method is that the use of these manikins, as representing critical test persons in design and evaluation activities, will facilitate accommodation of the expected part of the total, less extreme, population. Used in a design process, analysis of these boundary manikins can for example give information of required adjustment ranges for important product or work place dimensions, showed by Högberg et al. [7]. In this previous study the boundary manikin method was tested against the so called percentile method, where two measurements were set to a specific percentile value. In this case set as 5th percentile and 95th percentile values, thereby intending to give 90% accommodation coverage. The results from the previous study showed that using boundary manikins gave bigger adjustment ranges compared to using set percentile values, and that

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these larger adjustment ranges were needed to reach the expected accommodation level [7].

In literature sources there are differences in how many and in what way these group of manikins, so called manikin families, should be defined, even though the basic concept of the method is similar. Often the number of manikins is in direct relation to the number of chosen input variables, usually in the form of key anthropometric measurements that will have an influence on or be influenced by the design. The process for such a method is usually that a multidimensional confidence region is defined, and then points located on the edges of this region are identified as boundary cases. The dimensionality of the confidence region can be decreased using Principal Component Analysis (PCA) without much loss of the variance of the analysed data. How to calculate confidence regions mathematically has been published with a method that uses boundary cases found on the ends of the axes that defines the confidence region [2]. With this method the number of manikins will be twice as many as the number of key measurements chosen for the analysis.

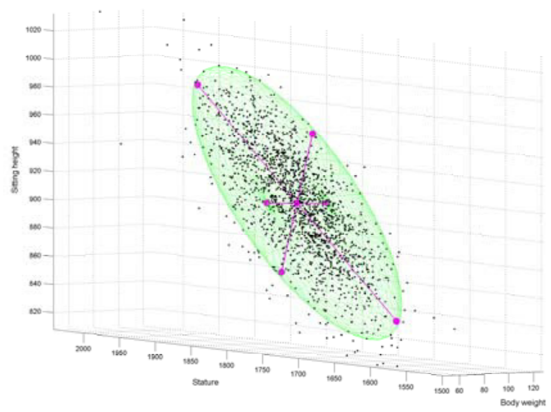

Fig. 1 Three dimensional ellipsoid for stature, body weight and sitting height plotted with male ANSUR data.

It can be argued if choosing boundary cases only at the ends of each axis will give a complete view of the analysed problem and one approach to handle that argument is to add the definition of boundary cases in-between the ends of the axes. When studying this problem similarity can be seen with the methodology of experimental design in which relationships between affecting factors of a process is studied by a systematic approach [11]. This similarity is especially evident when comparing a three dimensional confidence region (Figure 1) with a three factor Central Composite Design (CCD) defined with Response Surface methodology (Figure 2). This paper examines the possibilities to adopt methodology used in experimental design to define a group of manikins and apply analytic methods to evaluate the results from the ergonomic simulations done in a DHM tool. The goal is to evaluate if the methods can be useful in a context where boundary manikins are being analysed.

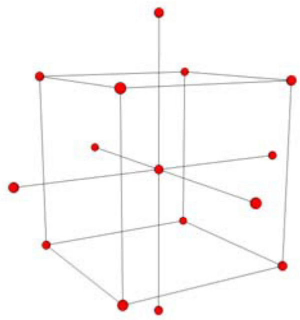

Fig. 2 Central Composite Response Surface Design.

2. Method

Different experimental designs were adopted to be used together with a confidence region and its axes. The lengths of the axes were chosen as input for the high and low value in the different experimental designs. The values obtained from the experimental designs were used to define points in the Z-score space. Anthropometric measurements were then calculated based on the values in the Z-score space.

2.1. Defining a confidence region and its axes

A confidence region is defined by calculating the length of each axis of a multi-dimensional ellipsoid. This is done with the assumption that the anthropometric measurements can be approximated with a normal distribution [10]. The method for calculating the confidence region is adopted from literature regarding multivariate statistical analysis [8]. By statistical analysis of the anthropometric data for p number of chosen key measurements a correlation matrix can be defined as

$$\rho = \begin{bmatrix} 1 & \rho_{12} & \cdots & \rho_{1p} \\ \rho_{21} & 1 & \cdots & \rho_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{p1} & \rho_{p2} & \cdots & 1 \end{bmatrix}. \quad (1)$$

Eigen pairs consisting of Eigen values ($\lambda_1, \lambda_2, \ldots, \lambda_p$) and Eigen vectors ($\boldsymbol{x}_1, \boldsymbol{x}_2, \ldots, \boldsymbol{x}_p$) of the correlation matrix are sought to describe the confidence region. These Eigen pairs are also the principal components of the analysed data. Eigen values describe the length of each axis and the corresponding Eigen vectors describe the direction of the axis. To obtain the length of the axes for a certain accommodation level the Eigen values have to be scaled using the equation

$$L_i = k\sqrt{\lambda_i}, i = 1, 2, \ldots, p \tag{2}$$

Where the scale factor k is calculated from the chi-squared distribution by

$$k = \sqrt{\chi_p^2(1 - P)} \tag{3}$$

where P is the sought accommodation level, e.g. $P = 0.9$ for 90 % accommodation level. After this is done a confidence region in standardized space can be defined using the scaled axes and Eigen vectors. Figure 3 shows such a confidence region in two dimensions.

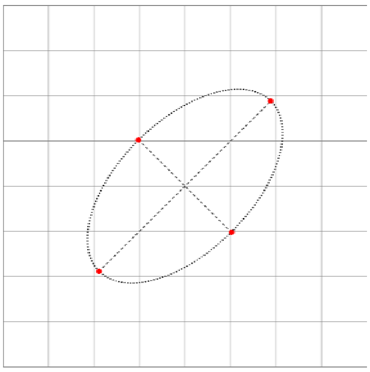

Fig. 3 Confidence ellipse for two factors with boundary cases defined at the end points of the axes.

2.2. Application of experimental design methods

It is possible to directly apply the calculated data to an experimental design using the endpoints of the axes as the axial points in an inscribed central composite design (Figure 4). The relation between the cube points L_C and the axial points L_A are calculated with the variable α defined by

$$\frac{L_A}{L_C} = \alpha . \tag{4}$$

The value for α can be calculated by a number of different methods. The method used in this study defines the axial distance α as

$$\alpha = \left(2^p\right)^{1/4} \tag{5}$$

where p is the number of chosen key anthropometric measurements. When α is known, the cube points, which make up the factorial part of the design, can be defined.

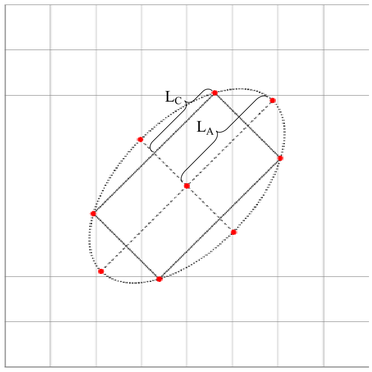

Fig. 4 Central Composite Design for two factors plotted in Z-score space.

The real anthropometric values ($m_1, m_2, \ldots, m_p$) for each manikin can be calculated by

$$m_i = Z_i \cdot \sigma_i + \mu_i, i = 1, 2, \ldots, p \tag{6}$$

where σ is the standard deviation and μ is the mean value for the anthropometric measurements.

2.3. Utilization of method in an workplace design

The method of using experimental design is tested in a task of extracting important measurements for the design of an office workplace. Two anthropometric measurements, stature and sitting height, was chosen as key variables for the design. Anthropometric data was taken from the ANSUR database and in this case female data was analysed [5]. Different types of manikin families were created and analysed in the DHM tool Jack 7.0 (Figure 5). Each manikin was positioned in the predetermined "seated typing" posture. Three dimensions important to the design, seat height, table top height and eye height, was measured the same way for each manikin.

The structure of this test is similar to an earlier study made by Högberg et al. [7], where the confidence approach, with boundary manikins at the end points of the ellipses axes, was tested against the so called percentile method, where two measurements, stature and sitting height are set to a specific percentile value. In this case set as 5th percentile and 95th

percentile values, thereby intending to give 90% accommodation coverage [7].

Fig. 5 Manikin in seated posture.

2.3.1. Confidence ellipse and Case 1

Figure 6 shows a 90% (P=0.9) confidence ellipse for stature and sitting height based on ANSUR female data. In this figure two manikins are defined with the percentile approach which gives a small 5th percentile manikin and a large 95th percentile manikin, intended to cover 90% of the population. Figure 6 also shows the percentile manikins forming a square together with two additional points, representing unrealistic body compositions. These unrealistic manikins are not used in following simulations because they would give unwanted results.

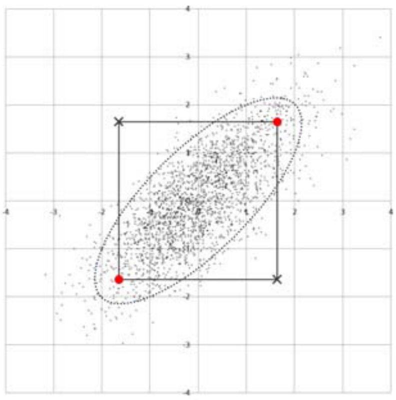

Fig. 6 Confidence ellipse in two dimensions as well as a square region shaped by two confidence intervals (scales in Z-score).

2.3.2. Case 2

In the second test the axes that defines the ellipse is used. Figure 7 shows the axes and axial end points which give four boundary manikins. An additional manikin with mean values for both stature and sitting height is added.

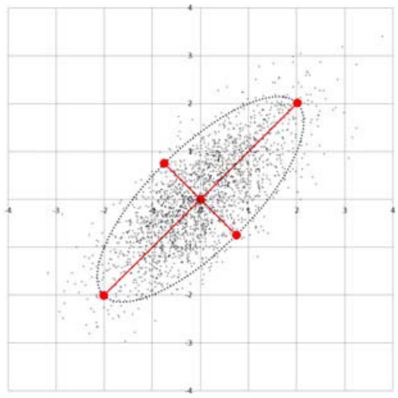

Fig. 7 Confidence ellipse in two dimensions and boundary manikins at the axial end points with an additional mean value manikin (scales in Z-score).

2.3.3. Case 3

To define other boundary manikins a factorial design was used (Figure 8). Using a factorial design gave no manikins at the axial end points. Instead four cube points were defined.

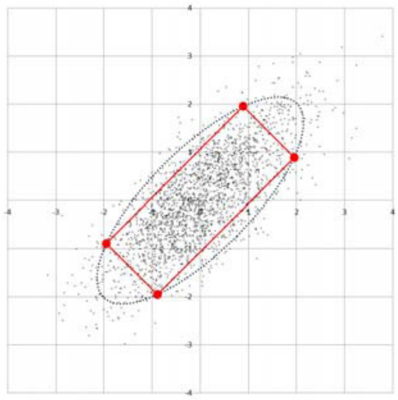

Fig. 8 Confidence ellipse in two dimensions and boundary manikins defined with factorial design at the cube points (scales in Z-score).

2.3.4. Case 4

In a final analysis the second and third test designs was combined which formed an inscribed central composite design (Figure 9). This design gave eight boundary manikins on the border of the ellipse and one additional mean value manikin.

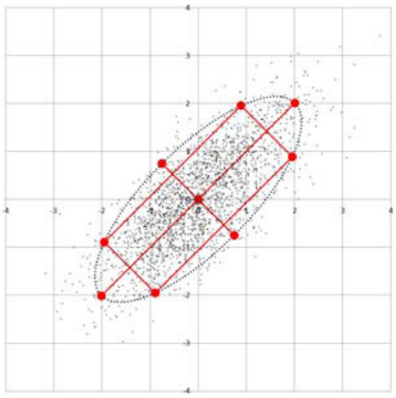

Fig. 9 Confidence ellipse in two dimensions and boundary manikins defined with central composite design (scales in Z-score).

2.4. Analysis using experimental design methods

Further analysis was done using methods common in experimental design. Main effect analysis was done on the factorial design in Case 3. Surface plot analysis was done on the central composite design in Case 4.

3. Results

3.1. Results from simulations

Each group of manikins was analysed and maximum and minimum values for each design measurement was observed (table 1). Analysis showed that the percentile approach gave a smaller adjustment range than the other test families. Case 2, with boundary manikins at the axial end points, gave a larger adjustment range, especially for eye height. Compared to Case 2, boundary manikins created using factorial design in Case 3 gave a smaller adjustment range for eye height and a larger adjustment range for seat height. The adjustment range for table height was of similar size but not on the same height for Case 2 and 3. Case 4, which is a combination of Case 2 and 3, gave the largest adjustment ranges. In Case 4 manikins from Case 2 defines the adjustment range for eye height and manikins from Case 3 defines the adjustment range for seat height. The adjustment range for table height are defined with a combination of manikins from Case 2 and 3.

3.2. Analysis of factorial design in Case 3

Through the factorial design it was possible to analyse the effect that the axes of the ellipse had on the three design measurements. Figure 10, 11 and 12 show the main effects for the axes for each design measurement. Note that these charts show the effects of the axes of the ellipse in their respective direction and not the actual measurements. The axes are in the same standardised space as the actual measurements but are rotated, in this case 45 degrees. None of the effects was statistically significant.

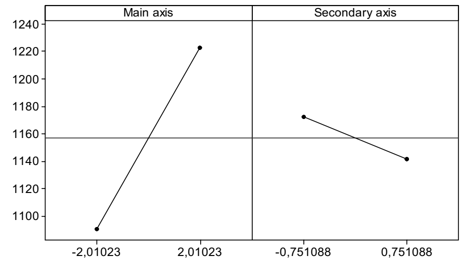

Fig. 10 Main Effects Plot for Eye height (mm)

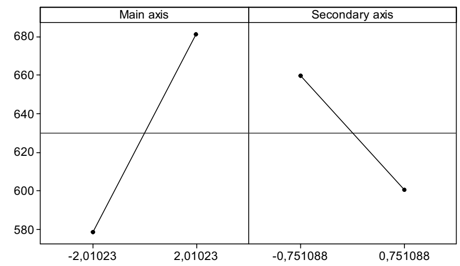

Fig. 11 Main Effects Plot for Table height (mm)

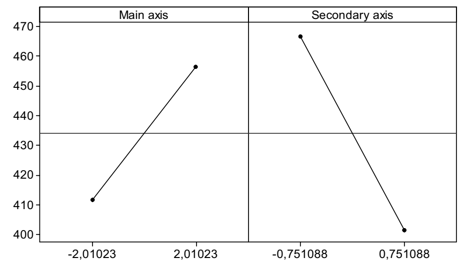

Fig. 12 Main Effects Plot for Seat height (mm)

Table 1

Measurement for each manikin in the different test cases and corresponding simulation results.

Case 1 - Percentile cases									
Manikin number	Stature			Sitting height			Resulting values from simulation		
	Value (mm)	Z-score	Percentile	Value (mm)	Z-score	Percentile	Eye height (mm)	Table height (mm)	Seat height (mm)
P1	1734	1.64	95.00	909	1.64	95.00	1236.5	681.2	461.1
P2	1525	-1.64	5.00	795	-1.64	5.00	1085	548.4	409.4
						Adjustment range:	**151.5**	**132.8**	**51.7**
Case 2 - Boundary manikins created using axial cases									
Manikin number	Stature			Sitting height			Resulting values from simulation		
	Value (mm)	Z-score	Percentile	Value (mm)	Z-score	Percentile	Eye height (mm)	Table height (mm)	Seat height (mm)
A1	1582	-0.75	22.63	878	0.75	77.37	1130.5	605	390.9
A2	1757	2.01	97.78	922	2.01	97.78	1247.6	710.4	465.4
A3	1677	0.75	77.37	826	-0.75	22.63	1185.6	637.6	482.2
A4	1502	-2.01	2.22	782	-2.01	2.22	1065.6	543.4	402.8
A5	1629	0.00	50.00	852	0.00	50.00	1156.2	652.1	437.6
Max:	1757	2.01	97.78	922	2.01	97.78	**1247.6**	710.4	482.2
Min:	1502	-2.01	2.22	782	-2.01	2.22	**1065.6**	**543.4**	390.9
						Adjustment range:	**182.0**	**167.0**	**91.3**
Case 3 - Boundary manikins created using factorial design									
Manikin number	Stature			Sitting height			Resulting values from simulation		
	Value (mm)	Z-score	Percentile	Value (mm)	Z-score	Percentile	Eye height (mm)	Table height (mm)	Seat height (mm)
F1	1573	-0.89	18.66	784	-1.95	2.54	1108.7	596.2	445.5
F2	1505	-1.95	2.54	821	-0.89	18.66	1072.0	561	378
F3	1754	1.95	97.46	883	0.89	81.34	1235.4	723.1	488
F4	1686	0.89	81.34	920	1.95	97.46	1210.7	639.7	424.8
Max:	1754	1.95	97.46	920	1.95	97.46	1235.4	**723.1**	**488.0**
Min:	1505	-1.95	2.54	784	-1.95	2.54	1072.0	561.0	**378.0**
						Adjustment range:	**163.4**	**162.1**	**110.0**
Case 4 - Boundary manikins created using response surface central composite design (Case 2 + Case 3)									
Manikin number	Stature			Sitting height			Resulting values from simulation		
	Value (mm)	Z-score	Percentile	Value (mm)	Z-score	Percentile	Eye height (mm)	Table height (mm)	Seat height (mm)
R1 (A1)	1582	-0.75	22.63	878	0.75	77.37	1130.5	605	390.9
R2 (A2)	1757	2.01	97.78	922	2.01	97.78	1247.6	710.4	465.4
R3 (A3)	1677	0.75	77.37	826	-0.75	22.63	1185.6	637.6	482.2
R4 (A4)	1502	-2.01	2.22	782	-2.01	2.22	1065.6	543.4	402.8
R5 (A5)	1629	0.00	50.00	852	0.00	50.00	1156.2	652.1	437.6
R6 (F1)	1573	-0.89	18.66	784	-1.95	2.54	1108.7	596.2	445.5
R7 (F2)	1505	-1.95	2.54	821	-0.89	18.66	1072	561	378
R8 (F3)	1754	1.95	97.46	883	0.89	81.34	1235.4	723.1	488
R9 (F4)	1686	0.89	81.34	920	1.95	97.46	1210.7	639.7	424.8
Max:	1757	2.01	97.78	922	2.01	97.78	**1247.6**	**723.1**	**488.0**
Min:	1502	-2.01	2.22	782	-2.01	2.22	**1065.6**	**543.4**	**378.0**
						Adjustment range:	**182.0**	**179.7**	**110.0**

3.3. Analysis of central composite design in Case 4

Using a central composite design makes it possible to create surface plots and evaluate how the main and secondary axes effect the design measurements in a more advanced approach. Figure 13, 14 and 15 show the surface plots for the axes for each design measurement. Note that these plots show the effects of the axes of the ellipse in their respective direction and not the actual measurements. The axes are in the same standardised space as the actual measurements but are rotated, in this case 45 degrees. Another fact is that these surface plots only show the smaller factorial part of the test design in the direction of the axes. Because of this the plots are not showing the max and min value for eye height and the min value for table height. Instead it will possible to predict the resulting dimensions for other less extreme persons within the factorial design.

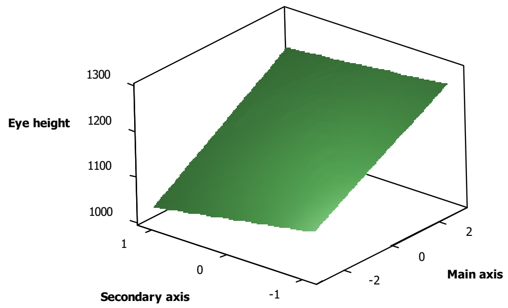

Fig. 13 Surface Plot of Eye height (mm) (Main and secondary axis are defined in rotated Z-score).

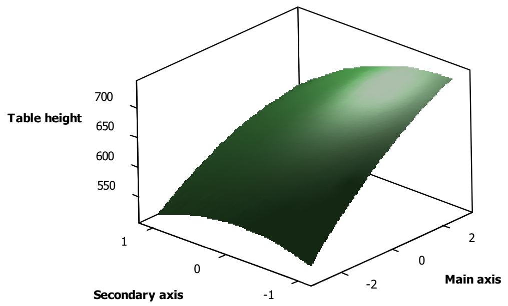

Fig. 14 Surface Plot of Table height (mm) (Main and secondary axis are defined in rotated Z-score).

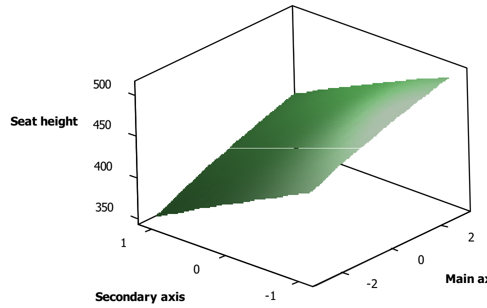

Fig. 15 Surface Plot of Seat height (mm) (Main and secondary axis are defined in rotated Z-score).

4. Discussion

The result from the study shows that it is possible to adapt the methodology of experimental design when creating group of manikins. Examples in this paper have only used two dimensions but the method works for any number of dimensions. Though, the cube points of a factorial design might not be situated on the boundary surface of a confidence region if more dimensions are added. This fact depends on the axial variable α and different methods for calculating this value should be evaluated in further research. The size of these groups of manikins depends heavily on the number of key measurements but also on the type of chosen experimental design. The result also shows that an increased accommodation level accuracy is achieved if more boundary manikins are included in the simulation. An important fact to realize is that additional boundary manikins added with factorial design are just as extreme or unusual combinations as axial end point manikins. In fact the level of extremity is the same for any manikin that is situated on the border of the ellipse. Simulations should therefore be done with enough number of manikins that will ensure the intended accommodation level. Thus, focus should not only be put on which manikins to simulate with but also how many manikins to simulate with.

The process of defining a biomechanical model differs between DHM tools and will affect the simulation results, as well as the simulation procedure that needs to be objective and repeatable. The method presented in this paper assumes that all measurements can be approximated by a normal distribution which often is not completely correct for weight, width and depth measurements [13]. In addition there is not just anthropometric variability within a population but also behavioural variability to consider [4].

All these uncertainties add up quite fast and the accuracy of the intended accommodation level might decrease. On the other hand does this study show that there is improvement potential in using more boundary manikins compared to the percentile approach which is often used in industry today [1].

The adaption of experimental design methodology when creating group of manikins can be utilized in different ways. This study shows utilization of methods where the effect that the confidence region axes has on design measurement can be measured. In this example effects calculated from the factorial design was not significant, most likely due to the low number of dimensions analysed. However, the plots showed that the main axis had the greatest effect on both eye height and table height. For seat height the secondary axis had a slightly greater effect. The central composite design and surface plots shows this effect more clearly with a plane that increases in the direction of the main axis in first two plots and in the direction of the secondary axis in the third and last plot. Though, these analyses only evaluate the effect of the axes of the ellipse and not the real measurements (stature and sitting height).

Another possible utilization is to use experimental boundary manikins in simulations that grade the ergonomic result in some way. Such approach would make it possible to study the effect of the ergonomic conditions of a product or workplace. In experimental design the goal is to combine and define the affecting factors to maximize or minimize the resulting factor. This will not be possible when doing ergonomics simulations because it is not feasible to change the size of people. Instead, by using experimental design methodology it might be possible to tell who the design will fit and who will not be accommodated. This will in turn highlight the areas of a product or workplace that has potentials for improvements.

5. Conclusion

This paper describes how experimental design can be used when defining boundary manikins. Using more boundary manikins increases the possibility to meet desired levels of accommodation. Additional methods within the field of experimental design can also be utilised when using DHM tools for the design of products and workplaces.

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