

Digital human arm models with variation in size, strength and range of motion

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Abstract

Digital human modelling (DHM) systems can be used to simulate production processes and analyse the human-machine interaction, particularly at early design stages. The human-machine interaction is affected and limited by factors or characteristics belonging to the human user and the machine or product but also the surrounding environment. DHM systems consider in most cases only physical user capabilities and with focus on consideration of body size related anthropometric diversity. However, the human-machine interaction is not only affected by the size and proportions of a user but for example also the user's muscle strength and range of motion (ROM). This paper describes a study where diversity in strength and ROM, together with diversity in body size, is implemented in the process of creating data for a group of human arm models. A literature study was done to investigate the diversity of strength and ROM and the correlation between such measurements and body size data. The results from the literature study showed that there is little correlation between body size, strength and ROM. The study also showed that there are few published studies where body size, strength and ROM have been tested at the same time. From the literature study, generic correlation coefficients between body size, strength and ROM were synthesized. Using these correlation coefficients and Principal Component Analysis, data for a group of 14 female arm models with varying body size, strength and ROM were calculated. The results show that it is possible to introduce additional variables such as strength and ROM, but also that data of the correlation between body size and other types of anthropometric measurements are scarce. New measurement studies are important to decrease the uncertainties when predicting correlation coefficients between body size, strength and ROM variables.

Keywords: Anthropometry, Diversity, Strength, Range of Motion, Digital Human Modelling, Principal Component Analysis.

1. Introduction

Digital human modelling (DHM) systems can be used to simulate production processes and analyse the human-machine interaction, particularly at early design stages (Chaffin et al., 2001; Duffy, 2009; Hanson et al., 2012). The human-machine interaction is affected and limited by factors or characteristics belonging to the human user and the machine or product but also the surrounding environment (Chapanis, 1996). These aspects should, in addition, be considered together with the task or result that the user wants to do or achieve (Pheasant and Haslegrave, 2006). The factors or characteristics of the human user can be connected to both physical and cognitive capabilities and it is important to consider the great diversity of these capabilities that exist within human populations

(Chapanis, 1996; Clarkson et al., 2013). DHM systems aimed at product and workstation design consider in most cases only physical user capabilities and with focus on consideration of body size related anthropometric diversity (Bubb and Fritzsche, 2009). Several methods have been developed for the consideration of body size related anthropometric diversity in design (Meindl et al., 1993; Speyer, 1996; Bittner, 2000; Dainoff et al., 2004; Parkinson and Reed, 2010; Brolin et al., 2012). Methods described in literature often use Principal Component Analysis (PCA) or factor analysis to reduce the dimensionality of the problem without much loss of the variance of the analysed data (Meindl et al., 1993; Bittner, 2000; Jolliffe, 2002; Parkinson and Reed, 2010). By analysing the correlation between measurements connected to body size and suggesting a group of

digital human models, so called manikins, to be used as virtual test persons in the design process, these methods enable increased accuracy in meeting desired levels of accommodation (Bittner, 2000; Brolin, 2012; Brolin et al., 2012).

However, the human-machine interaction is not only affected by the size and proportions of a user but also user capabilities, e.g. muscle strength and joint range of motion (ROM) (Frey Law et al., 2009). And, as DHM systems become more advanced with sophisticated motion prediction functionality, variables such as joint angles and torque profiles need to be included when establishing the capabilities of computer manikins (Abdel-Malek and Arora, 2009; Hanson et al., 2009).

This paper describes a study where diversity in strength and ROM, together with diversity in body size, is implemented in the process of creating data for a group of digital human arm models, aimed to better represent the diversity present in the target group related to these three characteristics.

2. Materials and Methods

A literature study was done to investigate the diversity of arm strength and ROM and correlations between such measurements and body size data. To compare the correlation coefficients within and between the groups of variables the average correlation was computed. This is similar to the median correlation Steenbekkers and Van Beijsterveldt (1998) compute to compare the correlation coefficients within groups of variables. The average correlation was computed in two steps; first, an average value for the correlation coefficients was calculated for each literature source. The values of the correlation coefficients from the literature study were then combined using the number of separate correlation coefficients that each average coefficient was calculated from. This gave a synthesized generic correlation matrix for body size, strength and ROM measurements. A total of 14 anthropometric variables were chosen to be included in the following analysis and generation of data for digital human arm models. Four variables were connected to body size, four variables were connected to strength and the remaining six variables were connected to ROM. Principal Component Analysis was used to reduce the dimensionality of the analysis. This was done by calculating the Principal Components (PC) of the synthesized correlation matrix and assessing the size of each PC. A cut-off value was set to 0.7 leading to PCs smaller than 0.7 being discarded (Jolliffe, 2002). A confidence region was defined by scaling the remaining PCs as axes of a multidimensional hyper-ellipsoid to theoretically

enclose 90% of the data using the chi-square distribution. The hyper-ellipsoid was then rotated using the eigenvectors for each PC (Brolin et al., 2012). The end points on each axis were used to define boundary cases (Dainoff et al., 2004; Brolin et al., 2012). By using values for average and standard deviation, variable data could finally be generated for each arm model.

3. Results

3.1. Literature study

The results from the literature study showed that there is little correlation between body size, strength and ROM (Table 1). The study also showed that there are few published studies where body size, strength and ROM have been tested at the same time. Instead, in most studies, where strength and ROM have been analysed, these variables have been connected to variation in age (e.g. Walker et al., 1984; Viitasalo et al., 1985; Roach and Miles, 1991; Lindle et al., 1997). An exception is Steenbekkers and Van Beijsterveldt (1998) where data of body size, strength and ROM is connected to age but where the relationships 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 is also presented (Steenbekkers and Van Beijsterveldt, 1998). Roy et al. (2009) have studied the rotational strength, ROM and function in people with unaffected shoulders from various stages of life and present the correlation between strength and ROM in addition to the correlation between those groups of variables and age. Andrews et al. (1996) present the correlation coefficients between isometric force in the upper and lower extremities and the body size variables stature and weight. Shklar and Dvir (1995) study the isokinetic strength relationships in shoulder muscles and present correlation coefficients between concentric and eccentric strength measurement for both sexes separately. 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. Mathiowetz et al. (1985) study the grip and pinch strength for a number of different age groups and present the correlation coefficients for both sexes separately. Viitasalo et al. (1985) study muscular strength profiles and anthropometry in random samples of men in different age groups and present correlation coefficients between strength measurements, anthropometric variables and age. Hupprich and Sigerseth (1950) study the specificity of flexibility in girls and present correlation coefficients between measurements of flexibility.

Table 1 Average of correlation coefficients within and between group 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)

3.2. Creation of data for arm models

From the literature study, generic correlation coefficients between body size, strength and ROM were synthesized (Table 2). The synthesized generic correlation matrix was created with data from studies of both male and female subjects. This was both due to the scarcity of data and similarity between correlation coefficients for each sex and the created generic correlation matrix was therefore considered to be applicable for analyses of both male and female data.

Table 2 Generic correlation matrix between body size, strength and range of motion

	Body size	Strength	ROM
Body size	From data*	0.600	0.018
Strength	0.600	0.587	-0.048
ROM	0.018	-0.048	0.185

*Calculated for each body size measurement combination based on data used in current analysis

The subsequent analysis was done with only female data as this was deemed enough to show the procedure and results of the method. Descriptive statistics were collected from different sources where data of relevant age groups (20-69 years) was given (Table 3). Average and standard deviation values for variables connected to body size were calculated from the ANSUR (Gordon et al., 1989) anthropometric data with measurements from 2208 females. Average and standard deviation for variables connected to strength were acquired from Steenbekkers and Van Beijsterveldt (1998); Roy et al. (2009); and D’Souza et al. (2012). Descriptive statistics for the remaining six variables connected to ROM were given from Steenbekkers and Van Beijsterveldt (1998); Roy et al. (2009); and Soucie et al. (2011). Where the descriptive statistics were divided between different age groups, combined values for the average and

standard deviation values were calculated (Dunlap, 1937).

Table 3 Average and standard deviation values for the 14 anthropometric variables

Measurement	Mean	SD
Elbow-fingertip length (mm)	442.9	23.4
Hand breadth (mm)	79.4	3.8
Hand length (mm)	180.5	9.7
Shoulder-elbow length (mm)	335.8	17.4
Internal shoulder rotation (Nm)	20.7	7.6
External shoulder rotation (Nm)	17.0	4.8
Elbow peak torque (Nm)	28.6	7.3
Hand grip (N)	296.2	65.7
Wrist flexion (degrees)	70.5	10.1
Wrist extension (degrees)	69.1	11.4
Elbow flexion (degrees)	149.2	5.6
Elbow extension (degrees)	4.2	5.2
Internal shoulder rotation (degrees)	70.1	19.1
External shoulder rotation (degrees)	89.5	11.5

The synthesized generic correlation matrices were used to create complete correlation matrices for all anthropometric variables (Table 4). Calculation of the Principal Components (PC) from the synthesized correlation matrix and evaluation of the size of each PC showed that seven PCs were smaller than the cut-off value of 0.7 and therefore discarded in the following analysis. The remaining seven PCs contributed to a cumulative percentage of the total variation of 80.7%. Using the seven remaining PCs as axes, a hyper-ellipsoid was created and the end points on each axis were used as boundary cases. In total, data for 14 arm models with varying body size, strength and ROM were calculated (Table 5 and 6). The boundary cases were visualized with graphs showing the standardised Z-value for the body size, strength and ROM variables (Table 6).

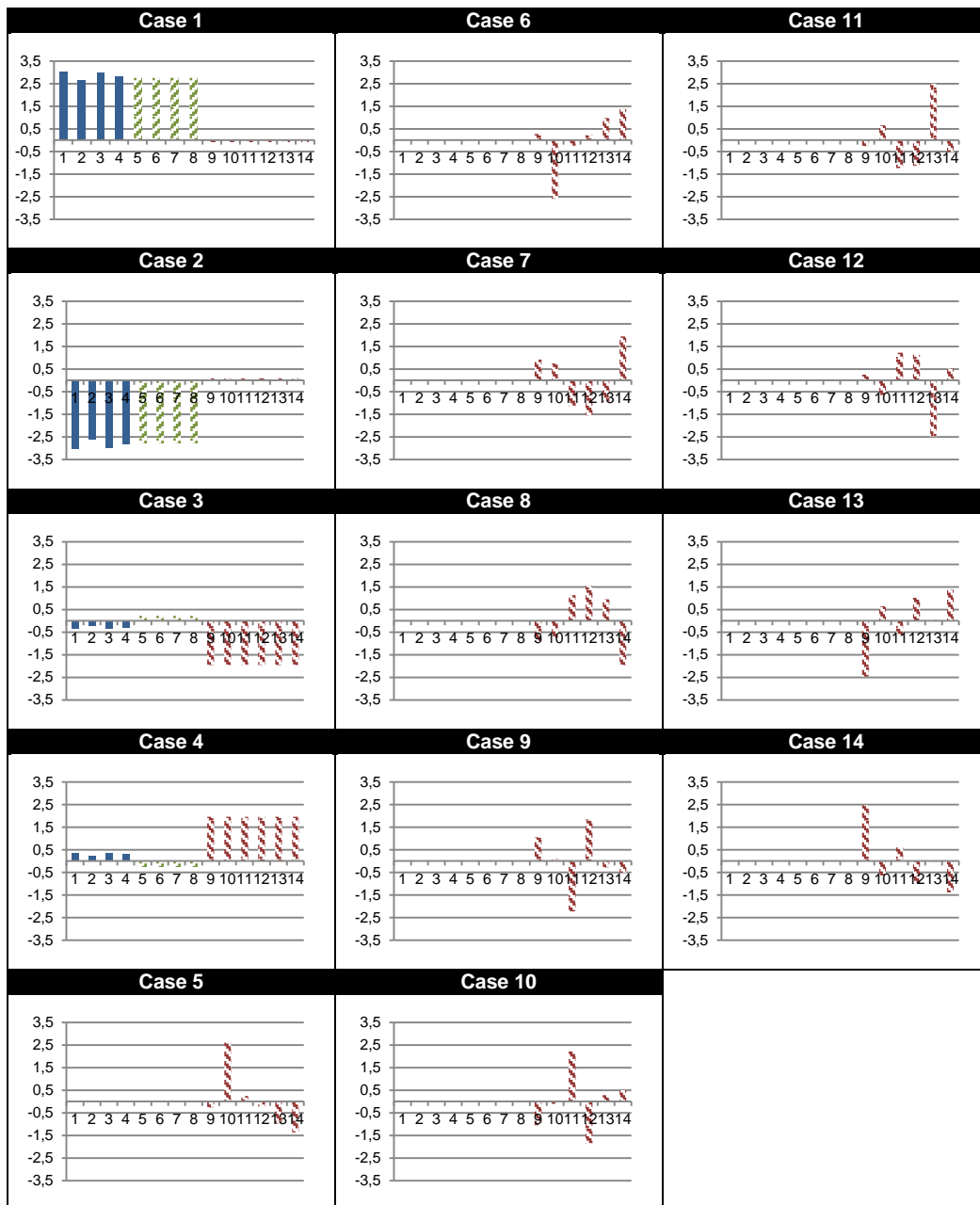
Table 4 Complete synthesized correlation matrix for all anthropometric variables for female data

Correlation data	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Elbow-fingertip length (mm)	1	0.542	0.887	0.777	0.600	0.600	0.600	0.600	0.018	0.018	0.018	0.018	0.018	0.018
2. Hand breadth (mm)	0.542	1	0.596	0.424	0.600	0.600	0.600	0.600	0.018	0.018	0.018	0.018	0.018	0.018
3. Hand length (mm)	0.887	0.596	1	0.655	0.600	0.600	0.600	0.600	0.018	0.018	0.018	0.018	0.018	0.018
4. Shoulder-elbow length (mm)	0.777	0.424	0.655	1	0.600	0.600	0.600	0.600	0.018	0.018	0.018	0.018	0.018	0.018
5. Internal shoulder rotation (Nm)	0.600	0.600	0.600	0.600	1	0.587	0.587	0.587	-0.048	-0.048	-0.048	-0.048	-0.048	-0.048
6. External shoulder rotation (Nm)	0.600	0.600	0.600	0.600	0.587	1	0.587	0.587	-0.048	-0.048	-0.048	-0.048	-0.048	-0.048
7. Elbow peak torque (Nm)	0.600	0.600	0.600	0.600	0.587	0.587	1	0.587	-0.048	-0.048	-0.048	-0.048	-0.048	-0.048
8. Hand grip (N)	0.600	0.600	0.600	0.600	0.587	0.587	0.587	1	-0.048	-0.048	-0.048	-0.048	-0.048	-0.048
9. Wrist flexion (°)	0.018	0.018	0.018	0.018	-0.048	-0.048	-0.048	-0.048	1	0.185	0.185	0.185	0.185	0.185
10. Wrist extension (°)	0.018	0.018	0.018	0.018	-0.048	-0.048	-0.048	-0.048	0.185	1	0.185	0.185	0.185	0.185
11. Elbow flexion (°)	0.018	0.018	0.018	0.018	-0.048	-0.048	-0.048	-0.048	0.185	0.185	1	0.185	0.185	0.185
12. Elbow extension (°)	0.018	0.018	0.018	0.018	-0.048	-0.048	-0.048	-0.048	0.185	0.185	0.185	1	0.185	0.185
13. Internal shoulder rotation (°)	0.018	0.018	0.018	0.018	-0.048	-0.048	-0.048	-0.048	0.185	0.185	0.185	0.185	1	0.185
14. External shoulder rotation (°)	0.018	0.018	0.018	0.018	-0.048	-0.048	-0.048	-0.048	0.185	0.185	0.185	0.185	0.185	1

Table 5 Variable values for the 14 arm models compared to the respective mean value

	1. Elbow-fingertip length (mm)	2. Hand breadth (mm)	3. Hand length (mm)	4. Shoulder-elbow length (mm)	5. Internal shoulder rotation (Nm)	6. External shoulder rotation (Nm)	7. Elbow peak torque (Nm)	8. Hand grip (N)	9. Wrist flexion (°)	10. Wrist extension (°)	11. Elbow flexion (°)	12. Elbow extension (°)	13. Internal shoulder rotation (°)	14. External shoulder rotation (°)
Mean value	443	79	180	336	21	17	29	296	71	69	149	4	70	90
Case 1	513	89	209	385	42	30	49	477	70	68	149	4	68	88
Case 2	373	70	152	287	0	4	9	115	71	70	150	5	72	91
Case 3	434	79	177	331	22	18	30	311	51	47	138	-6	33	67
Case 4	451	80	184	341	19	16	27	282	90	91	160	14	107	112
Case 5	443	79	180	336	21	17	29	296	68	99	151	3	51	74
Case 6	443	79	180	336	21	17	29	296	73	40	148	5	89	105
Case 7	443	79	180	336	21	17	29	296	80	78	143	-4	52	112
Case 8	443	79	180	336	21	17	29	296	61	61	156	12	88	67
Case 9	443	79	180	336	21	17	29	296	81	70	137	14	65	84
Case 10	443	79	180	336	21	17	29	296	60	68	162	-5	75	95
Case 11	443	79	180	336	21	17	29	296	68	77	142	-2	118	83
Case 12	443	79	180	336	21	17	29	296	73	62	156	10	22	96
Case 13	443	79	180	336	21	17	29	296	46	76	146	9	71	105
Case 14	443	79	180	336	21	17	29	296	95	62	153	-1	70	74

Table 6 Visualization of body size, strength and range of motion for the 14 manikins. Graphs show standardised Z-values on the Y-axes. For translation of numbers on X-axes see table 4 and 5.



4. Discussion

The results from the study show that it is possible to introduce additional variables such as strength and ROM, but also that data of the correlation between body size and other types of anthropometric measurements are scarce. New measurement studies are important to decrease the uncertainties when predicting correlation coefficients between body size, strength and ROM variables. One reason to why correlation data between these types of variables are not published can be that the low correlation coefficients cannot be used in predictive regression analyses. Only a few studies of this type

have been done and it has been necessary to include age and sex in the regression analyses (Andrews et al., 1996; D'Souza et al., 2012). However, in the type of study presented in this paper it is not important that the correlation is high or that the data gives a good foundation for predicting undefined data. Instead focus is put on mimicking the diversity regarding size, strength and ROM that exist within populations by a creating a number of digital test manikins with extreme but still realistic combinations of capabilities, i.e. boundary cases.

The validity of the generated human arm model data can be discussed due to the limitations of the data that they are based upon, both related to

amount and applicability of data. The synthesized generic correlation matrices are created with insufficient data. More studies where different types of variables are studied would decrease this problem. It is also important to include different types of age groups as strength and ROM variables are correlated to age. With studies combining body size, strength and ROM variables, more specific correlation coefficients can be defined. It is for example likely that the variables connected to a specific body part have higher correlation between each other than with variables of other body parts. An approach could be to evaluate such 'internal' and 'external' relationships between strength and ROM variables. The presence of such 'internal' and 'external' relationships is indicated when studying correlation data of joint flexibility in Hupprich and Sigereth (1950). However, ROM and joint flexibility has shown to be a specific factor varying considerably with each joint (Roebuck et al., 1975). Strength and ROM variables are also affected by the velocity in the joints and joint angular position (Frey Law et al., 2009). Therefore it is of great importance that the way that the measured variables are analysed matches the way they are modelled in the DHM software.

As human-machine interactions are not only affected by the size and proportions of a user but also other user capabilities, such as strength and ROM variables, it is important to include variation of these variables when creating computer manikins. However, as the correlation is low between and in-between the different groups of variables, especially for ROM variables, it is necessary to include more Principal Components (PCs) in the analysis for the PCs to retain intended part of the variation of the original variables. This leads to analyses with higher dimensionality and in the end that more computer manikins need to be created to represent the diversity of body size, strength and ROM.

Another approach could be to focus more on the design problem and human-machine interaction being analysed. A human-machine interaction could be limited by the body size as well the ROM and strength of a person. If the human-machine interaction would be limited by ROM or strength it is most likely the persons with smallest ROM and weakest persons that will have problems to use the product or workstation. It could therefore be argued that simulations should be done with manikins of different sizes but all with low strength and small ROM. However, if none of the manikins with low strength and small ROM would be able perform the simulated task it could in some cases be of interest to know if a manikin with average or high strength and ROM would be able to perform the simulated task. A solution could be to create manikins with

low, average and high values or a combination of these for variables connected to strength and ROM for each case from an analysis of body size variables. This would not mimic the diversity that exist within populations but would create test cases that would be of interest to use to evaluate a design.

Another approach that could be interesting to consider is to assess and simulate specific impairment diagnoses when determining values for strength and ROM variables. Marshall et al. (2010) use a similar approach where measurements for a number of variables of persons with different types of impairments are used to create virtual human models in the HADRIAN tool.

5. Conclusion

Results from the study indicate that it is possible to successfully include strength and ROM variables in addition to body size variables when creating boundary case based collections of manikins, exemplified with arm models in this study. However, the literature study showed that data of the correlation between body size and other types of anthropometric measurements are scarce. New measurement studies are important to decrease the uncertainties when predicting correlation coefficients between body size, strength and ROM variables.

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