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Workload Assessment Predictability for Digital Human Models

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28.1 Introduction

Physical loading on the human motor system at work is a direct consequence of workstation and workplace conditions, as well as work system organization. The most efficient way to shape the various work system components would be to address them at the design stage, when functional requirements and system limitations can be considered most effectively. It is much more difficult to correct any limitations after the systems, especially large or complex systems, have already been designed (Karwowski, 2005). First attempts to model the human body and its relevant characteristics for system design purposes date as early as the 1970s (i.e., Ryan et al, 1970; Ryan, 1971; Kroemer, 1973; Bonney et al., 1974). Rapid advances in personal computers facilitated applications of computer-aided design (CAD) techniques and stimulated development of a variety of concepts and frameworks for modeling the human body. Such models include, for example, COMBIMAN (Kroemer, 1973; Evans, 1976; McDaniel, 1990), Sammie (Bonney et al., 1974, 1982; Case et al., 1990; Porter, 1992; Feeney et al., 2000), Apolin (Grobelny, 1988; Grobelny et al, 1992), Crew Chief (McDaniel, 1990), Ergoshape (Launis & Lehtela, 1990, 1992), Heiner (Schaub & Rohmert, 1990), Safework (Fortin et al., 1990), Tadaps (Westerink et al., 1990), Werner (Kloke, 1990), Apolinex (Grobelny & Karwowski, 1994, 2000), Ramsis (Seidl, 1994, 1997; Bubb, 1998; Marach 6k Bubb, 2000; Bubb et al., 2006), Jack (Badler et al., 1995; UGS, 2004), Human (Sengupta & Das, 1997), Anthropos (Lippmann, 2000; Bauer et al., 2000; 1ST, 2002), and others. A comparison of such systems was discussed by Dooley (1982), Rothwell (1985), Karwowski et al. (1990), Porter et al. (1992), Hanson (2000), Wolfer (2000), Chaffin (2001), and Laurenceau (2001).

The main component of many computer-based models of the human body is the human mannequin generator that allows creation of virtual representations of the human body, with user-defined body segments according to the published anthropometric data (i.e., Pheasant, 1991). Typically, computer software generates desired models by scaling the human body according to the given percentile of body height. In some cases, it is also possible to specify additional parameters such as gender, nationality, or psychosomatic body type. Available systems differ from each other with respect to their modeling features, including precision of anatomical body representation, simulation of the effects of clothing, or the number of available parameters that define differences in the human body due to relevant or desired characteristics (Kee & Karwowski, 2002). In addition, some systems also allow for additional functions, such as the field of vision that aims to describe the effects of differing body postures at work (i.e., Anthropos, Apolinex, COMBIMAN, Safework, Sammie, Ramsis, Jack). Other useful design applications include simulated descriptors of physical workload, for example static force moments at different body joints calculated for a given body posture with due consideration of the eternal loadings and environmental conditions (i.e., Anthropos, Apolinex, COMBIMAN, Ergoshape, Safework, Sammie, Tadaps). Despite great progress in human body simulation, there are many outstanding issues that need to be resolved (Chaffin, 2005). Furthermore, limited validation of the available systems with respect to human body representation implies the need to exercise due care in reaching conclusions or making generalizations based on system-generated simulation results (Ruiter, 2000).

This chapter focuses on the applications of the Anthropos system operating in the 3D Studio Max environment, for analysis of static postural loading and comparison of results with estimates of perceived physical workload. The main objective of the study was to compare the results of the Anthropos ErgoMAX human body modeling system with the results of subjective estimates made by a group of industrial workers in one company. The results of this case study constitute a basis for discussing the advantages and disadvantages of applying human models for assessing physical workload. Some recommendations have also been proposed to evaluate the predictability of workload assessments carried out by the DHM software in a more systematic way. (

28.2 A Case Study

28.2.1 Company Profile

This study was carried out in a branch of an international company, located in Poland and operating in the automobile sector. The company specialized, among other things, in manufacturing various rear-view systems for cars—mostly internal and external mirrors. The enterprise was one of the leaders in this area with a production of 18 million mirrors a year, and with extensive experience of more than 30 years. The Polish branch employed more than 250 workers in 2006.

28.2.2 Subjects

Thirty-four employees from 12 different workstations took part in the study. In total, there were 10 females (29%) and 24 males (71%). The distribution of workers performing different tasks is shown in Table 28.1.

Eighteen of the participants were married (53%). One worker had primary education, five had vocational education, three had higher education, and the rest (25,74%) were graduates of secondary schools (high school or equivalent). Other personal characteristics of the participating workers are presented in Table 28.2.

28.2.3 Workload Assessment by Means of Digital Human Models

28.2.3.1 Methods

The Anthropos ErgoMAX 6.0.2, working in the 3D Studio Max 6.0 environment, was used to assess workload due to working body postures. Anthropos provides for the following indices of postural

TABLE 28.1 Characteristics of Work Assignments

No.	Work Position	Employees	Men	Women
1	Painter	3	2	1
2	Fitter (I)	4	2	2
3	Fitter (II)	5	3	2
4	Polisher (I)	2	2	0
5	Polisher (II)	2	0	2
6	Polisher (III)	2	2	0
7	Polisher (IV)	3	3	0
8	Presser	3	1	2
9	Technician	2	2	0
10	Forklift truck operator	2	2	0
11	Plastics deliverer	2	1	1
12	Stockroom deliverer	4	4	0

discomfort due to body postures at work (1ST, 2002): discomfort; posture (angular joint position within motion limits); joint resistance; joint torque; normal forces *(x, y, z,* and vector); and difference of current posture angles to NASA neutral posture where the body experiences zero load (NASA, 1995). For all these indicators it is possible to take into consideration the support of selected body segments, as well as assignments of additional weights to hands, feet, and a head. The values of all percentage measures in Anthropos have been classified into three zones according to the increasing level of postural loading: green zone for values below 70%, yellow zone for values between 71% and 90%, and red zone for all values greater than 90%.

28.2.3.2 Procedures

All potential subjects were informed about the goals and study procedures, and had volunteered to participate in the study. The most prevalent body postures at all work positions were identified based on interviews with participating workers, direct on-site observations, and analysis of video recordings of all workers. Such body postures were then simulated using the Anthropos system, for both a 50th-percentile male and a 50th-percentile female. The adult mannequin with normal somatic type (50% value) representing the middle-European population was used for this purpose. Figure 28.1 depicts examples of the simulated work postures.

For the purpose of this project, the percentage index of postural discomfort was selected from those available in the Anthropos indices of postural loading. Such an index takes into consideration the following loading factors: joint angles (posture); resistance; force; and torque, which are estimated using

TABLE 28.2 Detailed Subject Characteristics

Subject Data	Mean	Standard Deviation	Minimum	Maximum
Age (years)	27.8	6.45	20	48
Weight (kg)	72.2	14.1	49	105
Height (cm)	173	10.1	150	187
Overall work experience (years)	7.82	6.89	0.13	28
Seniority in the company (years)	1.88	2.74	0.08	12

FIGURE 28.1 Examples of body positions simulated in Anthropos software.

empirically based proportions. More information about the calculation of this index can be found in 1ST (1998) or Deisinger et al. (2000). It should be noted that the percentage index of postural discomfort is a static measure, and as such, it does not consider the dynamics of human motions. The level of discomfort is calculated for each body segment under a given body posture. The percentage values of discomfort were used to define an average discomfort score for arms and legs, as well as an average discomfort score for the whole body. All calculations for male and female workers were done separately for representative body postures for all work positions.

For any given work position, the average postural discomfort score was defined as the arithmetic average of all products of the average value of discomfort and weights related to time exposure to a given posture during the entire workshift and by taking into account all representative body postures. The overall postural discomfort for a given work position was calculated as the average value of the discomfort scores for male and female workers.

28.2.3.3 Results: Perceived Body Discomfort

Detailed results of the discomfort scores for all work positions are presented in Table 28.3. The highest values of average discomfort scores were attributed to plastics delivery operations (87%), and technician work. The forklift truck operator exhibited the lowest score of postural discomfort. In general, the perceived discomfort scores were higher for the arms than for the legs. The reverse trend was observed in only three cases—the forklift truck operator, plastics delivery operations, and stockroom delivery operations.

28.2.4 Subjective Workload Evaluation

Numerous subjective tools for workload assessment focused on mental work tasks and psychological workload of employees—Cooper-Harper Scale (Cooper 8c Harper, 1969), Bedford Scale (Roscoe, 1987; Roscoe & Ellis, 1990), Workload Profile (Tsang & Velazquez, 1996), Multiple Resources Questionnaire (Boles & Adair, 2001), Integrated Workload Scale (Pickup et al., 2005), and Subjective Workload Assessment Technique (Reid & Nygren, 1988). Subjective methods were also used for a comprehensive workload evaluation. In this area, NASA Task Load Index (Hart & Staveland, 1988) is widely used. One of the latest proposals that take into account the multi-dimensional nature of workload was presented by Jung and Jung (2001), and Michalski and Grobelny (2007).

TABLE 28.3 Mean Discomfort Values for All Evaluated Positions

	Discomfort (%)		
Position	Arms	Legs	Average
Painter	70.4	44.4	57.4
Fitter (I)	61.4	51.4	56.4
Fitter (II)	59.1	46.1	52.6
Polisher (I)	84.3	54.6	69.4
Polisher (II)	61.3	43.7	52.5
Polisher (III)	56.7	43.7	50.2
Polisher (IV)	63.1	43.8	53.5
Presser	66.5	50.3	58.4
Technician	90.5	69.7	80.1
Forklift truck operator	20.1	48.0	34.0
Plastics deliverer	81.2	92.8	87.0
Stockroom deliverer	42.2	57.9	50.0
Mean	63.1	53.9	58.5
Standard deviation	18.9	14.4	14.3
Mean standard error	5.5	4.2	4.1

The major advantage of the methods presented by Michalski and Grobelny (2007)—the Overall Workload Level (OWL) and Subjective Overall Workload Assessment (SOWA)—is an application of the Analytic Hierarchy Process (AHP) developed by Saaty (1980, 1994, 1996). In the AHP method, by means of pair-wise comparisons of available variants and some additional calculations, one can obtain a vector of weights that allows for setting the hierarchy of importance of the analyzed items. A big advantage of the AHP is the possibility of controlling the ratings conformance during the pair-wise comparisons by Calculating the inconsistency ratio (IR). One of the main drawbacks of this tool is the rapidly growing number of comparisons and increasing number of decision variants. Additional assessments of the virtues and constraints of various subjective methods of workload evaluation can be found, for example, in the works of Vidulich and Tsang (1986), Rubio et al. (2004), Phillips and Boles (2004), and Barriera-Viruet et al. (2006). An in-depth discussion of the subjective measures applied in ergonomics was presented by Annett (2002) and was followed by a series of commentaries.

28.2.4.1 Methods

In this work, the SOWA method (Michalski & Grobelny, 2007) and supportive software were employed to evaluate subjective workload levels. The method was based on the OWL (Jung & Jung, 2001) with some properties taken from other subjective techniques. The workload is evaluated in four fundamental dimensions: manual material handling (MMH); material work environment (MWE); body posture and movement (BPM); and mental demand environment (MDE). Each of these dimensions is characterized by several attributes. The detailed structure together with the full description of the SOWA method and supportive software can be found in the work of Michalski and Grobelny (2007).

28.2.4.2 Apparati

Specialized software supporting the SOWA technique was applied to improve the performance of questionnaire data input, and to allow for clear and comprehensible presentation of results. The computer application was based on the Microsoft Access database and was developed in the Microsoft Visual Basic 6.0 environment. All necessary information regarding these analyses, including personal details, parameters ratings, and comparisons together with inconsistency ratios, were compiled in a database file.

28.2.4.3 Procedures

A required number of assessment questionnaires were generated and printed out by means of the SOWA software. The generated reports consisted of four parts: a personal details survey, a workload attributes assessment form, and two pair-wise comparison forms. At first, subjects compared parameters within the confines of the individual workload dimensions. The same procedure was then used for all other workload dimensions. In the generated questionnaires, the order of parameters, parameters comparisons, and dimensions comparisons was set randomly. The assessment of the subjective workload was administered during work hours with groups of several employees.

The human subjects, who were all volunteers, were informed about the purpose and scope of the study. They were also instructed as to how to fill out the questionnaires, and they were assured of anonymity regarding their answers. The typical procedure for an individual group lasted 15 to 20 minutes. All subjects were given an opportunity to ask questions and received appropriate explanations and assistance any time during the study. The collected questionnaire data were entered into the software and then analyzed. The weights as well as overall perceived workload assessment index values (OPWAI) and inconsistency ratios were computed according to the AHP technique.

28.2.5 Results

The average value of the obtained workload index was 74.2%. The largest value of the OPWAI was registered for the stockroom delivery operators, which amounted to 91% of the maximum possible rate. A very high score was also received for the polisher (I) at 89.7%, while the lowest mean value of OPWAI were obtained for forklift truck operators at 58.6%. Taking into consideration the values calculated for different dimensions, it can be noted that the highest shares in the total value of OPWAI were attributed to the body posture and movement for the polisher (II) at 60.4%. In turn, the MWE component constituted a considerable part of OPWAI for the polisher (II) (44.9%) and painter (43.4%). In the case of stockroom delivery operations, the biggest value was observed for MMD (45.3%). The lowest value of the analyzed dimensions was obtained for polisher (I)—the relative share amounted to 1.6%.

In general, the highest scores were registered in the BMP factor, whereas the least important factor in all work positions was related to mental demands. Data about the overall workload index and mean IR values for all analyzed work positions are presented in Table 28.4. Because the applied software provides weighted scores for all attributes evaluated by an employee, it is possible to make further in-depth analyses within the confines of the given dimension. The most interesting dimension in this respect relates to body posture and movement (see Table 28.5).

28.2.6 Comparison of Results and Discussion

Figure 28.2 depicts the values of average discomfort scores with subjective average estimates of BPM for all work positions. In all cases, except for the polisher (II), the subjective estimates were much lower than indicators of discomfort generated by the Anthropos system. The largest differences were noted for the stockroom delivery workers, where subjective assessments of workload measured by BPM (11%) were nearly fivefold lower than the one derived from digital human modeling with an average score of discomfort of 50%.

A correlation analysis was performed in order to verify the results of the Anthropos analysis with subjective worker assessments of discomfort at each of the investigated work positions. Table 28.6 shows the correlation coefficients between the average values of postural discomfort (for arms, legs, and average) and main subjective workload indices (OPWAI MMH, MWE, BPM, MDE). The only statistically significant ($p < 0.05$) correlation was found between the reported arms discomfort and material work environment. The correlations between MWE and BPM and the average discomfort, as well as between BPM and arms discomfort, showed trends at the $p < 0.1$ level.

TABLE 28.4 Overall Perceived Workload Assessment Indices, Weighted Scores for Four Main Dimensions, and the Average Inconsistency Ratio for All Evaluated Positions

Position	OPWAI (%)	IR	[1] MMH (%)	[2] MWE (%)	[3] BPM (%)	[4] MDE (%)
Painter	75.8	0.568	4.2	43.4	23.2	5.0
Fitter (I)	68.2	0.251	7.4	13.1	40.1	7.6
Fitter (II)	64.7	0.214	12.0	14.2	31.6	6.9
Polisher (I)	89.7	0.198	1.6	44.9	40.0	3.2
Polisher (II)	75.1	0.642	3.5	6.9	60.4	4.3
Polisher (III)	85.4	0.952	22.1	12.3	39.2	11.8
Polisher (IV)	73.7	0.272	6.4	17.6	28.9	20.8
Presser	59.0	0.253	17.2	18.0	20.9	2.9
Technician	80.4	0.164	10.7	30.9	34.1	4.7
Forklift truck operator	58.6	0.312	22.5	6.3	15.6	14.3
Plastics deliverer	68.6	0.365	11.3	6.7	41.5	9.0
Stockroom deliverer	90.6	0.205	45.3	17.1	11.2	17.0
Mean	74.2	0.366	13.7	19.3	32.2	9.0
Standard deviation	10.9	0.237	12.1	13.4	13.5	5.8
Mean standard error	21.4	0.106	4.0	5.6	9.3	2.6

In general, it can be assumed that the anticipated positive relationship between the subjective scores of perceived workload due to posture at work and the average discomfort scores calculated with the help of Anthropos was only partially confirmed through the reported correlation coefficients. The low values of correlations between the indices of postural body discomfort and mental work demands were expected. Similarly, insignificant correlations were observed between the discomfort scores and OPWAI. Most likely this was due to the fact that the OPWAI value reflects a global loading on the human body, while

TABLE 28.5 Detailed Perceived Workload Assessment Weighted Scores for the BPM Dimension

	Decomposition of the BPM Dimension (%)				
Position	Standing	Stooping	Squatting & Kneeling	Twisting	IR
Painter	46.2	13.3	21.7	3.4	1.097
Fitter (I)	48.3	18.3	2.8	3.7	0.080
Fitter (II)	44.1	4.7	4.1	12.4	0.319
Polisher (I)	71.3	4.6	0.5	11.6	0.250
Polisher (II)	68.4	11.5	2.6	2.5	0.438
Polisher (HI)	50.4	20.1	5.9	16.5	1.336
Polisher (IV)	71.2	8.1	3	5.9	0.250
Presser	52.2	18.7	0.6	2.8	0.179
Technician	27.4	27.8	27.9	7.6	0.147
Forklift truck operator	2.4	37.8	11.3	10.7	0.402
Plastics deliverer	42.6	18.5	22.3	7	0.210
Stockroom deliverer	35.2	29.6	14.1	10.2	0.051
Mean	46.6	17.8	9.7	7.9	0.397
Standard deviation	19.6	10.2	9.6	4.5	0.403
Mean standard error	5.7	2.9	2.8	1.3	0.116

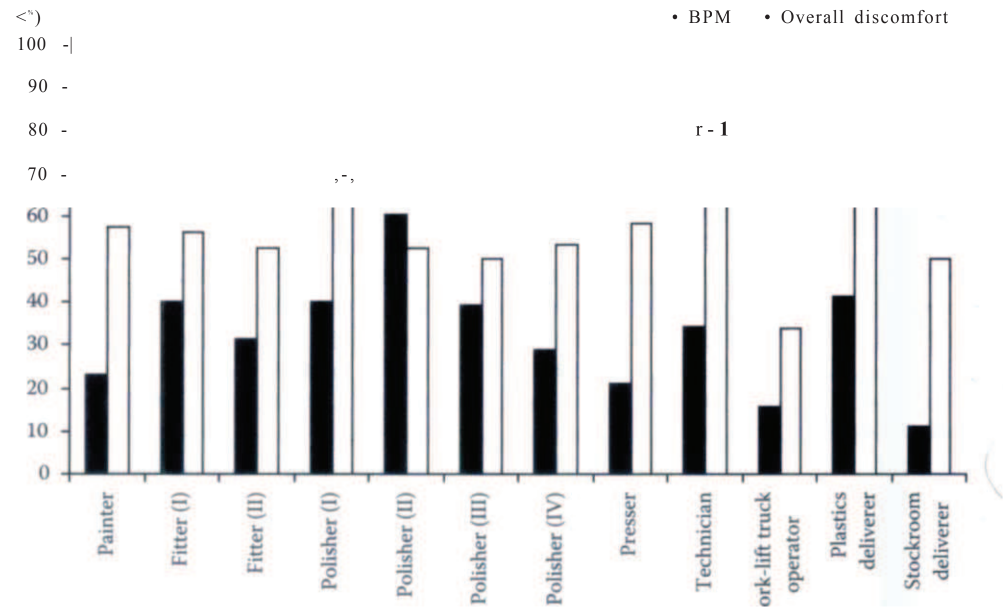

FIGURE 28.2 BPM assessment values and average discomfort indicators for all examined work positions.

the average values of discomfort reflect only the effects of static postural loading. While statistically insignificant, there was relatively high negative correlation (r = -0.493, p = 0.103) between MMH and arms discomfort. One possible explanation of this result is that manual material handlers are typically involved in dynamic work activities, which do not require supporting static body postures for a long period of time (Kee & Karwowski, 2001b).

The study results also revealed a positive linear relationship between work environment conditions and discomfort scores for arms and the average discomfort value. Such a relationship may indicate that those respondents who negatively assessed the quality of their working conditions also scored higher on the perceived postural loading at work. Therefore, poor postures at work can also negatively influence the overall subjective impression of working conditions.

In order to further explore results of this study, the correlation coefficients between the discomfort scores and the attributes of the subjective assessments of workload in the context of body postures and motions were also calculated (see Table 28.7). The highest correlation coefficient was observed between discomfort of the legs and squatting and kneeling posture (r = 0.616; p < 0.05). While statistically insignificant (p < 0.1), there was relatively high negative correlation between arms discomfort and standing and stooping posture, indicating less loading on arms during stooping at work. On the other hand, a

TABLE 28.6 Correlation Matrix between Calculated Discomfort Values and Subjective Workload Dimensions (p values in parentheses)

	OPWAI	MMH	MWE	BPM	MDE
Arms discomfort	0.291	-0.493	0.578	0.559	-0.058
	(0.359)	(0.103)	(0.049)	(0.059)	(0.857)
Legs discomfort	0.034	0.001	0.231	0.339	-0.029
	(0.916)	(0.998)	(0.471)	(0.281)	(0.929)
Average discomfort	0.210	-0.327	0.500	0.543	-0.053
	(0.512)	(0.300)	(0.098)	(0.068)	(0.869)

TABLE 28.7 Correlation Matrix between Calculated Discomfort Values and Components of a Body Posture and Movement Dimension (p values in parentheses)

	Standing	Stooping	Squatting & Kneeling	Twisting
Arms discomfort	0.505	-0.507	0.248	-0.372
	(0.094)	(0.093)	(0.436)	(0.233)
Legs discomfort	-0.232	0.239	0.616	-0.036
	(0.469)	(0.455)	(0.033)	(0.911)
Average discomfort	0.218	-0.216	0.476	-0.266
	(0.497)	(0.501)	(0.118)	(0.404)

positive correlation between arm discomfort and standing posture reflects that most workers engaged in standing postures performed tasks with a high level of static arm loading.

It should also be noted that the values of average IR indices were quite high (see Tables 28.4 and 28.5). This indicates the effect of inconsistent results of pair-wise comparisons and the final values of subjective assessment scores by the workers. If the subjective questionnaires were collected from a larger number of employees, the high values of IR for the individual workers would be less important, and would probably result in larger values of correlation coefficients (and also higher statistical significance of results). Moreover, it is also possible that IR values resulted from difficulties in distinguishing between different dimension variants because, for example, a given group of factors was found to be of no importance to the workers' perceived workload.

28.3 Conclusions

Despite their apparent shortcomings, the contemporary information systems that make possible digital modeling of humans at work are very useful in preventing basic errors at the system design stage. Furthermore, the tools and mannequins such as Anthropos provide very useful models of the human body characterized by relevant statistical parameters and high-quality visualization capability. Application of such systems can lead to better understanding of work system incompatibilities (Karwowski, 2005), and should help in developing comprehensive models of virtual working environments. Such models can also help in prevention efforts aimed at reducing the onset of work-related musculoskeletal disorders, especially those that are linked to poor workstation design and inadequate workspace organization.

The case study presented in this chapter is an example of applying the Anthropos system and SOWA software in order to simulate and analyze the extent of static loading due to different body postures at work in a single production company and a limited population of subjects. Therefore, the presented analysis does not constitute comprehensive verification of the usefulness and predictability of this applied human body modeling system. Such verification would require significantly enlarging the pool of subjects and performing similar studies at different companies. Furthermore, other DHM computer systems should also be considered.

Despite the above limitations, the results indicate that software modules for assessment of the effect of static postural loading on the human body in the context of virtual mannequins can be very useful as supplementary methods for physical workload analysis. Unfortunately, the high cost of virtual modeling environments (such as 3D Studio Max and Anthropos) may limit practical applications of these systems in the workplace. Another obstacle in this quest is the relative complexity of software generating digital human mannequins, as well as the complexity of the available human-computer interfaces. The clear benefit of the proposed approach is the ability to simulate static postural loading of workers for those workplaces and workstations that are still at the design stage. Finally, it should be noted that statistically significant correlations between subjective discomfort scores and some of the workload attributes make it possible to replace expensive analysis that utilizes virtual mannequins by a relatively simple and fast questionnaire for physical workload assessment.

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