Ergonomic Optimization of a Manufacturing System Work Cell in a Virtual Environment

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The paper deals with the development of a methodology for studying, in a virtual environment, the ergonomics of a work cell in an automotive manufacturing system. The methodology is based on the use of digital human models and virtual reality techniques in order to simulate, in a virtual environment, human performances during the execution of assembly operations. The objective is to define the optimum combination of those geometry features that influence human postures during assembly operation in a work cell. In the demanding global marketplace, ensuring that human factors are comprehensively addressed is becoming an increasingly important aspect of design. Manufacturers have to design work cells that conform to all relevant Health and Safety standards. The proposed methodology can assist the designer to evaluate the performance of workers in a workplace before it has been realized. The paper presents an analysis of a case study proposed by COMAU, a global supplier of industrial automation systems for the automotive manufacturing sector and a global provider of full maintenance services. The study and all the virtual simulations have been carried out in the Virtual Reality Laboratory of the Competence Regional Center for the qualification of transportation systems (CRdC "Trasporti" - www.centrodicompetenzatrasporti.unina.it), which was founded by the Campania region with the aim of delivering advanced services and introducing new technologies into local companies operating in the field of transport.

Keywords: Ergonomics, digital human models, manufacturing process, work cell optimization.

1 Introduction

The implementation of a so-called "*Digital Factory*" is a tremendous challenge for automotive engineering. The technical task is to effect a seamless information backbone spanning three key departments: Design, Production Process Planning, and Manufacturing. Also suppliers such as machine and tool vendors have to be integrated into the information flow. Furthermore, there is the challenge of assimilating the human factor into the digital factory. New production planning tools will significantly change not only the contemporary production process planner's work but also the collaboration with suppliers. This raises one major issue: how to integrate different user groups into the design of complex engineering applications for production planning. The authors focus on a case study about the development of a methodology for optimizing the workplace in the automotive field. In particular they investigate the feasibility of integrating virtual humans into design environments to perform ergonomic assessments [1]. The paper illustrates the general benefits of ergonomic assessments, detailed advantages due to the utilisation of virtual humans. A virtual human is an accurate biomechanical model of a human being. These models fully mimic human motion to allow an ergonomics (or human-factors) expert to perform process flow simulations. This study uses an analysis of the JACK software package to highlight the usefulness of such software options for applications in the manufacturing industry [2]. Workplace ergonomic considerations have traditionally been reactive, time-consuming, incomplete, sporadic, and difficult. The experience of an expert in ergonomic studies or data from injuries that have been previously observed and reported have always been necessary for these studies, and analyses are made after problems have occurred in the workplace. There are now emerging technologies supporting simulation-based engineering, and several operational simulation-based engineering systems to address this in a proactive manner. At present various commercial systems are available for ergonomic analysis of human posture and workplace design.

2 Related work

The importance of applying ergonomics to workplace design is illustrated by the Injuries, Illnesses, and Fatalities (IIF) program of the U.S. Department of Labor, Bureau of Labor Statistics [3]. According to this report, there were 5.2 million occupational injuries and illnesses among U.S. workers and approximately 5.7 of every 100 workers experienced a job-related injury or illness. Workplace-related injuries and illnesses increase workers' compensation and retraining costs, absenteeism, and faulty products. Many research studies have shown the positive effects of applying ergonomic principles in workplace design [4]. Riley et al. [5] describe a study to demonstrate how applying appropriate ergonomic principles during design can reduce many life cycle costs. Traditional methods for ergonomic analysis were based on statistical data obtained from previous studies or equations based on such studies. An ergonomics expert was required to interpret the situation, analyze and compare with existing data, and suggest solutions. The standard analytical tools included the NIOSH lifting equation [6], Ovaka posture analysis [7], and Rapid Upper Limb Assessment [8], among others. Various commercial software systems are now available for ergonomic studies. Hanson [9] presents a survey of three such tools, ANNIE-Ergoman, JACK, and RAMSIS, used for human simulation and ergonomic evaluation of car interiors. The tools are compared and the comparison shows that all three tools have excellent potential in evaluating car interiors ergonomically in the early design phase. JACK [10], an ergonomics and human factors product, enables users to position bio-mechanically accurate digital humans of various sizes in virtual environments, assign them tasks and analyze their performance. Gill et al. [11] provide an analysis of the JACK software to highlight its usefulness for applications in the manu-

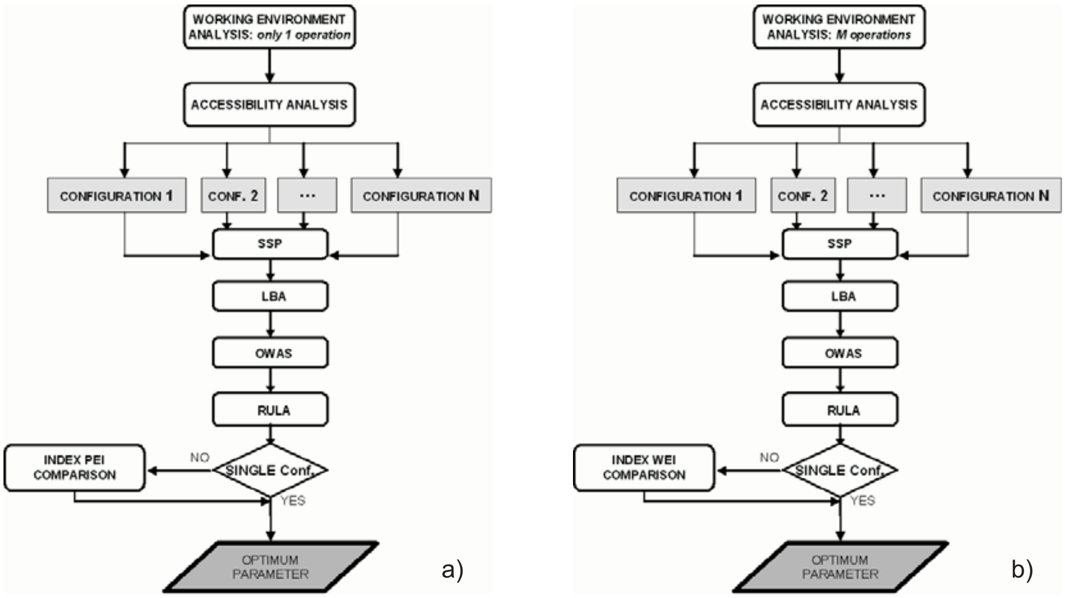

Fig. 1: a) PEI method Flow Chart, b) WEI method Flow Chart

facturing industry. Eynard et al. 12], describe a methodology using Jack to generate and apply body typologies from anthropometric data of the Italian population and compare the results with a global manikin. The study identified the importance of using accurate anthropometric data for ergonomic analysis. Sundin et al. [13], present a case study to highlight benefits of the use of JACK analysis in the design phase of a new Volvo bus. The importance of virtual humans in simulation and design has also been put set out Badler [1] & Hou [14]. Ford has made use of the "Design for Ergonomics" virtual manufacturing process, using JACK. The Ergonomic Design Technology Lab at Pohang Institute of Science and Technology is also involved in human modeling, design simulation, design evaluation in virtual environments and design optimization [15]. The potential value of ergonomics analysis using virtual environments is discussed in detail by Wilson [16].

3 The methodology for optimizing a workp1lace: PEI method & WEI method

In this paper the problem that the authors have faced is optimization of the geometric features of a workplace in order to guarantee the maximum postural comfort for operators from different anthropometric percentiles during assembly operations. Such optimization, which has to consider the presence of possible external restraints, is strictly connected to the layout of the physical elements present in the working area. For this purpose, a methodology is proposed, based on the application of the "*Task Analysis Toolkit* (TAT)" included in the JACK software, whose functions will be analyzed in the following sections. Among the tools made available by TAT for the analysis of a working activity (*NIOSH Lifting Analysis; RULA; Manual Material Handling Limits; Static Strength Prediction; OWAS; Low Back Analysis; Predetermined Time Standard*) it has not been possible to find "*one*" that enables us to determine, among several solutions, the *optimal* one.

If the geometric features characterizing a workplace influence the ergonomics of only one operation, in order to define the optimum combination of these features, the ***PEI method*** can be applied. It follows the phases illustrated in the flow diagrams of Fig. 1a. The aim of the ***PEI method*** is the ergonomic optimization of an operation within a work cell, so it is referred to a single operation. In general, more than one operation is performed in a work cell. In this case, the combination of geometric features could not influence the single operations in the same way and, therefore, the ***PEI method*** is not applicable. Therefore, the combination of geometric features that optimizes the posture of all human percentiles can be evaluated applying the ***WEI method***. Fig. 1b shows the flow diagram of this approach, where *M* represents the number of operations that have to be performed in the work cell.

3.1 First phase: analysis of the working environment

The first phase consists in an analysis of the working environment and in the consideration of all the possible movement alternatives: this, in general, involves considering alternative routes, postures and speeds of execution, which all contribute to the effective conclusion of the work. It is essential, in a virtual environment, to simulate all these operations in order to verify in the first place their feasibility. In fact, for instance, it cannot be taken for granted that all the points can be reached starting from different postures. The execution of this analysis guarantees the feasibility of the assignment. Among the phases of optimization this is the one that requires the longest time, since it needs the creation of a large number of simulations in real time, without taking into account that some of them will turn out to be useless, because, for instance, the simulation shows that some points cannot be reached with the movements that the designer had conceived. Other parameters that can be modified are the distances of the manikin from objects taken as a reference, and the possibility to move the objects in the working area.

3.2 Second phase: reachability and accessibility analysis

The design of a workplace always requires a preliminary study of the accessibility of the critical points. This is a very interesting problem, and often occurs in assembly lines. The problem consists in verifying that in the designed layouts it is possible to carry out the movements necessary to the operation and that all the critical points can be reached; in a lifting operation, for instance, it could happen that a shelf is positioned too high and that therefore the worker does not succeed in developing his assignment. Such an analysis can be conducted in JACK, activating the collision detection algorithm. The layout configurations that do not satisfy the accessibility analysis do not have to be taken into consideration in the following analyses. From the analysis of the working environment and the accessibility analysis the different configurations can be designed. If the number of configuration is high a *Design Of Experiments* (DOE) procedure can occur [17].

3.3 Third phase: static strength prediction (SSP)

Once the possible working sequences have been conceived, the question is: how many workers will be able to expound the necessary efforts for these movements? The answer can come from the *Static Strength Prediction*. In the case that the task must be developed, during a given period of time, by workers of different stature, age and sex, it can be accepted only in the hypothesis that the tool appraises in 100 % the percentage of workers capable of the working activity. In practice, this cannot be done, because many activities provide percentages lower than 100 %. In the workplace design phase, the operations that have a percentage of 0 % should not be taken into consideration in the following analyses. The operations that have an evaluation of the percentage below a certain limit should also be discarded.

3.4 Fourth phase: Low Back Analysis (LBA)

Low Back Analysis is a tool that allows the strengths to be evaluated on the virtual manikin's spine, according to each posture assumed by the digital human model and any loading action. This tool evaluates, in real time, the actions linked to the tasks imposed on the manikin according to the NIOSH standards and according to the studies carried out in this field by *Raschke* [18]. The *Low Back Analysis* tool offers information related to the compression and cut strengths on the L4 and L5 lumbar disks, together with the reaction-moments in the axial, sagittal and lateral plane on the L4 and L5 lumbar disks and the activity level of the trunk muscles to balance the spine moments. In particular, in the following, we use the value, expressed in Newton, of the compression on the L4 and L5 lumbar disks.

3.5 Fifth phase: Ovako Working Posture Analysis System (OWAS)

OWAS is a simple method for verifying the degree of comfort related to working postures and for evaluating the degree of urgency that has to be assigning to corrective actions. The method was developed in the Finnish metallurgic industries in the 1970s. It is based on a classification of postures and on an observation of working tasks. The OWAS method consists in the use of a four-digit code to assess the position of the back side of the body, the arms and legs together with the intensity of existing loads during the performance of a specific task. The activity under examination has to be observed according a period of about thirty seconds. During each step, the positions and the applied strengths have to be registered, in accordance with a decomposing technique of complex activities. In this way, the distribution of the postures, the repeated positions and the critical positions are focused. The data collection and the successive analysis enable the working procedure to be redesigned to reduce or eliminate postures that are potentially dangerous. In fact, the tasks are classified using four principal classes: 1) no harmful effect, 2) a limited harmful effect, 3) recognised harmful effect on health, 4) highly harmful effect on health.

3.6 Sixth phase: Rapid Upper Limb Assessment Analysis (RULA)

From the initial scenario of possible layout configurations, the procedure progressively discarded those that: 1) did not ensure accessibility of the critical points, 2) asked for efforts that the workers were presumably not able to perform, 3) were potentially dangerous for the lower back. In this phase, the postural quality is analyzed. The purpose is to minimize the risks of muscular-skeletal pathologies in the medium-to-long term. The tool used is RULA. RULA analysis refers to exposure to risk of disease and/or damage to the upper limbs. The analysis takes into account loads, biomechanical and postural parameters focusing on the position of the head, body and upper limbs. The RULA method is based on data sheet filling. The sheet enables the user to quickly compute a value that indicates the degree of urgency of an intervention that needs to be adopted in order to reduce the risk of damage to the upper limbs. The method enables not only arm and wrist analyses, but also head, body and leg analyses. The first analysis, together with the information about muscles in use and existing loads, enables an assessment of the final score that represents the evaluation of the working posture. The risk is considered "acceptable" when the score is 1 or 2, "in need of further investigation" (a score of 3 or 4), "in need of further investigation and a rapid change" (a score of 5 or 6) or "investigation and immediate change" (a score of 7).

3.7 Seventh phase: PEI evaluation

At this point a comparison can be established among the layout configurations, through the critical postures associated with them. The comparison allows us to establish a classification of risk of the operator contracting muscle-skeletal pathologies in the medium-to-long term. The choice of this optimal solution passes through the individuation of the more comfortable posture, which can be carried out using a *Posture Evaluation Index* (PEI), which integrates the results of LBA, OWAS and RULA [19]. In particular, PEI is the sum of three adimensional variables I_1, I_2 and I_3. The variable I_1 is evaluated normalizing the LBA value with the NIOSH limit for the compression strength (3400 N). Variables I_2 and I_3 are respectively equal to the OWAS index normalized with its critical value ("3") and the RULA index normalized with its critical value "5".

$$\mathrm{PEI} = I_1 + I_2 + I_3 \tag{1}$$

where: $I_1 = \mathrm{LBA}/3400\ \mathrm{N}$, $I_2 = \mathrm{OWAS}/3$, $I_3 = \mathrm{RULA}/5$.

PEI definition and the consequent use of LBA, OWAS and RULA task analysis tools depend on the following consideration. The principal risk factors for work requiring biomechanical overload are: repetition, frequency, posture, effort, recovery time. The factors that mainly influence the execution of an assembly task are extreme postures, in particular of the upper limbs, and high efforts. Consequently, attention has to be paid to the evaluation of compression strengths on the L4 and L5 lumbar disks (I_1 determination), to the evaluation of the level of discomfort of the posture (I_2 determination), and to the evaluation of the level of fatigue of the upper limbs (I_3 determination). PEI enables us to select the modus operandi to perform the disassembly task in a simple way. In fact, the optimal posture associated to an elementary task is the critical posture with the minimum PEI value. The variables defining PEI depend on the discomfort level associated with the examined posture: the greater the discomfort, the higher are I_1, I_2 and I_3 and, consequently, PEI.

PEI expresses, in a synthetic way, the "quality" of a posture with values varying between a minimum value of 0.47 (no loads applied to the hands, values of joints angles within the acceptability range) and a maximum value depending on the I_1 index. In order to ensure the conformity of the work with the laws protecting health and safety, a posture whose I_1 index is more than or equal to 1 is assumed not valid. In fact, in this way the NIOSH limit related to compression strengths on the L4 and L5 lumbar disks will be exceeded. According to these considerations, the maximum acceptable value for PEI is 3 (compression strength on the L4 and L5 lumbar disks equal to the NIOSH limit 3400 N; values of joints angles not acceptable). Iterating the procedure for all the elementary tasks of the assembly sequence, it is possible to associate to each of them the optimal posture to be assumed and, finally, to individuate the optimal value of the geometric parameters for the assembly task.

3.8 Eighth phase: WEI evaluation

Once we have individuated the optimal value of the geometric parameters for each operation within a work cell (M represents the number of operation), the WEI (*Work Cell Evaluation Index*) index is introduced [20]. This is defined as:

$$\mathrm{WEI}(Configuration_j) = \sum_i \mathrm{PEI}_i * W_i\,, \qquad (2)$$

where: $W_i = Time\ of\ Operation_i$/Work Cell Time cycle.

The best index WEI is obtained by the following expression:

$$\mathrm{WEI}_{BEST} = \mathrm{MIN}_J \left\lfloor \mathrm{WEI}(Config_j) \right\rfloor. \qquad (3)$$

The WEI definition depends on the following consideration: if the aim is the ergonomic optimization of the work cell, it is necessary to establish a single optimal solution.

4 Case study

In order to test the PEI method and the WEI method, a case study proposed by COMAU was analyzed. The goal was to optimize a body welding work cell by using the methodology explained above.

5 Working environment analysis

The geometric model of the body welding work cell was imported into the JACK software, and then the 9 operations that have to be realized in the work cell were simulated. The 9 operations are as follows:

1. Welding Visual Control	4. Smearing Sealer with Gun	7. Upper Cross member Wind Screen Loading
2. Welding Imperfections Restoring with Brush	5. Smearing Sealer Renewal	8. Back Cross member Wind Screen Loading
3. Braze Welding Renewal	6. Bottom Cross Member Wind Screen Loading	9. Upper Front Rafter Loading

Fig. 2: Sequence of operations in the Body Welding Work Cell

Table 1: Definition of the parameters to be optimized

Operations / Parameters	OP 1	OP 2	OP 3	OP 4	OP 5	OP 6	OP 7	OP 8	OP 9	Score
	1	3	2	1	2	3	2	2	4	$\sum_{i=1}^{9} S$
Worker										
Percentile	√	√	√	√	√	√	√	√	√	20
Postural positions	√	√		√					√	5
Geometric parameters body										
Locking point body	√	√	√	√					√	7

Score value	Meaning
0	Not critical
1	Low injury
2	Middle-low injury
3	Middle-high injury
4	High injury

HEIGHT OF BODY WITH RESPECT TO
NOT CRITICAL … MIDDLE-HIGH … HIGH

Fig. 2 shows the sequence of operations performed in the body welding work cell. Simulating the operations that have to be performed in this work cell, a qualitative analysis of the postural sequence for each operation was conducted, in order to individuate the geometric parameters to be optimized. Table 1 shows the results of this first phase. As shown in the same table, a score was assigned to each operation and a calculation was made of the total score associated to each geometric parameter that influences the postural positions of the workers while they are performing the tasks.

It can be asserted that in this case study there is just one geometric parameter to be optimized, represented by the body height with respect to the assembly line, and one external factor, represented by the percentile of the worker.

6 Accessibility analysis

The analysis of the geometry was conducted in order to define the range of the body height, taking into account the geometric constraints of the work cell. Then, the range was reduced through the accessibility analysis. The visual control of the welding (operation 1) and the smearing sealer with a gun (operation 4) defined the limits of the range, as shown in Fig. 3 and Fig. 4. The lower limit is –5 cm, because the body positioned at –10 cm does not allow the spot welding to be visualized completely (Fig. 3 b), and the upper limit is 20 cm, because the body positioned at 25 cm does not allow the smearing sealer to be realized by the 5th percentile. A step of 5 cm was established, so the possible body height values are 6 ($L_1 = 6$), and the percentiles considered are 3 ($L_2 = 3$): 5th, 50th, 95th.

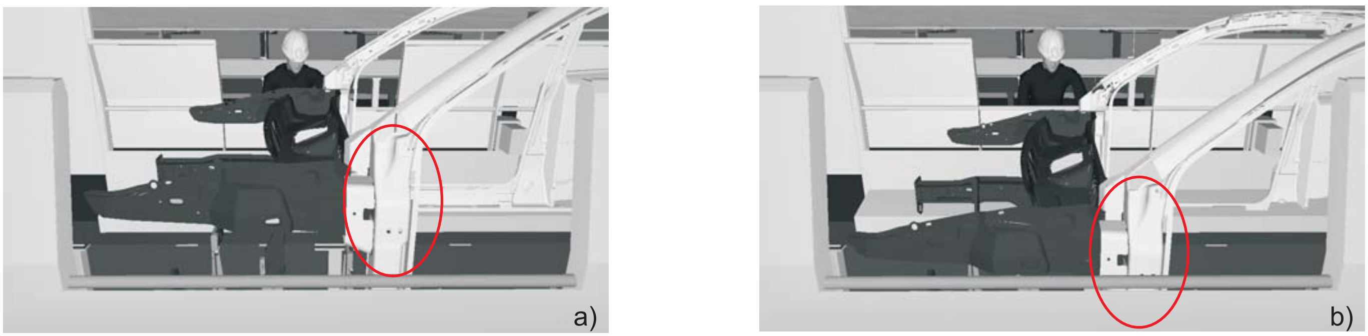

Fig. 3: a) Spot Welding visible, b) Spot Welding not completely visible

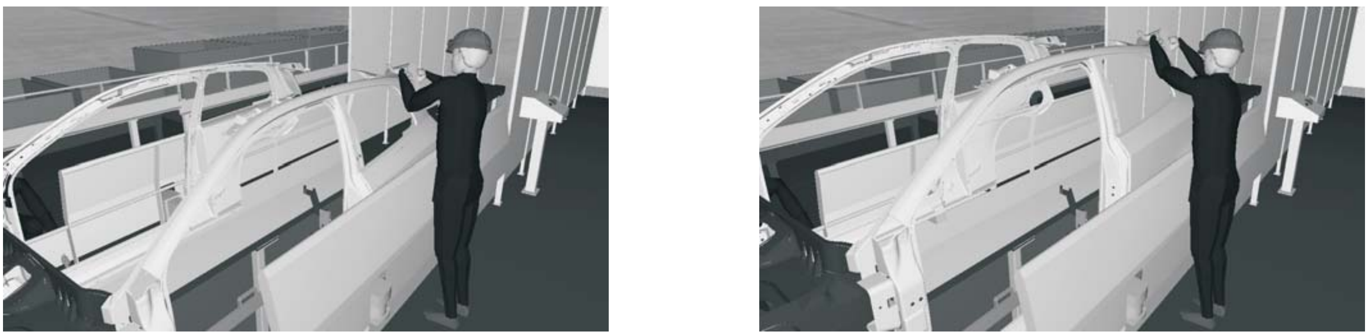

Fig. 4: The Smearing Sealer operation realized by the 5th percentile (on the left), vs the Smearing Sealer operation not practicable by the 5th percentile (on the right)

Now it is possible to define the number of configurations (N): from the combinations of the values of these parameters there are 18 configurations, as shown in Table 2.

Table 2: Experimental plain

Configuration	Height body	Percentile
$N = L_1 * L_2$	$L_1 = 6$	$L_2 = 3$
1	–5	5°
2	–5	50°
3	–5	95°
4	0	5°
5	0	50°
6	0	95°
7	5	5°
8	5	50°
9	5	95°
10	10	5°
11	10	50°
12	10	95°
13	15	5°
14	15	50°
15	15	95°
16	20	5°
17	20	50°
18	20	95°

7 PEI method & WEI method results

By applying the SSP, LBA, OWAS and RULA tools for each configuration and operation, the configurations injurious for the worker have been discarded. Table 3 shows results for the WEI method & PEI method. Note that PEI has been evaluated taking into account an average value among those obtainable. It can be asserted that the height of the body with respect to the assembly line, corresponding to the optimal postural sequence, is 20 cm. Table 3 shows the evaluation of PEI and WEI in some exhaustive cases.

8 Conclusions

The proposed methodology makes available a valid tool for workplace analysis. The following objectives have been achieved: to appraise the quality of the postures assumed during a working activity; in designing a new layout, to establish if it ensures the feasibility of the operation (based on the criteria of accessibility of the critical points, of compatibility of the efforts, and danger for the lower back); to compare the possible alternatives for the configuration of the layout, supplying useful criteria for the designer to choose which is the most convenient to realize in the production chain. The reliability of the results depends on the extent to which the assumptions on which the tools of the TAT are based will be respected: almost static movements, non excessive temperature and humidity of the environment, satisfactory times of rest. Such assumptions are generally satisfied in the normal workplace. The objective of industry is to apply ergonomic criteria to reduce the number of accidents in the workplace and, secondly, to increase productivity. Currently only large firms turn their attention to this sector, because the simulation software has a certain cost, and also because the time for applying the software requires human resources that small firms do not have. The future objective is, on the one hand, to improve the interaction between the theoretical concepts of the ergonomics and the software, and, on the other, to simplify the analytical procedures to reduce time and costs.

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Table 3: WEI method & PEI method results

Conf.	Height body	Perc.	Op1 $W = 0.044$ PEI	Op2 $W = 0.088$ PEI	Op3 $W = 0.088$ PEI	Op4 $W = 0.133$ PEI	Op5 $W = 0.133$ PEI	Op6 $W = 0.159$ PEI	Op7 $W = 0.133$ PEI	Op8 $W = 0.133$ PEI	Op9 $W = 0.088$ PEI	WEI $\sum_i PEI_i * W_i$
10	10	5										
11	10	50	1.937	1.600	1.611	1.801	1.600	2.599	1.627	1.644	2.218	1.864
12	10	95										
13	15	5										
14	15	50	1.854	1.432	1.527	1.679	1.433	2.590	1.869	1.814	1.859	1.821
15	15	95										
16	20	5										
17	20	50	1.753	1.263	1.534	1.543	1.263	2.527	1.863	2.057	1.721	1.771
18	20	95										

References

[1] Badler, N.: Virtual Humans for Animation, Ergonomics, and Simulation. In: Proceedings of the IEEE Non Rigid and Articulated Motion Workshop, 1997, p. 28–36.

[2] Choi, H.: *Integration of Multiple Human Models into a Virtual Reality Environment*. Thesis, Washington State University. 2003.

[3] U.S. Department of Labor (Bureau of Labor Statistics) Workplace Injuries and Illnesses in 2001. Available online via <http://www.bls.gov/iif/home.htm.> [accessed January 2004].

[4] Das, B., Shikdar, A.: . Participative Versus Assigned Production Standard Setting in a Repetitive Industrial Task: a Strategy for Improving Worker Productivity. *International Journal of Occupational Safety and Ergonomics*, Vol. **5** (1999), No. 3, p. 417–430.

[5] Riley, M. W., Dhuyvetter, R. L.: Design Cost Savings and Ergonomics. In: Proceedings of the XIVth Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Association, "Ergonomics for the New Millennium", San Diego, CA USA, July 29–Aug 4, 2000.

[6] Dempsey, P. G.: Usability of the Revised NIOSH Lifting Equation. *Ergonomics*, Vol. **45** (2002), No. 12, p. 817–828.

[7] Keyserling, W. M.: *OWAS: An Observational Approach to Posture Analysis*. Available online via <http://ioe.engin.umich.edu/ioe567/OWAS.pdf> [accessed January 2004].

[8] McAtamney, L., Corlett, E. N.: RULA: A Survey Method for the Investigation of Work-Related Upper Limb Disorders. *Applied Ergonomics*, Vol. **24** (1993), No. 2, p. 91–99.

[9] Hanson, L.: Computerized Tools for Human Simulation and Ergonomic Evaluation of Car Interiors. In: Proceedings of the XIVth Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Association, "Ergonomics for the New Millennium", San Diego, CA USA, July 29–Aug 4, 2000.

[10] Di Gironimo G., Martorelli M., Monacelli G., Vaudo G.: Use of Virtual Mock-Up for Ergonomic Design. In: Proc. of 7th International Conference on "The Role of Experimentation in the Automotive Product Development Process" – ATA 2001 [CD Rom], Florence, May 23–24 2001.

[11] Gill, S. A.,Ruddle, R.A.: Using Virtual Humans to Solve Real Ergonomic Design Problems. In: Proceedings of the 1998 International Conference on Simulation, IEE Conference Publication, 457, p. 223–229.

[12] Eynard, E., et al.: Generation of Virtual Man Models Representative of Different Body Proportions and Application to Ergonomic Design of Vehicles. In: Proceedings of the XIVth Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Association, "Ergonomics for the New Millennium", San Diego, CA USA, July 29–Aug 4, 2000.

[13] Sundin, A., Christmansson, M., Ortengren, R.: Methodological Differences Using a Computer Manikin in Two Case Studies: Bus and Space Module Design. In: Proceedings of the XIVth Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Association, "Ergonomics for the New Millennium", San Diego, CA USA, July 29–Aug 4, 2000, p. 496–498.

[14] Hou, H., Sun, S., Pan, Y.: Research on Virtual Human in Ergonomics Simulation. *Chinese Journal of Mechanical Engineering*, Vol. **13** (2000), p. 112–117.

[15] *Ergosolutions Magazine*, 2003. Available on-line via http://www.ergosolutionsmag.com/.

[16] Wilson, J. R.: Virtual Environments Applications and Applied Ergonomics. Applied Ergonomics, Vol. **30** (1999), No. 1, p. 3–9.

[17] Park, S. H.: *Robust Design and Analysis for Quality Engineering*. London, Chapman and Hall, 1996.

[18] Raschke, U.: *Lumbar Muscle Activity Prediction During Dynamic Sagittal Plane Lifting Conditions: Physiological and Biomechanical Modeling Considerations*. Ph.D. Dissertation Bioengineering, University of Michigan USA, 1994.

[19] Di Gironimo, G., Monacelli, G., Patalano, S.: A Design Methodology for Maintainability of Automotive Components in Virtual Environment. In: Proc. of International Design Conference – Design 2004, Dubrovnik, May 18–21, 2004.

[20] Love, R. F., Morris, J. K., Wesolowsky, G. O.: *Multi-objective & Methods*, North-Holland, 1989.

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