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ERGONOMIC ASSESMENT IN CONCEPTUAL AND EMBODIMENT DESIGN

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1. Introduction

The aim of the study reported in this paper was to investigate the possibilities for ergonomic assessment in early phases of product development, focussing on the development of the metrics for ergonomic features that could be utilised by engineers in conceptualization and embodiment. The number of the ergonomic methods existing is huge, but most of them are developed for professionals often supported by equipment that is not available to the engineers in engineering design phase. The objective of the study was to indentify key issues related to ergonomic assessment and to propose a general methodology for product development practitioners that don't have specific knowledge in ergonomics and possibilities to gain empirical studied. In particular, it was important to identify methodology that could be applied for the quick ergonomic assessment in engineering design, in order to support user centered design methodology. Proposed methodology is validated on example of medical diagnostic table. This paper firstly presents overview of the different ergonomic methods and challenges related to the consideration of the human factors in engineering design. The ergonomic assessment methodology based on the evaluation of the ergonomic features is then described, followed by evaluation case study results and discussion.

2. Background and related work

Many methods have been proposed in a literature for assessing different human factors and ergonomics, focusing on [Stanton et al. 2005]: human capabilities and limitations, human–machine interaction, teamwork, environmental factors, work and organizational design tools, machines, and material design. These methods put an emphasis (sometimes implicit) on analysis of human performance, safety, and satisfaction. [Hancock and Diaz, 2002] argue that, as a scientific discipline, ergonomics holds the moral high ground, with the aim of bettering the human condition. They suggest that this may be at conflict with other aims of improving system effectiveness and efficiency. No one would argue with the aims of improved comfort, satisfaction, and well-being, but the drawing of boundaries between the improvements for individuals and improvements for the whole system might cause some heated debate. [Wilson, 1995] suggests that the twin interdependent aims of ergonomics might not be easy to resolve, but people working on this topic have a duty to both individual jobholders and the employing organization.
The benefits of different user centered methodologies are also well documented in the literature [Lofthouse and Lilley, 2006]. They can reduce the potential for poorly designed or misused products; provide an insight into the complex relationship between people and their products, and be a persuasive tool for communicating wants and needs to higher management. Through these techniques, developers can gain powerful insights into the 'actual' practices, habits and needs of the users they are

designing for, rather than having to rely on their own perceptions. Of especial importance is inclusive design research that seeks to address mentioned problems by making mainstream products usable by as many people as reasonably possible, without requiring them to use specialised adaptations [Clarkson et al. 2007]. Although there are many methods available for assessing inclusivity of products and services, most of these do not consider the whole range of diversity within the population nor do they directly relate their usability assessments to population figures [Waller et al. 2009]. Another problem with such methods is that most of them are often unsuitable to predict users' exclusion when several capabilities are used in combination to perform a task.

2.1 Ergonomics Methods

The importance of human factors and ergonomics methods cannot be overstated. Ergonomics methods offer a structured approach to the analysis and evaluation of design problems [Karwowski 2001]. Most engineers involved in product development will work somewhere between the poles of scientist and practitioner considering human factors and ergonomic problems, varying the emphasis of their approach depending upon the problems that they face. Despite the rigor offered by available methods, however, there is still plenty of scope for the role of experience. Stanton and Annett (2000) summarized the most frequently asked questions raised by practitioners that face such problems in different phases of product development:

- How deep should the analysis be?
- Which methods of data collection should be used, and how should the analysis be presented?
- Where is the use of the method appropriate?
- How much time and effort does each method require?
- How much and what type of expertise is needed to use the method?
- What tools are there to support the use of the method?
- How reliable and valid is the method?

There are six specialized fields of ergonomics methods representing all facets of human factors and ergonomics in systems analysis, design, and evaluation. The brief description of each group is presented in Table 1.

Table 1. Classification of the ergonomic methods

Groups of ergonomic methods	Brief description
(I) Physical methods	This group deals with the analysis and evaluation of musculoskeletal factors. The topics include: measurement of discomfort, observation of posture, analysis of workplace risks, measurement of work effort and fatigue, assessing lower back disorder, and predicting upper-extremity injury risks.
(II) Psychio-hysiological methods	This group deals with the analysis and evaluation of human psychophysiology. The topics include: heart rate and heart rate variability, event-related potentials, galvanic skin response, blood pressure, respiration rate, eyelid movements, and muscle activity.
(III) Behavioural-cognitive methods	This group deals with the analysis and evaluation of people, events, artefacts, and tasks. The topics include: observation and interviews, cognitive task analysis methods, human error prediction, workload analysis and prediction, and situational awareness.
(IV) Team methods	This group deals with the analysis and evaluation of teams. The topics include: team training and assessment requirements, team building, team assessment, team communication, team cognition, team decision making, and team task analysis.
(V) Environmental methods	This group deals with the analysis and evaluation of environmental factors. The topics include: thermal conditions, indoor air quality, indoor lighting, noise and acoustic measures, vibration exposure, and habitability.
(VI) Macro ergonomics methods	This group deals with the analysis and evaluation of work systems. The topics include: organizational and behavioural research methods, manufacturing work systems, anthropotechnology, evaluations of work system intervention, and analysis of the structure and processes of work systems.

Three of the presented methods groups (groups I through III) are concerned with the individual person and his or her interaction with the world. One of the methods groups (group IV) is concerned with the social groupings and their interaction with the world. Another of the methods groups (group V) is concerned with the effect that the environment has on people. Finally, the last of the methods groups (group VI) is concerned with the overview of whole work systems.

2.2 Challenges for human factors and ergonomics methods

Ergonomics researchers and practitioners abounds with methods and models for analyzing tasks, designing work, predicting performance, collecting data on human performance and interaction with artefacts and the environment in which this interaction takes place [Stanton et al. 2005]. Despite the diversity of methods, there are several significant challenges faced by the developers and users of human-machine interaction related methods. These challenges include: developing methods that integrate with other methods in engineering design, linking methods with ergonomics theory, making methods easy to use, providing evidence of reliability and validity, showing that the methods lead to cost-effective interventions, encouraging ethical application of methods.
The key questions regarding the utilization of the methods are usefulness and reliability. Method should be demonstrably stable over time and between people. Any differences in analyses should be due entirely to differences in the aspect of the world being assessed rather than differences in the assessors. Therefore criterion-referenced empirical validation should be an essential part of the method development and application process. The ultimate criteria determining the usefulness of methods in this field will be whether or not they help in analyzing tasks, designing work, predicting performance, collecting data on human performance and interaction with artefacts and the environment in which this interaction takes place.
It is obvious from descriptions of methods presented in a literature that they are multidisciplinary and cover wide areas of implementation. Most of the existing methods require specific equipment; complex knowledge related to the human behaviour, experimentation and measurement and therefore is not fully employed/utilized for implementation in early phases of product development process. This is case specifically for product development departments of SME. In this paper we are going to focus on proposal of features for ergonomic assessment in product development with a goal that designer/engineer may access relevant information considering ergonomic issues and improve design as early in a process as possible without need for employing specialists in this field.

3. Ergonomic assessment methodology based on ergonomic features

Ergonomic evaluations usually focus on subject (human), object (product), and environment (usage situation) as the part of the whole system, or in some cases, combination of relevant elements. Of course, product is made for human use so the separation of the two could be truly misleading and incorrect in order to get the full picture [Sušić, 2006]. Furthermore, when different ergonomic evaluations are conducted, appears that functional, physiological, aesthetic, ambient and safety standards or criterions are acknowledged as human factors. When considering ergonomic assessment in the context of design process it should be emphasized that subject (human) shouldn't be separated and compromised, since it may have a negative impact on the overall evaluation.
Subsequently, syntheses of different aspects based on the theoretical background [Kroemer and Grandjean 2000, Lehto and Buck 2008] and practical experience from previous work, resulted in this research with a recognition of user-centered objectives/criterions that are necessary for evaluation during ergonomic assessment. Authors assume that ergonomic evaluations in engineering design should be conducted during all phases (requirements specification, conceptualisation, embodiment, detailing), where for every single phase should be defined adequate level of assessment. Instead of ergonomic assessment method synopsis and implementation steps description, authors in this paper propose the list of feature groups for ergonomic assessment in early stages of the product development:

1. *Setup assessment* - covers all aspects of implicit features of object: positioning, installation, preparations, calibration, etc. (for example: focus on number and complexity of operations, time for their completion, etc.);

2. *Settings assessment* - covers all aspects of implicit features of object determined by subject participation: adaptability, adjustments, alignments, outreach, etc. (for example: focus on number and complexity of operations, time for their completion);
3. *Subject experience assessment* - covers all aspects of implicit features of subject:: physiological response, psycho-physical effort, mastery/skilfulness required, complexity of actions, comfort, perception of usage, atmosphere, ambient, etc.;
4. *Anthropometrical appropriateness/adequateness/sensitivity assessment* - cover all aspects of implicit features of object determined by appropriateness for subject: adaptability, reach, size, etc.
5. *Exploitation knowledge assessment* - covers all aspects of implicit features of subject determined by its experience: knowledge about usage and familiarity with, understanding of complexity of instructions, foreknowledge, etc;
6. *Restrictions assessment* - covers all aspects of implicit parameters determined by position and accessibility of the object or its parts in the location: manipulation and transport options, options for denial or grant access of use, etc. (for example: entrance or manway width);
7. *Usage autonomy assessment* – covers all aspects and conditions of object utilization which evaluate independence of subject: is there extra help during operation needed or not, who, when and how should provide help, etc. (for example: wheelchair).

Assessment process for each of the features groups should cover as many separate features as applicable, with appropriate evaluation method utilised. Detailed list of features could provide better understanding of design problems. Furthermore, such approach could enable benchmarking of the products/concepts, by proposed ergonomic features in the same product group (the same function and rank, different structure and form), it may identify products' advantages and disadvantages, or more important, point out the improvement goals and directions. Overall idea in presented method is to focus on objects of designing and expected experience of the subjects during utilisation of the products.

4. Case study – medical diagnostic table

In order to explain how the assessment procedure based on ergonomic features should be applied; evaluation of the medical diagnostic table for ultrasound screening during breast cancer detection is described. The diagnostic table usage scenario during examination is as follows. Female subject should approach the table and adjust the upper torso to specified area on the diagnostic table. After few seconds of standstill, or duration of diagnostic procedure, subject should leave the posture. It is required that all subjects aged from 15 years on, which are capable to move by their own, should be able to complete the task, as fast as possible. The presumption is that subjects have to complete the required task spontaneously. Also, it is assumed that the location and surrounding of diagnostic table do not impact table functionality. For the purpose of this research, three table concepts were evaluated in order to assess their ergonomic property (Figure 1). The concepts differ by their design and consequently the way how they should be used and approached by subjects.

Diagnostic table concept 1

Table is designed as a horizontal panel, 75 cm high, with specific area (illustrated as rectangular aperture) for medical diagnosis procedure predetermined and unchangeable. Approach activities are illustrated as walking approach, starting to climb up on the table, with objective to lie down on the upper table surface and simultaneously settle upper trunk to the rectangular aperture. This posture should be held for some time (medical diagnostic process), followed by activities to get off the table.

Diagnostic table concept 2

Table is designed as vertical panel with perpendicular footrest and adjustable specific area positioning. Rotation of entire table from vertical to horizontal position is enabled with fixed rotation axle. Ending delimiters are included as well as option for operator to manually adjust speed of rotation and centre of mass when female subject climb on. Female subject is only required to approach the table, thus other adjustments and operations are left for operator. After subject approach the table and stops at specified place on footrest, operator adjusts and set the table for use and rotates it to reach horizontal position required by diagnostic procedure. After some time at horizontal stand still position, operator rotates table back to vertical position, and subject leave the table.

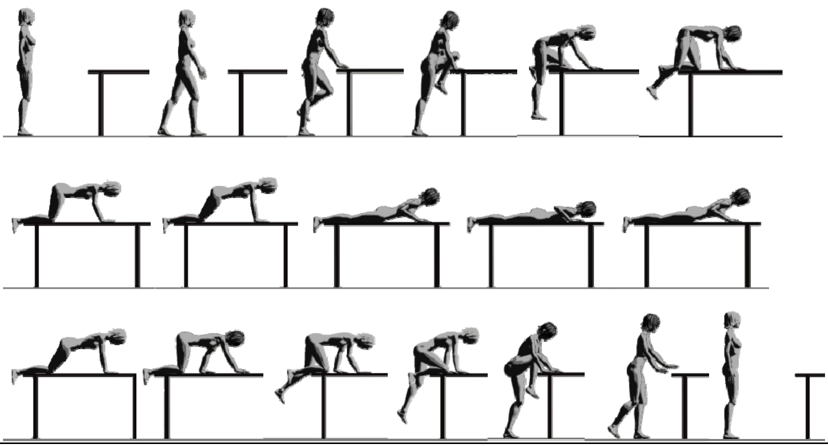
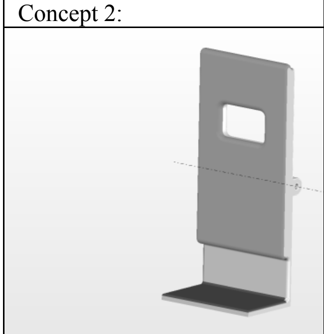
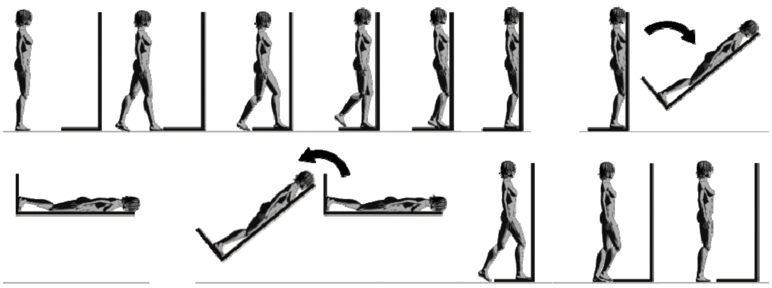
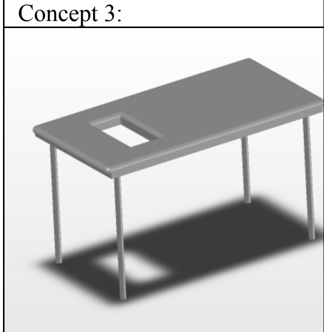
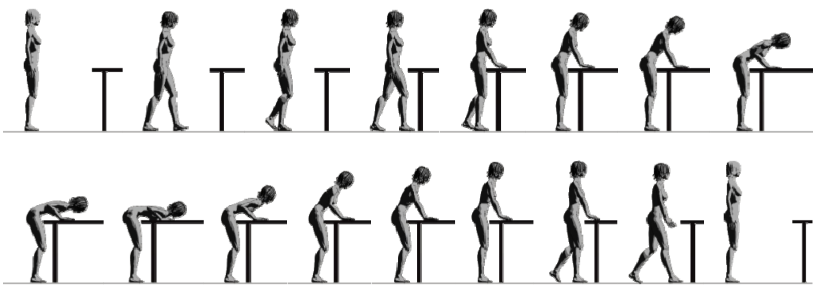
DIAGNOSTIC TABLE CONCEPTS	APPROACH PROCEDURES
Concept 1:	Climbing up on the table with lying down on it
	
Concept 2:	Approach to the table with table rotation
	
Concept 3:	Approach to the table with upper trunk bent over and reclined
	

Figure 1. Diagnostic table concepts with corresponding approach activities

Diagnostic table concept 3

Concept 3 is similar to the first one, with different specific area position, placed closer to table edge and expected approach position. Most differences are in approach procedure, where subject should approach the table, bent over the table and position the upper trunk aligned with specific area.

For ergonomic assessment four features groups were chosen from the list of previously proposed features groups: *settings, anthropometrical appropriateness, subject experience as demands on subjects (effort, skilfulness need, and posture)* and *table usage autonomy*. Reason for selection of four features groups in this case could be explained by fact that authors have been focused on object design and subject interaction (user centered design), while other circumstances are considered as distractive for this case. Groups of features like *Setup, Exploitation knowledge* and *Restrictions* were excluded since authors assumed that regardless of table concept, subject is not interfered or restricted by this ergonomic features groups and that final solution will be detailed as simple as possible.

4.1 Assessment method

In order to demonstrate evaluation of selected concepts, subjective assessment method was selected as a simplification of the more objective and accurate methods proposed by ergonomic literature with all disadvantages that we have already discussed before. With this in mind, grades for this assessment were defined as much as descriptive as follows:

0.90 Very appropriate 0.75 Appropriate 0.50 Almost appropriate
0.25 Weakly appropriate 0.10 Inappropriate

Evaluator should estimate the grade for every single feature, moderately thorough. For *Settings*, the task is to estimate the amount and complexity of adjustments and settings needed to assure medical diagnosis, mostly operations that proceed. Among the *Anthropometrical appropriateness* evaluation, the task is to evaluate ability of the table to assure that anthropometrical difference of subjects wouldn't restrict approach ability, or ability to accomplish compliance of table dimensions with subject needs. When *Demands on subjects* (*Subject experience*) are evaluated, the task is to estimate three parameters, *Muscular effort*, *Skilfulness need* and *Posture*, as features describing approach procedure and subject - table interaction. Estimation of *Muscular effort* reveals severity of approach procedure, *Skilfulness need* level of locomotion and adjustments skills required, while *Posture* estimation review subject's ability to hold in required body posture for a requested period of time. *Table usage autonomy* is used for estimation of subject's autonomy in order to reveal disadvantages of table concept design and need for operator to be involved, regardless of approach phase.

Table 2. Final assessment results

Features group:	Feature:	η_j	k_{sj}	Design 1	Design 2	Design 3
Settings		η_1	1	0,75	0,5	0,75
Anthropometrical appropriateness		η_2	9	0,1	0,9	0,5
Demands on female subjects	Muscular effort	η_3	9	0,25	0,9	0,75
	Skilfulness need	η_4	5	0,25	0,9	0,75
	Posture	η_5	3	0,75	0,75	0,5
Table usage autonomy		η_6	3	0,9	0,1	0,9
		η_e		**0,34**	**0,79**	**0,67**

At this point, the impact level as an addition to the every single ergonomic feature has been introduced, in order to emphasize significance of each feature. The computation of final review grade has been done by following equation (1):

$$\eta_e = \frac{\eta_1 \cdot k_{s1} + \eta_2 \cdot k_{s2} + ... + \eta_i \cdot k_{si}}{k_{s1} + k_{s2} + ... + k_{si}} = \frac{\sum_{j=1}^{n} \eta_j \cdot k_{sj}}{\sum_{j=1}^{n} k_{sj}} \tag{1}$$

In previous equation, η_j represents evaluated grade for every reviewed feature, k_{sj} is feature significance coefficient, and η_e is final ergonomic assessment score. For the purpose of this particular case, impact level coefficients were determined as follows:

$k_s = 9$ for highest impact level features;

$k_s = 5$ for moderate impact features;

$k_s = 3$ for low impact features;

$k_s = 1$ for parameters which are considered basic.

Such simplified form of final assessment grade is adjusted for the purpose of this paper, where its form implicit that sum of products represents formation of dimensionless assessment grades. By using equation (1) we may reduce the set of assessment grades to a single value, comparable between benchmarked models. It should be cleared that method itself is based on idea that every product should be possible to evaluate and compare objectively, considering human factors criterions. Final results of ergonomic assessment are shown in table 2.

4.2 Discussion of the results

Settings assessment shows small difference between the evaluated concepts, where no one have got the highest score. Settings for all the concepts are appropriate, except for concept 2, which is almost appropriate. This may be obvious from the fact that all three cases are somewhat demanding in adjusting of upper trunk to the table aperture. Impact level of this feature is set as basic, since it may cause some minor prolongations, however not important or decisive. *Anthropometrical appropriateness* assessment shows more differences between the concepts. Concept 2 is completely able to follow anthropometrical differences for all potential subject population, while concept 1 may cause severe difficulties for subjects. Concept 3 although better, still doesn't cover anthropometrical appropriateness. Impact level of this feature is set as highest, since impact of this feature on execution of approach activities and following demands is crucial. *Muscular effort* assessment shows that concept 2 is characterised by minimal muscular effort demands, noticeably better than concept 3. Concept 1 demands a lot of coordinated and a few intense movements, yet it is still feasible. Similar as previous feature, impact level is set as highest, since level of muscular effort needed to complete the task may be restrictive, or cause injuries. *Skilfulness need* assessment is equally as *Muscular effort*, but not on purpose. Still, there is obvious connection between those two features, since table designs causes similar level of demands on skills required to complete the task. Impact level of this feature is set as moderate, which can be explained by fact that skills needed is another risk or discomfort factor, yet this can be hardly described as restrictive or unsafe.

Posture assessment considers final posture and ability of subject to hold it for a period of time, without discomfort or significant fatigue. Concept 1 and 2 presume the same posture, lying on the stomach, with hands set apart similar to push-ups, which is evaluated as appropriate, but is somewhat harder than lying on the back. Concept 3 is more demanding than previous two accordingly to the standing position (and possibly holding on hands). Impact level of this feature is set as low, since expected duration of posture for medical diagnostic purpose is predicted as short.

Table usage autonomy assessment considers ability of subject to use table independently, which includes not only table usage but also settings and adjustments needed prior to medical diagnostic procedure. Concept 1 and 3 are graded the highest since subject can't change anything on the table (everything is set and calibrated previously). Concept 2 is graded lower since subject can't do independently most of required table usage activities. Impact level of this parameter is set as low, since autonomy of table usage doesn't restrict or deny access to expected medical diagnostic process.

As the final result of the ergonomic assessment procedure, Concept 2 earned highest final score regarding ergonomic property, although it was completely new design. Weakest point of concept 2 is autonomy of usage, which may be considered as focus point for further development, since in presented form it requires that medical staff /operator/doctor interact with diagnostic table during preparation for medical examination. Concept 3 is following by some margin, with conclusion that the improvements in size/height adjustability may significantly improve overall impression, while posture as other weak point can't be significantly altered. Concept 1 illustrates that when user is not considerably taken into account, and the solution is designed without possibilities for proper adjustments, such solution is not acceptable from the ergonomic point of view. Of course, it is expected that more detailed, accurate and objective assessments should follow in later phases of design – embodiment and detailing of selected concepts.

5. Conclusion

Ergonomics researchers have successfully defined different methods for assessments of ergonomic properties from the different point of views relating to the user-product systems. As an initial step towards enabling practitioners in engineering design to cover these issues for them without need of acquiring specific knowledge and measurement equipment, the method for ergonomic assessment in early phases of product development has been developed and presented. Use case study has been used to illustrate application of the methodology for assessment of the design concepts on the example of the new medical diagnostic table. Results indicated that proposed method using ergonomic features is helpful for consideration of the ergonomic issues that are usually taken for granted in engineering design. It was shown that method could help practitioners in engineering design to evaluate ergonomic property of design in consistent and efficient way, even if they are not trained in ergonomic field. As the future steps, there are few possible directions: standardization and broadening of features list for each of proposed feature groups, investigation for trustworthiness of assessments without proffesionals supervision, and association of proposed ergonomic assessment procedure with other solution validation procedures. Also, with some modifications, suggested procedure may also serve in other phases of design, as well as for final product benchmarking and evaluation.

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