Ergonomic Optimization of Human-Machine Systems in Virtual Environments – A Systematic Literature Review Identifying Research Gaps

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Abstract

Enhancing product ergonomics is becoming increasingly important in the development of human-machine systems. But it requires a high development effort due to costly iterations of physical prototypes and user studies. The use of digital human, product, and interaction models as well as an optimizer redesigning the product using ergonomic assessment and optimization algorithms has the potential of reducing this effort. Since there is a variety of methods and models for the ergonomic assessment and design optimization, a systematic literature review based on the PRISMA statement is presented, analyzing 22 relevant studies. The information of application context, ergonomic assessment methods including human posture, external and internal physical human stress, and product design methods were extracted. Research gaps were identified and further research projects were derived. These gaps involve the appropriate selection of ergonomic assessment measures and criteria, a formulation of an objective function based on the ergonomic assessment, and the selection of suitable design parameters for the ergonomic design optimization. These research questions are to be answered based on a specific use case which is to be selected.

Keywords

Product ergonomics, Digital Human Models, User-centered Design, Design Optimization, Human factors

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1. Introduction

In the development of human-machine systems, product requirements become increasingly extensive. These include increasing ergonomics, comfort, and usability as well as reducing discomfort and health risks such as harmful body postures [1, 2]. Consequently, the effort required for product development increases. Virtual product development can reduce this effort, especially when employed early in the product development process. For human-machine systems, the use of digital models enables early predictions regarding product design, user characteristics such as posture and physical stress, and their interaction. This can minimize the need for costly iterations of physical prototypes and physical user studies [3, 4]. In addition, the use of digital human models (DHMs) enables an objective and reproducible ergonomics assessment within the product development [5, 6]. This includes an analysis of various human factors indicating the physical stress on the human, e.g., the human posture and forces acting on the human. In order to improve product ergonomics with a reduced number of physical prototypes, it is useful to apply DHMs in an early stage of the product development process. However, a human model alone is not sufficient. A complete digital model of the human-machine system is required, including a human, a product and an interaction model. In this way, the factors influencing the human by the product can be considered, e.g., the human posture and forces by the product, and the physical human stress can be estimated. To increase the product ergonomics, the physical human stress of a specific use case needs to be reduced. This could be done by changing boundary conditions, such as the product or environment design. Since the product design is part of the overall model, product design adjustments can be made and the ergonomic effect can be evaluated.

However, creating an overall digital model of a human-machine system for a resource-efficient improvement of product ergonomics still poses some challenges. First of all, DHMs often require time-consuming and costly acquisition of experimental data for each subject [7]. To enable a consideration of various user types for the product design, the number of experimental data required for the simulations are to be minimized, including data 1) to scale a model to the subject's dimensions and 2) to apply the subject-specific motion to the model. Some CAD DHM tools such as Siemens JACK [8], RAMSIS [9], and IPS IMMA [10] enable model scaling based on population databases using anthropometric parameters such as body percentile, sex, age, and population type. However, these tools lack musculoskeletal structures and cannot estimate stress on joints and muscles. Biomechanical software like OpenSim [11] and AnyBody [12, 13], on the other hand, are more suitable for certain use cases, as they utilize musculoskeletal models. Helmstetter et al. [7] developed a scaling approach in OpenSim based on the German population using body height, weight, and sex as input. Miehling et al. [5] developed a population-based modeling approach to create musculoskeletal models in OpenSim for various user groups by adjusting body height, mass, sex, age, range of motion, and strength. Additionally, some approaches and methods for motion synthesis and prediction aim to reduce the amount of experimentally captured motion data required for DHM simulations, as summarized by Wolf et al. [14]. A further challenge lies in modeling the interaction between user and product. Such interaction models need to offer a combination of specific predictivity and universal validity [14]. The review paper on interaction modeling from Wolf et al. [14] includes an overview of some approaches and methods. Also, Scherb et al. [15] conducted a literature review on the interaction modeling between user and exoskeleton.

Despite these challenges, the use of a complete digital model of a human-machine system shows high potential of supporting the user-centered product development by enhancing product ergonomics resource-efficiently.

Figure 1 shows an approach for improving product ergonomics virtually, based on the work of Miehling [16] and Meißner et al. [17]. The approach includes a musculoskeletal human model, a parametric product model, and a prediction model. The prediction model consists of a prediction of the human motion and an estimation of external and interaction forces between product and user. By applying the motion and forces to the musculoskeletal model, the stress on joints or muscles can be simulated. To reduce the effort of adjusting the product model, an optimizer could be added to the procedure. Based on the physical simulated user stress and its ergonomic assessment, the optimizer could adjust the product design. As a result, the approach of Figure 1 could enable to enhance the product ergonomics with a reduced number of physical prototypes.

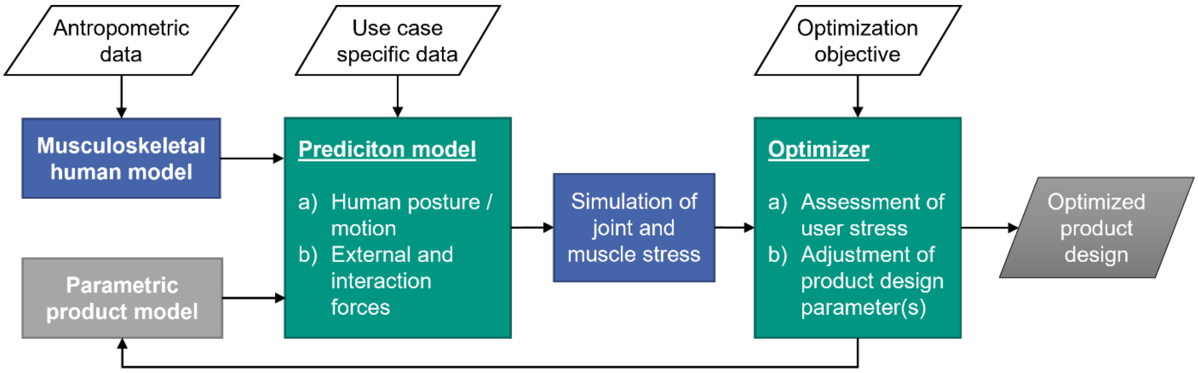

Figure 1: Approach for an automated ergonomic optimization of a product design using simulated user stress; own illustration based on conducted steps in the work of Miehling [16] and Meißner et al. [17], colors indicate software environments: musculoskeletal modeling (blue), CAD (grey), numeric computing (green)

To be able to improve the product ergonomics by applying the approach above to a specific use case, some issues regarding the optimizer need to be addressed. First, the input parameters of the optimizer in the approach are simulated factors of the physical user stress such as joint torques and muscle activity. To be able to use it for an ergonomic assessment, it needs to be clarified which parameters to use as ergonomic measure. These can be either part of the model, the simulation results or can be derived from them. Second, the chosen ergonomic measures need to be assessable. Thus, the ergonomic assessment needs to include clear criteria based on these ergonomic measures. Finally, the product design needs to be adjusted automatically based on the ergonomic assessment to be able to find the best solution. For this, the optimizer has to include an optimization algorithm with an objective based on the ergonomic measures and criteria. Since there is a variety of methods, models, and approaches for ergonomic assessment and optimization, it is important to select a suitable one for the specific use case. From these issues, the following research questions were derived:

What methods and approaches are used in the current state of research to

1. *assess the ergonomics of a specific use case based on measures of the physical user stress using DHM?*
2. *optimize a product or workplace design based on ergonomic assessment of a specific use case using DHM?*

The objective of this paper is to conduct a systematic literature review based on these questions and the optimizer of the approach above in order to identify research gaps and derive further research questions.

2. Methods

To find suitable literature, a systematic literature was conducted based on the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) statement [18]. Figure 2 shows the corresponding procedure.

To identify relevant studies, Scopus and PubMed were used as search engines. The search was limited on English titles and abstracts and the following search string: *(TITLE-ABS-KEY ((ergonomic* OR biomechanic*) AND (assess* OR *valuati*)) AND TITLE-ABS-*

KEY (optimiz AND (product* OR workplace* OR workstation*) AND design*) AND TITLE-ABS-KEY ((musculoskele* OR digital AND human) AND model*))*. This search string was applied to find ergonomic assessment measures and criteria applied in case studies as well as approaches or specific algorithms for the redesign. The search in the electronic databases revealed 56 literature results (s. Figure 2).

First, the titles and abstracts were screened to exclude irrelevant records. Subsequently, the full papers were assessed for eligibility based on the following pre-defined exclusion criteria: 1) the record does not include an ergonomic assessment based on defined criteria or a redesign based on ergonomic criteria, 2) the record does not include a case study and 3) the record is not an open-access source or accessible through our research institution.

In this way, 21 reports were excluded. After selecting 20 eligible studies, 2 relevant papers were additionally added, as they include case studies from a paper which was excluded due to the second criterion. As a result, 22 studies were identified as significant to answer the research questions and thus are included in this literature review. For analyzing these papers, they were clustered based on the application context. We extracted the used ergonomic assessment measures and criteria as well as the design optimization methods used to adjust the generic design based on the ergonomic assessment. In this review paper, we focus on ergonomic measures influencing the physical human stress, such as human posture, internal and external stress. These categories were applied to further classify the ergonomic assessment methods extracted from the studies reviewed.

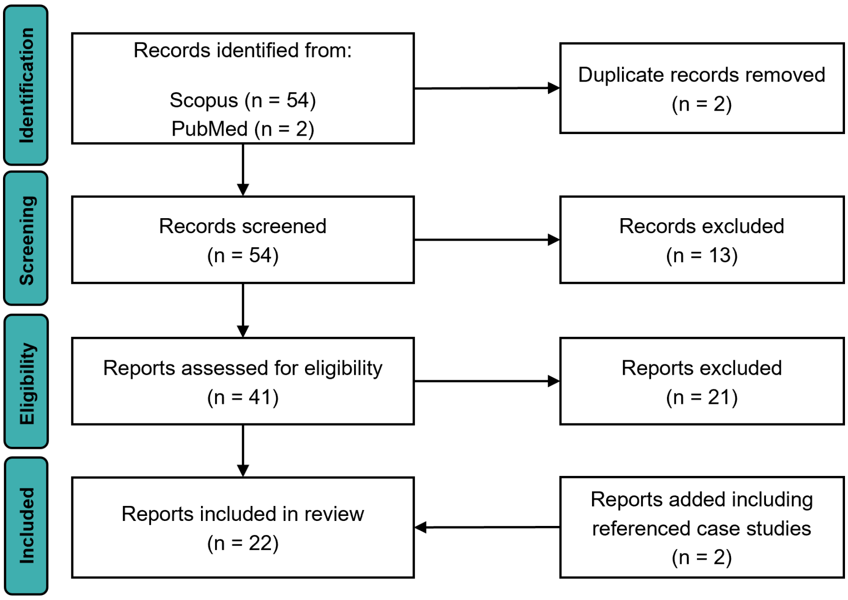

Figure 2: PRISMA flowchart describing the procedure of the paper selection

3. Results

The extracted information regarding ergonomic assessment and design optimization are listed in Table 1 and clustered into the following application contexts: design of ergonomic industrial workstations (11 studies), driver's cabins and cockpits (4 studies), seated workplaces (3 studies), room layouts (2 studies), and human-driven vehicles (2 studies).

Most of the studies found deal with redesigning industrial workstations based on the ergonomic assessment. In most of them, an ergonomic pre-assessment was performed to identify the most critical tasks, e.g., assembling and lifting tasks. For the ergonomic analysis, various human factors such as posture, reachability, visibility, mental load, and satisfaction, as well as task parameters, e.g., task frequency, load weight and time, can be taken into account. As mentioned above, we focus in this review paper on the measures influencing the physical human stress, such as posture, internal and external stress. The main evaluation value of the studies found was the human posture. In the following sections, the assessment methods based on the ergonomic parameters and criteria as well as the design optimization methods applied in the studies are further described.

3.1. Ergonomic assessment

3.1.1. Human posture

For a postural analysis of certain tasks, most of the studies reviewed used *"3D CAD and Modeling"* DHM tools according to the thermology of Demirel et al. [21] such as Siemens JACK [8], IPS IMMA [10], Santos [19], Dessaults Systèmes DELMIA [20], and RAMISIS [9]. The task is applied to the model, either using experimental or predicted motion data. Most of the studies implemented a human as well as a product or workplace model in a virtual environment, e.g., CATIA and DELMIA by Dessault Systemès, to be able to model the entire task. In addition, reach analyses can be performed by placing the DHM relatively to the objects. To evaluate reachability in driver's seats, cockpits or at industrial workstations, most studies use DHMs based on different anthropometric data. This enables a consideration of different body heights.

After applying a posture or motion to the DHM, the postures can be ergonomically analyzed and assessed. For this purpose, international standard methods for ergonomic assessment are used, including RULA (Rapid Upper Limb Assessment) [22], REBA (Rapid Entire Body Assessment) [23], and OWAS (Ovako Working Posture Analysis System) [2]. Rhén et al. [24] applied national guidelines, the Swedish standard for computer work [25] and US checklist for computer work recommended by the U.S. Department of Labor's Occupational Safety (OSHA) [26], specially developed for the ergonomic assessment of VDU work. All these guidelines describe which joint angles to analyze and how to evaluate them. As a result, a score can usually be calculated which indicates the musculoskeletal stress on the worker or user. Thus, the score enables an identification of the critically stressed body segments. In addition, it can be used as objective parameter for a design optimization which needs to be minimized.

Some of the studies did not apply an existing postural guideline, but a self-developed assessment score. Di Gironimo et al. [27] developed the EEI, an index including the RULA score and p-index of DELMIA. Moussavi et al. [28] used an in-house ergonomic method called SES. It contains 20 ergonomic parameters describing quantities such as energy consumption, force, material handlings, work posture, and repetition and is based on Swedish guidelines [29]. Such included task parameters are further described in the next section.

3.1.2. External human stress

Besides the human posture, some methods such as EAWS (European Assembly Work Sheet) [30], NIOSH (National Institute for Occupational Safety and Health) [31], and OCRA (Occupational Repetitive Actions) [32] evaluate task-induced parameters, e.g., exerted forces, load weight and repetition (lifting, carrying, push, pull). This is necessary for an ergonomic assessment of physical work, e.g., lifting tasks, so that the entire physical stress is taken into account. These guidelines are also applicable to ergonomic design optimizations, as they incorporate assessment criteria for categorizing ergonomic risks. Furthermore, the walking distance is a relevant parameter which needs to be minimized for an ergonomic layout of a patients room or industrial plant [33, 34]. For the design of ergonomic seated workplaces, the consideration of external human stress plays a rather minor role and was therefore rather neglected in the studies reviewed.

3.1.3. Internal human stress

Under the term *internal human stress*, we summarized all loads that occur inside the human body. In the studies examined, loads on the spine, joints, and muscles served as ergonomic assessment measures. First, the lower back compression force (LBCF) on L4/L5 was used as indicator for load on the back which needs to be minimized. Harari et al. [35] set 3400 N as critical threshold based on cadaver studies and biomechanical models. Second, the oxygen-consumption rate (VO_2) was used as indication for the energy expenditure during physical work. Harari et al. [31] applied 1000 ml/min as critical threshold based on the U.S. Work Practices Guide for Manual Lifting [36]. This is a threshold for aerobic and muscle fatigue. Further measures of internal human stress used in the studies reviewed are parameters of stress on joints and muscles (joint torques, joint reaction forces, muscle forces, muscle activity). There was no assessment criterion mentioned for these measures. All the measures for internal human stress were minimized as low as possible, when using them within an objective function for an ergonomic design optimization.

3.2. Design Optimization

After the assessment, design parameters affecting the ergonomic measures need to be identified. Most of the studies reviewed did not mentioned a specific method for selecting the design parameters, but analyzing the design. In this way, design parameters affecting the human posture or reach capacity could be identified, e.g., the height and depth working surfaces, the distance between object and user, or the seat height. In contrast, Liu et al. [37] derived a complex correlation (PLNR) matrix between joint angles or load and various design parameters to identify relevant design parameters.

After identifying design parameters, most studies described an optimization of the generic product or workstation design based on the ergonomic assessment, either by manual redesign (9 papers) or by applying an optimization algorithm (9 papers). The optimization algorithms were implemented using either a single- or multi-objective problem, including at least one ergonomic measure. Most of the studies used an Evolutionary Algorithm (EA) to solve it. The remaining papers did not perform a design optimization in the described case study.

Finally, the new design was compared to the generic one based on the ergonomic assessment which was used before. All studies included in this review reported an improvement of the new design.

4. Discussion

To enhance the product ergonomics with a reduced number of physical prototypes, Figure 1 shows a possible approach including a digital model of a human-machine system and a product optimizer. With regard to the optimizer, we conducted a literature review on the ergonomic assessment and design optimization methods applied in various studies in order to find research gaps.

In most of the studies reviewed, the performed steps were similar: 1) selection of ergonomic assessment measures and criteria or, if available, an existing ergonomic assessment method, 2) selection of an optimization method and, in case of an optimization algorithm, formulation of an objective function, 3) selection of design parameters, and 4) execution of a case study with an ergonomic assessment and redesign. In the following, aspects of these steps are discussed and gaps for an ergonomic optimization of a product design are identified.

For the selection of suitable ergonomic assessment measures and criteria, we focused only on the ergonomic assessment measures and criteria in regard to physical human stress. However, there is variety of measures and guidelines to choose from. RULA was the most frequently used ergonomic measures for postural analyses, since it was developed for a wide range of tasks [24]. However, it is not suitable for all tasks, e.g., VDU work [24]. In general, it is not clear for every use case which ergonomic measures need to be considered. As seen in the results, various task parameters can be taken into account for the ergonomic assessment of industrial workstations. Thus, a less researched or more complex use case such as a

Table 1: Classification of the ergonomic assessment and design optimization methods from 22 reviewed studies

Application context	Ergonomic assessment methods			Design optimization methods
	Human posture	***External human stress (Task parameters)***	***Internal human stress***	
Industrial workstations	RULA [35, 39–43] OWAS [42] Norman's model of interaction (incl. RULA, REBA) [44]	NIOSH lifting equation [35, 45] EAWS index (incl. posture, exerted forces) [46, 47] OCRA (incl. posture) [47] Self-developed method SES (incl. posture) [28]	Lower back compression force (LBCF) < 3400 N [35, 39] Oxygen-consumption rate (VO_2) < 1000 ml/min [35] Muscle activity [45]	Manual redesign [40–42, 44–46] Evolutionary algorithm (EA): NSGA-II with single-objective based on RULA [43] GA with multi-objective based on productivity, LBCF, RULA, VO_2 [35] Mathematic model GUROBI solver with single-objective based on SES score [28]
Driver's cabins (car, tractor, excavator), cockpits	Self-developed EEI index (RULA and p-index of DELMIA) [27] Reachability: reach gap [48], NASA TLX [49]		Joint torques: Self-developed method PLNR [37]	Manual redesign until EEI < 0.5 [27] PLRN correlation design parameters - joint angles / load (no redesign) [37] Evolutionary algorithms (EA): PSO with single-objective based on reach gap [48]
Seated workplaces (VDU work-places, dentist)	RULA [50] US checklist for computer work [24] Swedish standard for computer work [24]	OCRA (incl. posture) [51]		Manual redesign [24, 51]
Room layouts	RULA [33] REBA [33, 34]	Walking distance [33, 34]		Evolutionary algorithm (EA): NSGA-II multi-objective based on RULA, area of occupation, walking distance [33] SPEA-2 multi-objective based on clash points, walking distance [34]
Human-powered vehicles (bike, rowing boat, trike)			Muscle force [16] Joint reaction forces [17]	Non-linear optimization: Single-objective based on muscle force required [16] Multi-objective based on muscle force required, performed work on oars [16] Parameter study: Evaluation of various design configurations [17]

grinding application including a dynamic force exerted by the product, needs to be analyzed extensively, before suitable ergonomic measures can be selected.

Furthermore, the postural measure is frequently used for ergonomic evaluation in various application contexts and is therefore well researched. The risk levels for postures are accurately defined in the guidelines. In contrast, this does not always apply to the measures of external and internal human stress. To analyze critical tasks such as lifting, there are some standard guidelines like the Norman's lifting equation. However, they often cannot be transferred to different tasks. For the measures of internal human stress, there are only some ergonomic criteria. For example, acceptable joint torques are often defined by an acceptable external force in a defined posture. However, the studies reviewed did not apply a guideline or a specific ergonomic criterion. Instead, the objective was to reduce the joint torques as much as possible. For the other mentioned measures of internal human stress, there are often no official guidelines, including evaluation criteria or thresholds for an ergonomic or low risk level. There are different thresholds for parameters such as oxygen consumption rate, depending on the studies. Possibly, the ergonomic thresholds and criteria also depend on the use case they are applied to. As a result, there is a partial lack of clear evaluation criteria for all ergonomic measures used in the studies reviewed, or they are not widely known or acknowledged as suitable. Subsequently, it is partly unclear to identify which body segments are critical and which are to be included in the ergonomic assessment and the redesign process.

Also, it needs to be clarified how the selected ergonomic measures can be combined and weighted. This enables to formulate an objective function for an optimization algorithm. Compared to a manually redesign, the use of an automated design optimization enables a significantly reduced effort and a greater chance of finding the best design solution, provided that the objective function has been appropriately selected. Some of the studies found such as Di Gironimo et al. [27] and Moussavi et al. [28], combined various ergonomic measures. They used mainly their experience with the specific use case to find a suitable combination.

Finally, it is necessary for the design optimization to select appropriate design parameters affecting the chosen ergonomic measures. Most of the literature found did not mentioned a specific method for selecting the design parameters. They were probably chosen by analyzing the entire system, including the product or workstation design as well as the boundary conditions and requirements. However, selection of the design parameters is crucial to optimize the design resource-efficiently and to find the best solution. Thus, the design parameters need to be selected systematically, e.g., by analyzing their correlation with the ergonomic measures such as Liu et al. [37].

In conclusion, the literature review on existing methods for an automated ergonomic optimization of a product design in terms of assessment measures and specific algorithms for redesign revealed different research gaps. From these gaps, the following research questions can be derived:

- RQ1: *How can ergonomic assessment measures and criteria be identified which are suitable for a specific use case in product design?*
- RQ2: *How can an objective function and optimization algorithm be developed for a chosen use case using the selected ergonomic measures and criteria?*
- RQ3: *How can relevant design parameters be selected that significantly affect the assessment measures or objective function for the specific use case?*

5. Conclusion and Outlook

The objective of this paper was to perform a systematic literature review based on the optimizer of the approach illustrated in Figure 1. Implementing this approach has the potential to improve product ergonomics, while reducing the number of physical prototypes. From the PRIMA-based literature review, we identified several research gaps and derived key research questions. These questions focus on the selection of an appropriate ergonomic assessment method, the formulation of objective functions based on ergonomic measures and criteria, and the identification of suitable design parameters for the ergonomic design optimization. These research questions will guide further investigations. For these, a specific use case must be carefully selected to further explore the potential of the proposed approach.

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