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Review of Recent Developments in Ergonomic Design and Digital Human Models

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Abstract

Background: Ergonomic interventions and ergonomic redesign are researched upon today in the realms of 'Prevention through Design' towards addressing the occupational health and safety concerns of the industry.

Objective: To review the developments over the past ten years relating to computer aided ergonomic design, and propose an ergonomic intervention framework for manufacturing systems.

Methods: The literature was selected from ergonomics journals indexed in the SCOPUS bibliographic database, by filtering abstracts and titles using select words such as 'ergonomic design', 'ergonomic evaluation', 'ergonomic intervention', 'virtual reality' and 'digital human model'.

Results: The three areas reviewed include: Ergonomic interventions and Ergonomic Design, Ergonomic analysis and tools, and Digital human model (DHM) and Virtual Ergonomics. The DHM modeling approach is favored by designers towards ergonomic redesign of products and systems. DHM software is being integrated with ergonomic analysis tools and human features. A DHM based intervention framework is proposed that attempts to integrate human and machine performance metrics in making interventions, thereby making a sustainable human compatible system.

Conclusions: The review has emphasized on design focus in intervention strategy. An ergonomic intervention framework has been proposed. Participative ergonomic approach with multiple stakeholders is suggested for implementation of interventions.

Keywords: Musculoskeletal disorders; Intervention framework; Cumulative exposure; Ergonomic surveillance; Digital human model; Virtual ergonomics

Introduction

Improving worker productivity, occupational health and safety are major concerns of industry today. The work system issues such as improper workplace design, adverse environment, ill-structured jobs, incompatibility between worker abilities and job demands results in development of musculoskeletal disorders, occurrence of injuries and accidents. The work-related portion of the injuries and resulting disability is potentially preventable, and there is large evidence base to highlight interventions for reducing work-related musculoskeletal disorders [1-4]. There is a need for examining methodological aspects of interventions for work system design.

Over the years there have been focused efforts towards integrating ergonomic principles into product development and work system/ system design [5-7]. Integration of ergonomics into work system design is being made possible by the developments in three primary domains, i.e., epidemiology, ergonomic evaluation, and intervention. Digital Human Model (DHM) and Virtual Ergonomics are rapidly emerging as enabling technologies, promising to change how products or systems are designed, how ergonomic analyses are performed, how disorders or impairments are assessed, and how therapies or surgeries are conducted. There is increasing cooperation between designers and ergonomists towards integrating realistic human models into computer aided design that mimics human capabilities and interactions. The challenge lies in embracing the significant advances in design methodology and computer technology, and applying it to real-time manufacturing environment.

The objective of the paper is to review the developments over the past ten years relating to computer aided ergonomic design and applications of DHM.

Methods

The literature was selected from the SCOPUS bibliographic database. The keywords used for identifying the literature include 'ergonomic design', 'ergonomic evaluation', 'ergonomic intervention', 'virtual reality' and 'digital human model'. Some of the original articles from the last ten years were selected from reputed ergonomics journals such as Ergonomics, Applied Ergonomics, International Journal of Industrial Ergonomics, Human Factors, IEEE, Theoretical Issues in Ergonomics Science, Work, IIE Transactions on Occupational Ergonomics and Human Factors, Human Factors and Ergonomics in

Manufacturing, International Journal of Human Factors Modelling and Simulation for conducting the review. Some of the recent conferences connected with the theme were also reviewed. Over 300 articles were found. By reviewing the abstracts and conclusions the 60 articles have been selected for this review. The source of literature is primarily from the ergonomics domain and supplemented from the design domain. The literature has been classified into three categories i.e., Ergonomic Intervention and Ergonomic Design, Ergonomic Analysis and Tools, and Digital Human Modeling and Virtual Ergonomics.

Discussion

Ergonomic interventions and ergonomic design

Work place issues that affect the safety and health of workers cause absenteeism and reduced productivity. In order to address this problem targeted ergonomic interventions are necessary. The approaches to ergonomic intervention are, (i) mechanical exposure or engineering interventions that focus on engineering the exposure route and pathways, (ii) production and administrative interventions that focus on work schedule and policies and (iii) modifier and behavioural interventions that focus on individual worker's behavior through training or coping methods. There is a large body of literature which shows case studies of interventions across health care [8], automotive [9], agriculture [10], and IT and Office [1] that have used different intervention methods and strategies at both micro and macro levels. The benefits of ergonomic interventions include reduced compensation costs, improved productivity and quality, safety-health-comfort, and usability [11-16]. Overall, the benefits from intervention components need to be quantified towards making business case for interventions.

The impacts of interventions are dependent on the strategies adopted and the role of participatory approach needs to be emphasized here [17,18]. The stakeholders in the participatory approach are ergonomists, health practitioners, designers, engineers, managers and workers. The focus has now shifted from current micro level corrective interventions to preventive ergonomic design solutions through attempts to integrate human factors and ergonomics (HFE) into design. Neumann and Village [19] and Village et al. [20-22] have proposed frameworks for integrating ergonomic factors into work system design by introducing the concept of 'action research' by means of a participatory ergonomic intervention approach for proactive integration of human factors into design process.

Though there are numerous literatures on ergonomic interventions, two important intervention issues that need to be addressed are (i) methodological issues for undertaking interventions, and (ii) cost-benefit analysis for acceptability of interventions by industries. Interventions can be effective by providing inputs based on sound ergonomic principles. Here in, the need for surveillance and exposure measurement, and its integration into design through robust ergonomic design methodology is necessary. Gambatese [23] has highlighted the need to address barriers pertaining to 'cost modelling and dissemination', 'surveillance and causal models', 'design tools and methods' and 'work system interaction' towards achieving and practicing 'Prevention through Design'. A human factors and ergonomics (HFE) integrated design framework with specific focus on exposure measurement is discussed in HFE integrated work system intervention framework.

A multivariate work system performance matrix (Figure 1) would include 'ergonomic stress', 'productivity', 'quality' and 'safety' parameters [21,22,24-26]. The proposed HFE framework (Figure 2) integrates these performance parameters. Here, ergonomic evaluation of products and work systems can be done by a wide variety of approaches and ergonomic tools. But for better integration of HFE into design process, the choice of appropriate design tools and techniques is essential to account for multiple performance criteria. Literature provides numerous design techniques used for ergonomic design of products and systems which include Functional analysis [27], Expert system [11], Focus groups [28], Quality function deployment [29], Axiomatic design [30,31], TRIZ [32], Digital Human Modeling and Virtual Reality [33,34], Behavioural design approach [35], among many other approaches. The design tool or technique must account for the 'ergonomic', 'productivity' and 'quality' parameters. The set of design solutions derived from the any of the chosen method would provide one of the inputs to the intervention module. The choice of design method therefore plays a key role in the HFE intervention framework.

Over the past decade, the focus of industry has shifted from making 'point' or isolated workplace changes and modifications that account for ergonomic factors to that at a system level where integration of ergonomic factors into production system are made. The main focus of the HFE discipline in the 21st century will be the design and management of systems that satisfy human compatibility requirements [30]. But, the challenge is in providing an intervention framework (process, techniques, people and structure) that not only integrates HFE but also sustains it. An HFE integrated work system design framework is proposed and is discussed further in 3.4 HFE integrated work system intervention framework.

Ergonomic analysis and tools

A large number of ergonomic analysis tools have been developed to assess posture, physiological demand, biomechanical and cognitive demand, and human-machine productivity analysis. Some of these are listed in Table 1 [36-46]. Many of the techniques in Table 1 have been incorporated as standalone modules in software or integrated into design software. In a survey conducted by Dempsey et al. [36] on professional ergonomists on the use of various types of basic tools, direct and observational measurement techniques, and software, it was found that 50.6% of them used some form of software tools. For example, RULA, NIOSH lifting equation, and Psychophysical Databases have been incorporated in design software such as CATIA and ProE, OWAS in winOWAS, Three-Dimensional Static Strength Prediction Program (3DSSPP) etc. MVTA, VIDAR, and ErgoSAM are a few video based ergonomic analysis tools used for motion analysis and preliminary musculoskeletal disorder risk identification. Works of Rajesh et al. [45], Binay et al. [47], Battini et al. [24], and Vilas et al. [26] are examples in which computer aided ergonomic analysis have been undertaken. Input to ergonomic assessment is largely dependent on the surveillance or exposure measurement technique employed. The nature of ergonomic assessment is therefore dependent on the resources available, the work system characteristics and also on the expertise of the ergonomist. Given the multi-factorial nature of ergonomic problems a comprehensive ergonomic assessment involves the use of multiple tools.

Types of tool and approaches	Name of method
Observational tools and integrated tools	RULA; REBA; OWAS; QEC; MVTA; PLIBEL; Cube Model; ACGIH HAL and lifting TLV; Cube model; NIOSH equation; EWS; Ergo Toolkit
Physiological models	Energy Expenditure equation; Oxygen consumption models
Biomechanical models	WATBAK; LMM risk assessment model; Three-Dimensional Static Strength Prediction Program; Continuous Assessment of Back Stress, Muscle effort
Cognitive models	Critical incident technique; NASA Task Load Index; Cognitive Task Load Analysis; Cognitive Work Analysis; Critical Decision Method; Team Cognitive Task Analysis Techniques; Hierarchical Task Analysis; Verbal Protocol Analysis; Subjective Workload Assessment Technique
Psychophysical scales and models	Psychophysical Databases; Borgs scale of perceived exertion; Body Part Discomfort Scale
Productivity analysis	ErgoSAM; ErgoMOST; DMSP; EMA
Note: RULA: Rapid Upper Limb Assessment; REBA: Rapid Entire Body Assessment; OWAS: Ovako Working Posture Assessment System; QEC: Quick Exposure Checklist; MVTA: Multimedia Video Task Analysis; PLIBEL: Checklist Tool Developed by Kemmlert; ACGIH HAL: American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value for hand activity level; NIOSH: The National Institute for Occupational Safety and Health; LMM: Lumbar Motion Monitor	

Table 1: Ergonomic methods and its classification.

The developments over the years have been to integrate multiple ergonomic tools into a single analysis environment. Digital human modeling (DHM) is one such platform of integration, and is discussed in DHM and Virtual Ergonomics. Along with advances in modeling and ergonomic tools there is a need to integrate productivity and costing-benefit analysis [11,48]. Some of these aspects are accounted for in the 'Surveillance module' and 'Digital Ergonomics Simulation Module' of the proposed HFE intervention framework.

DHM and virtual ergonomics

Computer-aided simulation tools and DHMs are considered to be promising in the facilitation of proactive ergonomic investigations. Digital human modelling and simulation is a biomechanical representation of the human body along with the computational algorithms that configure or drive the mannequin to produce postures or motions. It is an emerging technology which can be used to redesign products according to human comfort and safety, to assess disorders and impairments, and how therapies and surgeries are conducted. The implementation of digital human modelling technology allows easier and earlier identification of ergonomic problems, and lessens or sometimes even eliminates the need for physical mock-ups and real human subject testing [33,49]. Some examples of software that use human manikins are SAMMIE, BOEMAN, JACK, Anybody, SANTOS, HumanCAD, RAMSIS and SAFEWORK [50]. They permit to define complex scenes, analyze postures, simulate tasks and optimize working environments and are used especially in automotive and aeronautic domains. The works of Gironimo et al. [5], Vilas et al. [26] and Laring et al. [51] highlight the Methods-Time Measurement (MTM) based simulations tools (i.e., ErgoSAM, ErgoMOST, MTM-UAS), and works of Cimino et al. [52] highlight the simulations in virtual environment to integrate ergonomic solutions.

Virtual ergonomics, with developments in virtual reality (VR) and virtual manufacturing (VM), permit designers to create and manipulate virtual humans and to investigate the interaction between the consumer or worker and the product [20,21,26,53]. For example, in product design, human factors such as positioning, visibility, reaching, grasping and lifting of weights can all be evaluated providing a feedback to designers in the early steps of product development. Some examples showing VR and VM applications are the work done by Hu et al. [27] in which the ergonomic analysis of drilling task is performed in virtual environment; work done by Gironimo et al. [5] in which virtual reality and DHM was used to study maintenance procedures of industrial products; work done by Qiu et al. [40,41] in which VR was used for interactive assembly and disassembly activities in automotive and maintenance operations. Increased performance in the field of computer graphics enables consequent implementation of many phases of product design into virtual environments.

In this article traditional design signifies the use of some of the computer aided tools and methods such as 3D modeling, rendering and view generation, finite element and computation analysis of validation of designs generated. Traditional design does not encompass ergonomic analysis, but in HFE integrated analysis, design software and hardware are used to account for human strength and capabilities (i.e., physical and cognitive). Adequate focus of HFE in early design phase may involve higher development cost, but it is likely to improve productivity and quality, lower compensation claims and man-days loss in its operational life. Figure 3 shows the product/work system cost along its life cycle. Integration of DHM and product life cycle management tools increases the capability to perform engineering design and analyses, improves the product ergonomics, enables human-machine virtual reality applications and provides cost and time saving. Many challenges are faced by human modelers in achieving HFE integration. The manikin integrated in today's software needs to realistically represent the human body's capabilities and functionalities, and also needs to be time-efficient. A simulation analysis is often done with only one or two manikins and the rest of the results are produced by imagining how the outcome would be if another person did the task [54]. To completely utilize the functions available in manikin families in a proper way, there is a need for the DHM simulation systems to evolve and be more automatic and supportive for the user. System or macro level ergonomic simulation based study that accounts for ergonomics, productivity and quality appears to be next logical developments in DHM integrated work systems.

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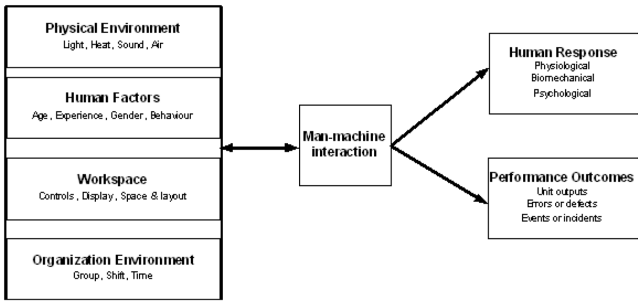

Figure 1: Performance and outcomes for a man-machine work system.

HFE integrated work system intervention framework

Work systems have previously been designed using the Industrial Engineering concepts of work-study, method-study or motion study, work-measurement or time-study, the focus being on engineering the system for productivity without much concentration on the 'human' element in the work system. Many of the task-analytic tools used for workplace analysis are rooted in the philosophy of dividing work into elements, analyzing the individual elements, and synthesizing the results into conclusions about the entire job [55]. An ergonomic study on the man-machine work system emphasizes on four major dimensions, i.e., immediate environment (e.g. workspace design, control design, effector design), general environment (e.g. light, sound, temperature, vibration), human factor (e.g. age, experience, strength) and work (e.g. content, schedule, organization). Figure 1 shows the work system performance and outcomes using the man-machine model adapted from Bridger [56].

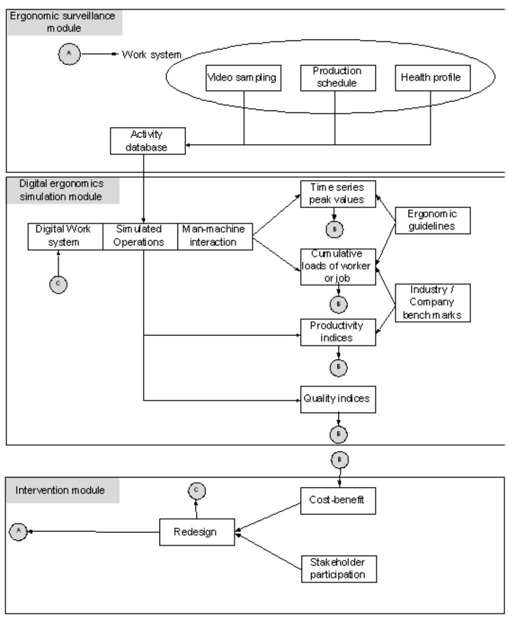

Figure 2: HFE intervention framework, Note: A, B and C are connecting links between three modules in the above flowchart.

For making business sense of the design solutions cost-benefits needs to be shown with specific definition of the time dimension. Time is a key issue for both ergonomists and engineers when they engage in production system interventions, and activities of the two groups when attempting to manipulate time aspects of work may be contradictory [57]. The work system performance metrics need to account for 'time' dimension. From ergonomic perspective, cumulative exposure integrates instantaneous forces/moments to represent the effect of time. Further, the time unit may be day, shift, week or year. Similarly, from productivity perspective turnover or production achieved per day or week would represent the integration of standard time for a unit product. From the traditional Industrial Engineering perspective the time study, standard time, time standard database are of significance. After the time dimension for performance metrics has been defined, the next step would be to resolve the design solution procedure. Within a multi-objective scenario a system level intervention would require optimization approach in deciding the design solutions. Battini et al. [24] presented an integrated methodological framework to assess productivity and ergo-quality performances in assembly system design. Garcia et al. [48] have presented an ergonomic project methodology with a continuous improvement procedure unified with a cost-benefit analysis with the help of DHM tools in a laundry service industry. The work output from any work system is best driven via sound industrial engineering expertise operating within an active learning organization. This calls for building and using intervention or design knowledge base. The focus of any intervention framework is to provide a dynamic feedback loop with respect to work system factors to make human-compatible systems.

An HFE integrated framework is proposed for effective and sustainable ergonomic interventions (Figure 2). It consists of three parts, i.e., ergonomic surveillance module, digital ergonomic simulation module and intervention module. First, the ergonomic surveillance system captures ergonomic effects from a real-time manufacturing environment by observation, correlating production schedule and health profile to create an activity database. The real time internal responses to be captured may include joint forces or moments, discomforts like ache, pain and strain, heart rates or oxygen consumption, fatigue or blood-oxygen level and blood pressure. Video technology appears to be the suitable choice for motion capturing, but wearable sensors are among the new ways for capturing motion. Vignais et al. [58] have demonstrated an ergonomic feedback system consisting of inertial sensors for industrial manufacturing. Further technological advances are required for obtaining ergonomic feedbacks in a non-obtrusive manner. Video technology also provides opportunity for pace rating [59] as a traditional form of work measurement technique. The use of MTM and its integration with motion data base is another approach.

Second, the digital work system operates on the generated activity database to simulate operations and output of the man-machine interaction, i.e., macro level performance indices such as peak, instantaneous or cumulative loads and productivity and quality indices. The ergonomic stresses can be through physical or cognitive workload from the task/work undertaken. The review of Wells et al. [57] calls for system level variables and metrics for ergonomic responses and its variation across time. The concept of cumulative loads is gaining focus recently, and is likely to play a significant role in the development of system level ergonomic metrics for digital human models and simulations. The cumulative loads could be at specific joint level, set of joints (e.g., upper extremity, lower extremity) or whole body, and the time component considered in cumulative load

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estimation could be based on seconds, days, weeks, and months or based on task element, task, and job. The ergonomic stress indices estimated from such internal biomechanical or physiological responses are compared with ergonomic guidelines and industry benchmarks to provide dynamic design requirement inputs to work-system designers. It would be an interesting addition within the current product life cycle management software to provide colour coded stress indicators on human body to aid ergonomic designers.

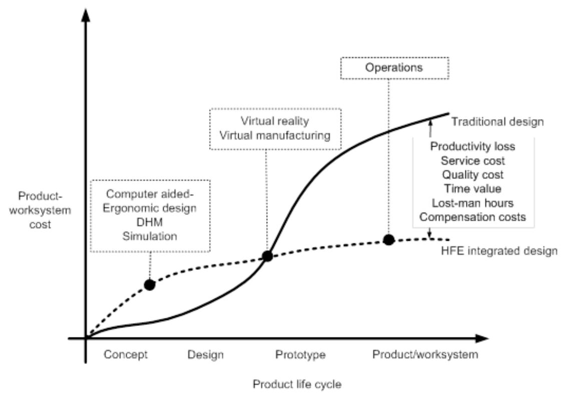

Figure 3: Product-work system cost vs. product life cycle [49].

Third, the intervention module calls digital ergonomics simulation module for ergonomic analysis and verification. A cost-benefit analysis of design solution shall be weighed by different stakeholders to decide on the suitable interventions. The fundamental principle invoked here is 'designing for a range' of population using the concept of flexibility in design variables, thereby, making a design fit for a production system rather than for a unit machine. The concept of 'range' in an anthropometric design variable accounts for the temporal aspects of the strength/human capabilities, and is dependent on factors such as age, gender, health-profile, team-composition etc. Based on the estimated (for current design) or simulated (for new design) man-machine performance matrices, a cost-benefit analysis of design solution shall be weighed by different stakeholders to decide on the suitable interventions. The cost-benefit modules shall help the Industrial Engineers and Work system designers to make informed decisions in making sound interventions. The modified design is constantly evaluated from the updated activity database from time to time. The closed loop feedback component shall enable validation of the design, and also allow Industrial Engineers to apply concepts such as statistical process control for targeting human-machine compatibilities at work system level.

The current ergonomic tools provided in DHMs often fail to consider time-related ergonomic factors. The cost and infrastructure component of the ergonomic surveillance module has not been dealt with in this paper, and shall be one of the limitations of this framework. Nonetheless, the proposed HFE framework can lead to a paradigm shift from 'micro ergonomics', where the focus is on product or machine level (man-machine interaction) human compatibility to 'macro ergonomics' where emphasis is on organizational or system level human compatibility.

Conclusion

The review has revealed that design as an intervention strategy is gaining significance because of increasing awareness of human well-being as a business enabler. There is a need for new investigation strategies that are suitable for complex systems and for practical and well conducted multifactor interventions. Professionals involved in workplace design and interventions need to learn and work to improve their understanding of how to effectively operate in both the design and implementation dimensions of change processes.

VR and VM along with developments in DHM are creating greater avenues for integrating ergonomic tools into computer applications for both product and work system design. The design requirements have been incorporated through ergonomic assessments from physical and cognitive characteristics in the DHM. At product and work system level, newer ergonomic design techniques and ergonomic design frameworks are being researched upon. With the advent of VR and VM this further increases the scope for ergonomic design techniques and framework. An HFE intervention framework using DHM environment has been proposed. The proposed framework attempts to integrate human and machine performance metrics in making interventions, thereby making a sustainable human compatible system. This calls for participation from three major stakeholders in engineering design based interventions, i.e., product life cycle software designers, work-system designers (includes users and managers) of manufacturing system and design academicians.

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