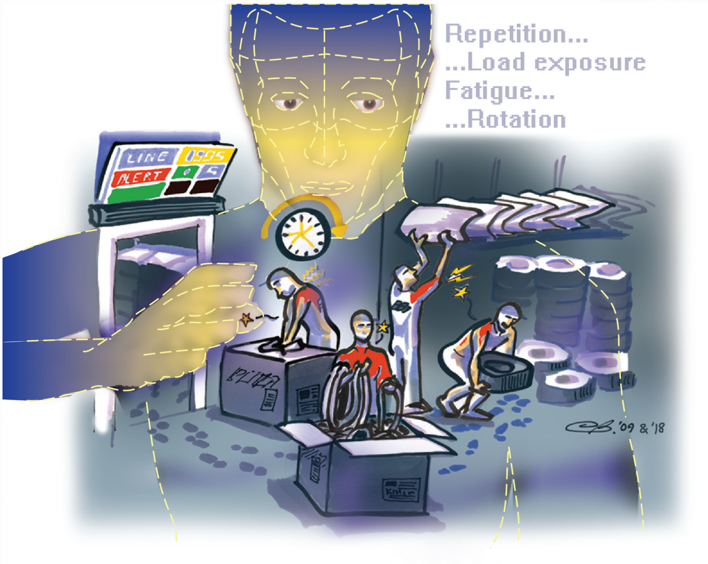
CHALMERS



Production Ergonomics Evaluation

– Needs, Procedures and Digital Human Modeling Tools

CECILIA BERLIN

Department of Product and Production Development
Division of Production Systems
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2009

THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

PRODUCTION ERGONOMICS EVALUATION

- NEEDS, PROCEDURES AND DIGITAL HUMAN MODELING TOOLS

CECILIA BERLIN

Dept. of Product and Production Development
Division of Production Systems
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2009

Production Ergonomics Evaluation

- Needs, Procedures and Digital Human Modeling Tools

By Cecilia Berlin

ISSN 1652-9243
Technical report No. 40

All illustrations by Cecilia Berlin (some images modified for online publication, 2018)

Contact information:
Department of Product and Production Development
Division of Production Systems
Chalmers University of Technology
SE-412 96 Göteborg, Sweden
Telephone +46-(0)31-772 1000

cecilia.berlin@chalmers.se

Chalmers Reproservice
Göteborg, Sweden 2009

ABSTRACT

Production Ergonomics Evaluation - Needs, Procedures and Digital Human Modeling Tools

Cecilia Berlin, *Department of Product and Production Development, Division of Production Systems, Chalmers University of Technology*

In production systems, human operators may be at risk for developing work-related musculoskeletal disorders (MSDs), resulting in pain, inability to work and high costs. An increasingly capable tool for identifying MSD risks early in the production design process are Digital Human Models (DHMs), although their built-in analysis tools are in great need of development regarding how they address time-related aspects of load exposure. Some examples of time-related exposure phenomena provoking MSDs are repetitive work patterns, lack of variation, fatigue effects, work rotation effects, and distributions of activity/rest. The aim of this thesis is therefore two-fold; to explore pragmatic industrial needs regarding ergonomics evaluation and compare this to the State-of-the-art of scientific evaluation methods that address time-related aspects.

The first approach, a case study in an automotive setting, revealed that switching from one evaluation method to another in a factory may be for pragmatic contextual reasons rather than based on educated selection. It was also shown that companies who do this may unintentionally risk producing evaluation results that are not equal regarding criteria levels or degree of analysis detail, rendering results unsatisfactory to use for some actors in the process.

The second approach, a literature review, categorizes several time-related ergonomics terms and has proposed a 'process-flow' framework for the terms, based on an *input-throughput-output* concept. This framework can give DHM tool developers an overview of which time-related aspects interact and which combinations are suited to different analysis goals.

Lastly, the thesis reflects on actor roles and time perspectives.

Keywords: Production Ergonomics, Digital Human Modeling, DHM, Virtual Tools, Time, Cumulative, Musculo-Skeletal Disorders, Prevention

LIST OF APPENDED PAPERS

Paper I: Berlin, C., Örtengren, R., Lämkull, D. & Hanson, L. (2009)*
Corporate-internal vs. National Standard – A comparison study of two ergonomics evaluation procedures used in automotive manufacturing.

Berlin performed the interviews, carried out the statistical analyses together with Hanson, and was first author of the paper.

Paper II: Berlin, C. (2009) **
Time-Related Factors in Ergonomics Evaluation Part II: a Literature Review and Scientific Basis for the Framework

Paper III: Berlin, C. (2009) **
Time-Related Factors in Ergonomics Evaluation Part I: a Development Framework for Digital Human Modelling

Berlin initiated and wrote both papers.

* Submitted for approval to *International Journal of Industrial Ergonomics*

** Submitted for approval to *Applied Ergonomics*

*The research presented in this thesis was made possible by the MERA-project **4D-Ergonomics**, which is carried out within Virtual Ergonomics Centre (www.vec.se) and is financially supported by VINNOVA (the Swedish Agency for Innovation Systems) within the MERA (Manufacturing Engineering Research Area) program under the grant no. 2005-01998 and by the participating organizations (Alviva, Dassault Systèmes, Etteplan, SAAB Automobile, Siemens / UGS and Volvo Car Corporation). This support is gratefully acknowledged.*

PREFACE AND ACKNOWLEDGEMENTS

"...Where one stops in the search for conclusive answers will depend on contestable judgements as to what one thinks it is crucial to explain, and how far outward in time and social space one wants to explore in search of a satisfactory account."

R. Dahl, 1982 (p.25)

Being a Ph.D. student in a multidisciplinary field can sometimes be an off-road experience. Rather than let me navigate completely haphazardly, the following people have through their involvement, extensive knowledge and kind support provided me with directions, welcome pit-stops, new fuel and purpose along the way.

First of all, warm and heartfelt thanks to my main supervisor Roland Örtengren. You have provided my research with a wider perspective, patiently guided me past some mentally challenging obstacles and given me plenty of insightful responses to my work without ever taking over the wheel, which I consider a big privilege.

My colleagues in the *4D-Ergonomics* research team – Roland Örtengren, Dan Lämkull, Lars Hanson, Dan Högberg, Hans Sjöberg and Ann-Christine Falck – thank you for plenty of supportive collaboration and for sharing your knowledge, time, and expertise. I would especially like to direct extra warm thanks to my colleague Dan Lämkull, for all the helpful moral support, pep talks, tips and 'coaching' along the way.

Thank you to the Division of Production Systems chief, Johan Stahre, for taking interest in my work and opening doors to new exciting opportunities and contacts. Thanks to the SIMTER research team from VTT in Finland and Chalmers in Sweden for adding *production system insight* to my researcher's toolkit. Thank you Lars-Ola Bligård for always cheerfully volunteering support and feedback on things I've written.

I would also like to thank all my department colleagues at the Division of Production Systems for providing a nurturing and supportive atmosphere. Also, cheers to the 'extended family' divisions Design and Human Factors, Product Development and the 'Rock People'. It's a pleasure to go to work with people like you around.

Thanks to all my supportive friends.

Lastly, my zany and wonderful family – Isa, Örjan, Inang and Robert – for keeping me safe, sane, well-fed and grounded and helping me remember to balance out my life. *Salamat po, talaga.*

Cecilia Berlin

Gothenburg, March 18, 2009

ADDITIONAL PUBLICATIONS

2009

Lämkull, Dan; Berlin, Cecilia; Örtengren, Roland: *DHM - Evaluation Tools* in *Handbook of Digital Human Modeling: Research for Applied Ergonomics and Human Factors Engineering* (Human Factors & Ergonomics). Vincent. G. Duffy (Ed.). Taylor & Francis, CRC Press 2009. ISBN/ISSN: 0805856463

2008

Lind, Salla; Krassi, Boris; Johansson, Björn; Viitaniemi, Juhani; Heilala, Juhani; Stahre, Johan; Vatanen, Saija; Fasth, Åsa; Berlin, Cecilia: *SIMTER: A Production Simulation Tool for Joint Assessment of Ergonomics, Level of Automation and Environmental Impacts.* Proceedings of the 18th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM 2008), Skövde, Sweden, Jun. 30 – Jul. 2, 2008, pp. 1025-1031

Lind, Salla; Krassi, Boris; Viitaniemi, Juhani; Kiviranta, Sauli; Heilala, Juhani; Berlin, Cecilia: *Linking Ergonomics Simulation to Production Process Development*. Proceedings of the 2008 Winter Simulation Conference, WSC 2008, Miami, Florida, USA, Dec. 7-10

Berlin, Cecilia; Örtengren, Roland; Lämkull, Dan; Hanson, Lars: National Standard vs. Corporate-Internal Ergonomics Evaluation - an Industrial Case Study. The 40th annual Nordic Ergonomic Society Conference, NES 2008, Reykjavík, Iceland, Aug. 11-13

2007

Berlin Cecilia; Bligård, Lars-Ola [Eds]. *Proceedings of the 39th Nordic Ergonomics Society Conference, Oct 1-3 2007, Lysekil, Sweden*. Göteborg: Nordic Ergonomic Society.

Berlin, Cecilia: On the Development of a Time-Sensitive Ergonomics Evaluation Method. *39th annual conference of the Nordic Ergonomics Society NES 2007 Conference CD*, pp. 119.

Högberg, Dan; Bäckstrand, Gunnar; Lämkull, Dan; De Vin, Leo; Case, Keith; Örtengren, Roland; Hanson, Lars; Berlin, Cecilia: Towards Dynamic Ergonomics Analysis of Work Sequences in Virtual Environments.. *Proceedings of the 17th International Conference on Flexible Automation and Intelligent Manufacturing (2007 FAIM), Philadelphia, USA, June 2007*, pp. 581-588. ISBN/ISSN: 978-1-4276-2092-7

2005

Berlin, Cecilia: *Step Right Up!*, MSc Thesis. Göteborg: Chalmers University of Technology.

TABLE OF CONTENTS

1. INTRODUCTION

This chapter expresses the author's point of departure, gives an overview of the problem area and provides the context and rationale for the research presented in this thesis and the appended papers.

1.1 BACKGROUND

With all the heavy, awkward and/or repetitive work tasks that are prevalent in manual production work, human operators are continually at risk for developing or triggering work-related musculoskeletal disorders (MSDs). In the past few decades, the notion has grown that production system workplaces need to be designed so that the humans (typically regarded as company employees) should be proactively safe-guarded against sustaining work-related injuries.

Production ergonomics is the name of an endeavour to avoid such risks by actively focusing attention on factory-floor ergonomics. There are chiefly two strategies for avoiding MSD risks in production: one is to use knowledge of healthy physical work behaviours to design new production lines with as much attention to ergonomics as possible before implementation (known as *pro-active* ergonomics). The other way is to place efforts on analyzing the ergonomics risks of an *existing* workplace layout, in order to target individual workers at risk and/or workstations that cause unhealthy physical load. Identified problems are then remedied by re-design of the unhealthy workstation, implementation of help structures to relieve physical load (such as motorized lifting aids), involvement of occupational health service professionals, etc. Such measures are called *reactive* ergonomics.

One tool for working pro-actively with production ergonomics that has gained momentum the last few decades has been *virtual tools* and *computer simulation* of production systems. Modern software currently allows production system designers not only to test different production flows, but also to introduce human representations into the system and analyze the effects of how work is performed. These representations are called *Digital Human Models*, or *DHMs*[1].

DHMs do what their name implies – they model (visualize) the actions of human workers, allowing a production designer or analyst to 'go through the motions' of planned production work and evaluate different solutions. The motions of the DHMs can be modeled using feed-forward kinematics models or motion databases of recorded motion of a real human performing the work motions (Chaffin, 2005). DHMs with built-in ergonomics analysis methods can serve as a helpful toolkit for identifying potentially harmful work postures and actions. This way, it is possible to avoid risks of costly worker injury already at the production planning stage. Since DHMs require input of intended production work and react accordingly, it can be said that DHMs are 'reactive tools for pro-active purposes'.

The other side of the coin is that despite the powerful animation capabilities of modern computers, the 'dynamic' evaluation capability of many DHMs lags far behind. Most ergonomics evaluation methods that have been established and gained recognition by the scientific community are based on *static* posture analysis, meaning that evaluations are based solely on the 'frozen-in-time' posture that the worker (or the animated DHM) assumes at any given moment. No consideration is taken of the nature of the motions, the order in which they occur, the influence of work-pause distribution or handling of 'dynamic' weight loads whenever objects are lifted or moved. Also, when analysis is based on selection of a few risky postures, there may be an overlooked possibility that the pragmatic context for the planned work posture places other demands on the worker than are evident from the isolated posture. For instance, being able to see one's work might take priority over working in a healthy posture.

Another reason for concentrating efforts on 'dynamic' analysis is that the human body's various segments have been shown to respond differently to different motion components of movement, e.g. velocity and acceleration

---

[1] sometimes also known as *manikins*

(Grant, 1994; Marras 1992). In general, it seems that the term 'dynamic' is used (somewhat carelessly) to signify the influence of motion on force exposures to the human body at work.

1.2 ABOUT THE RESEARCH PROJECT

The starting point for the research presented in this thesis was the project *4D-Ergonomics*[2]. Its main goal was to improve DHMs (also known as *manikins*) in several aspects. As the name *4D Ergonomics* implies, one focus area of development for the project was *time aspects* (also known as the 4th dimension) for DHMs. The research group proposes that with the capability of modern-day computer performance, which allows for rapid calculations, simulation and evaluation of human work motions should be made more 'dynamic' (Högberg et al., 2007 and Chiang et al., 2008).

The context in focus for the project is chiefly evaluation of production systems. Human involvement in production tends to incorporate repeated or 'cyclic' actions distributed across a working shift, meaning that DHMs can be a useful tool for early evaluation of planned task distributions and identification of MSDs, which tend to arise gradually (as opposed to sudden accidents or injuries). With DHM technology as the point of departure, its application on a production system setting raises the questions: What user needs exist for DHM tools? Who are the users? And what work objectives do they need to fulfil?

The research team members of *4D-Ergonomics* propose that more attention needs to be paid to the development of 'dynamic' analysis methods and tools which can accurately evaluate an animated motion sequence and take time-varying factors into consideration. This notion has been seconded in literature

---

[2] The 4D-Ergonomics project started in May 2006 and is expected to wrap up in July 2009. It is financially supported by VINNOVA (the Swedish Agency for Innovation Systems) within the MERA (Manufacturing Engineering Research Area) program under the grant no. 2005-01998 and by the participating organizations (Alviva, Dassault Systèmes, Etteplan, SAAB Automobile, Siemens / UGS and Volvo Car Corporation).

but it has been unclear how far the collective efforts of the research community have come in this aspect. Therefore, placing more focus on time-varying components of ergonomics evaluation methods is a step towards taking DHMs to a level where they become the useful prognostic tools they have the capacity to be.

1.3 PURPOSE OF RESEARCH AND THESIS

The central theme of the research as a whole is to produce knowledge that will improve the ergonomics evaluation capacity of DHMs. Although they are powerful tools, they are in considerable need of improvement regarding the evaluation methods they use to assess a simulated workflow. Therefore, placing efforts on examining and developing *evaluation methods* is an important aspect of improving DHMs. However, there is another surrounding context, which is the needs of the people who are the intended users of DHMs. Their professional requirements on information regarding ergonomics analysis determine the usefulness of the evaluation methods that are chosen for implementation into DHMs. Thus, efforts also need to be placed on examining the industrial DHM user needs.

Figure 1 illustrates how the thesis author’s research has moved between these fields in the chronological sense. Starting from the outermost ‘layer’, the author began her PhD work with a case study to explore industrial user needs, resulting in Paper I. The following step used an entirely different approach which was more theoretical; a literature review exploring time-related ergonomics evaluation methods and concepts was performed, resulting in Papers II and III.

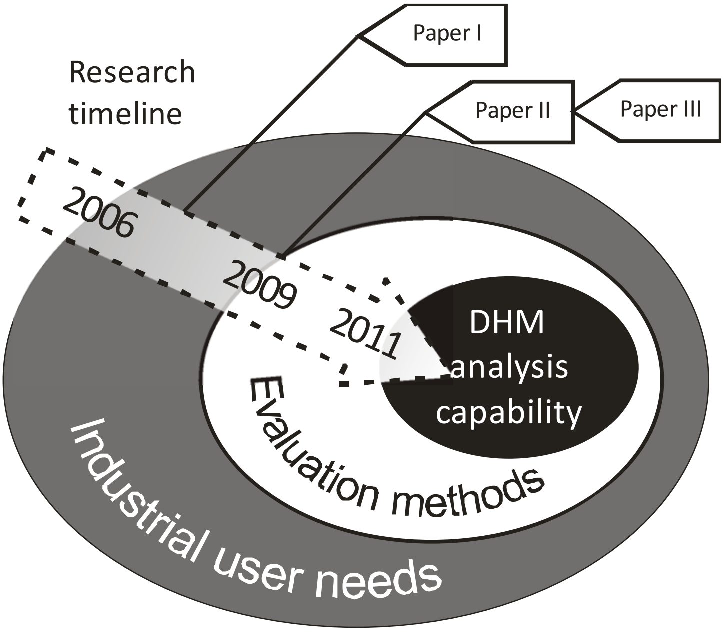


Figure 1 – The imagined pathway towards the central objective – contributing to knowledge that can improve the analysis capability of Digital Human Models – traverses two fields of knowledge. The outmost 'layer', Industrial needs, provides a context that determines which Evaluation methods are suitable for implementation into DHMs.

The aim of the thesis is to present the two explorative fields of research that appear in Figure 1 as the two outer fields surrounding DHM development. The results are largely independent of each other, yet they address two sides of the same problem. The thesis will discuss the ways in which the appended papers (and hence the two sides of the problem) are interconnected. It will also provide a synthesis of the research contributions by describing some additional insights that arise from carrying the 'lessons learned' from one field into the next. This in turn points the way towards further research areas to explore.

1.4 OUTLINE OF THESIS

Introduction *– This chapter expresses the author's point of departure, gives an overview of the problem area and provides the context and rationale for the research presented in this thesis and the appended papers.*

Frame of Reference *– In this chapter, the author introduces concepts of theory that are important to understand the context of Production Ergonomics, the use of Digital Human Models (DHMs) and the two fields of research that are explored.*

Research Questions and Delimitations - *This chapter summarizes the aims and objectives of the research as a whole in light of the theoretical background.*

Methodology *– This chapter presents the general research approach and the specific methods used in the appended papers.*

Results (Summary of Papers) *– This chapter provides a summary of the appended papers, describing the procedure, results and an evaluation of the research quality.*

Synthesis and Discussion *– This section brings up parallel insights that are the result of reflection on the contributions made in the papers and how they interrelate.*

Conclusions and Further Work *– This concluding section answers the research questions and summarizes the most important findings, as well as proposing further potential areas of continued research.*

2. FRAME OF REFERENCE

In this chapter, the author introduces concepts of theory that are important to understand the context of Production Ergonomics, the use of Digital Human Models (DHMs) and the two fields of research that are explored.

2.1 WORK-RELATED MUSCULOSKELETAL DISORDERS (MSDS)

Work-related musculoskeletal disorders (also known as WMSDs according to Kuorinka and Forcier, 1995) are defined as a term signifying “a heterogeneous group of disorders” caused by a multitude of potential (physical) factors. Specifically, the word ‘disorders’ is used to signify “the pathological entities in which the functions of the musculoskeletal system are disturbed or abnormal” (Kuorinka and Forcier 1995, p. 11). Pain, discomfort and fatigue are considered common first symptoms, while loss of function, limited movement range and loss of muscle power are more manifest signs of the presence of a WMSD. It is suggested (Table 1) that they may be caused or triggered by one or more of the following working conditions[3]:

Table 1: Working conditions that may cause MSDs (Adapted from Kuorinka and Forcier, 1995).

- Repeated physical efforts, such as movements and postures
- Static work
- Continuous loading of tissue structures
- Lack of recovery time

---

[3] Accident-related injuries are per definition excluded from the term’s scope, according to Kuorinka and Forcier, 1995.

Many sources indicate that the injury mechanisms that may (gradually) lead to MSDs are different for different body parts (e.g. Juul-Kristensen et al., 1997; Marras, 1992; Ma et al., 2009; Yen and Radwin, 2000). Thus, many evaluation methods and guides that have been developed are focused on a specific body region or type of injury. Some methods are targeted to identify back pain and disorders, e.g. the NIOSH lifting guide (NIOSH WPG, 1981), 3DSSPP (Chaffin, 1997) and 4D WATBAK (Neumann et al., 1999). Others, such as RULA (McAtamney and Corlett, 1993) and OCRA (Occhipinti, 1998) are specifically focused on assessing upper limb activities. Yet other methods have been developed to focus on other factors such as energy expenditure (*Garg Energy Model*; Garg et al., 1978), repetitiveness (*OCRA*) and lifting limits (*Liberty Mutual Force Tables,* a.k.a. *Snook Tables*; Liberty Mutual, 2004 and Snook and Ciriello, 1991).

2.2 COMMON PRINCIPLES OF POSTURE ANALYSIS

Many methods for posture analysis are based on *biomechanical* assumptions, i.e. the notion that forces, loads and torques on the tissues, joints and bone structures of the body can be measured and classified as risky or safe. This section will not go into detail of any specific method or guide, but will describe some of the most common principles for observation-based posture analysis.

One general principle is that the postures of individual body segments are assessed or rated one at a time. Many methods are based on the principle that the more an individual body segment or limb deviates from a relaxed, standing pose with arms hanging down (Figure 2a), the greater the risk for MSDs (see Figure 2). This limb-by-limb rating principle is quite evident in static posture assessment methods such as OWAS (Karhu et al., 1977), RULA (McAtamney and Corlett, 1993) and REBA (Hignett and McAtamney, 2000).

The measure of body segment deviation is sometimes expressed in terms of joint angles. The underlying biomechanical principle for this is that the weight loads of the deviating body segments cause torques on the joints and may require muscle exertion to be sustained.

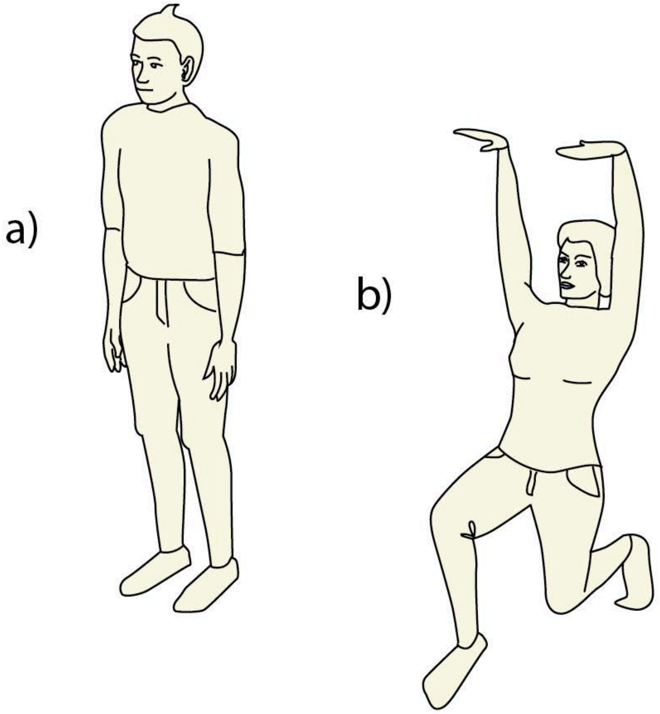


Figure 2 - a) A typical definition of a 'relaxed' standing posture. b) A largely deviating body posture that would generally receive high ergonomic risk scores according to most posture analysis methods.

Additional factors considered to decrease or increase the severity of the posture are sometimes taken into account by posture assessment methods. Examples of negative factors (that increase severity) are additional weight loads, sustained or repetitive occurrences of the posture, rotation or abduction of body parts, etc. Some examples of ameliorating factors that decrease severity are body support structures (e.g. for leaning on), good grips on handled weights, postures being assisted by gravity, etc. (McAtamney and Corlett, 1993; Hignett and McAtamney, 2000).)

Typically, the individual scores for each body segment are weighed into a total assessment of the body posture (plus relevant factors) as a whole, generating an assessment rating that indicates whether the working posture is acceptable, needs to be investigated further or needs to be addressed (and if so, with which degree of priority). So-called 'stop-light'-principles (where levels of acceptability follow the pattern "acceptable *(green)* – needs review *(yellow)* –

unacceptable *(red)*") are frequently employed in production system evaluations.

Other principles for posture analysis focus primarily on conditions for healthy lifting, in such cases taking consideration of the weights of objects being handled, lifting distance from the spine, resulting torques on the lower back, etc. This is the case for e.g. the Swedish national standard ergonomics provision AFS 1998:1 (AFS, 1998) and the NIOSH lifting guide (NIOSH WPG, 1981).

Some disadvantages of the described principles is that they are largely limited to the analysis of isolated postures, which are as a rule selected on the basis of the analyst's experience, training or suspicion that the posture is significant for the work being performed. Another thing to remember is that the majority of posture-based methods are also observation-based, meaning that they require a free, unobscured view of the work being performed (or an otherwise mediated way of correctly perceiving movements; e.g. the continuous joint angle data in a computer-generated manikin) to evaluate the situation correctly. Although observations may also be carried out using recorded material, it has been pointed out that 2D-representations of three-dimensional movement may cause analysis difficulties (Berlin, 2007).

2.3 PRODUCTION ERGONOMICS

It is difficult to describe a production design process that is applicable to all companies. However, the contribution of this thesis work may not appear clear without having been put in a context, which in this case is that of a production design process executed by a team of corporate actors.

The issue of monitoring and improving ergonomics in production is handled differently in different situations, depending on a number of contextual factors. Such factors may be the size of the company, the number of employees involved in the production planning process, the level of involvement that management allows the workforce over their tasks, the technological equipment and tools at disposal, the presence of an external occupational health service, and the company history of using formalized evaluation methods.

When planning a new (or re-designing an existing) production system, a great number of parameters need to be balanced against each other to achieve a cost-effectively designed system that maximizes productivity and minimizes the risk of quality deficiency and MSDs. In this section, focus will be placed on how different objectives may influence the chosen approach for identifying, monitoring and controlling ergonomics problems that arise in production. Depending on where in the process ergonomics are addressed and what is considered the root of the problem, different basic approaches (or a combination of them) may be used.

Perhaps the most basic approach is *observation* of the work being performed. One or more actors with some degree of ergonomics knowledge may use this approach to investigate the on-going production ergonomics status, assessing the occurring work activities against some kind of baseline for acceptable/unacceptable conditions. Depending on the actor's profession, the baseline may be personal knowledge and experience (as in the case of a trained ergonomist), a corporate or national standard (e.g. an occupational health service provider), or an observation guide or method for assessment (e.g. a production engineer, a process designer, a worker or even a researcher). A great number of evaluation methods and guides have been developed for observation purposes, most of them related to posture analysis.

Another approach is *task-based analysis* (Dempsey et al., 2006), where the work-related ergonomics risks are studied in relation to the individual sub-tasks that the work can be broken down into*.* This approach is closely associated with method-time measurement (MTM), a technique whose main objective is to determine how much time work requires by measuring the time taken to complete individual movement sub-tasks (see Laring et al., 2002). Task-based ergonomics analysis is a strategy that enables production engineers to pay attention to and reduce ergonomics risks in relation to time consumption issues. According to Dempsey et al. (2006), task-based analysis is useful for identifying peak or individual task loads but not as successful regarding cumulative or variation-related exposure. This insight is reflected in Laring et al.'s (2005) development of the tool ErgoSAM, an MTM-based method that graphically shows ergonomic load distributed over the work cycle (making peak loads easily discernable).

Another way to approach ergonomics exposure is to measure *physiological response to exposure.* This approach is perhaps more common in laboratory experiments, epidemiological studies and sports research. The aim is then to study human physiological responses to different load exposures and measure physical limit levels such as maximal voluntary contractions, endurance times until exhaustion, electric activity levels in musculature (EMG) etc. Studies of this nature sometimes involve or require advanced equipment, invasive study methods or relatively large experimental populations, earning them higher etiological and epidemiological credibility (e.g. Norman et al., 1998 and Seidler et al., 2001). Other approaches are very calculation-intensive (Yen and Radwin, 2000). For these reasons, physiological response studies may not be a first-hand choice of approach for ergonomics evaluation in a corporate context. Still, such on-site studies have been performed by researchers in order to validate models and investigate correlations between exposure and response (e.g. Seidler et al., 2001; Mathiassen and Winkel, 1991; Bao et al., 2009)

Another issue that needs to be resolved is whether to associate ergonomics assessment to human operators (individuals in the exposed workforce, a workforce team consisting of a limited group of individuals, *or* a generalized population), *or* to product- or production-related parameters (e.g. product construction features, workstations, equipment or materials). Depending on the supposed ‘culprit’ causing ergonomics problems, different actors may choose different ‘units of improvement’ to associate assessment results with. An occupational health service professional may want to identify and remedy an identified unhealthy exposure for one or more individuals (*reactive* intervention), while a pre-production engineer or ergonomist may instead want to pinpoint product- or workstation-related parameters that can cause a risk for MSDs, thus being able to give feedback to product development engineers much earlier in the design process (*pro-active* intervention).

2.4 VIRTUAL TOOLS AND DIGITAL HUMAN MODELING (DHMS)

To facilitate pro-active work with production ergonomics, a number of virtual software tools have been developed to visualize the combination of humans and machines in a planned production system. Many of these tools include a Digital Human Model (DHM), a.k.a. *Manikin*, whose purpose is to visualize and help evaluate the risks for MSDs in the proposed work sequences. This section will focus on the use of DHMs as ergonomics analysis and design tools.

A number of different DHMs have been developed to facilitate ergonomics evaluation, e.g. Jack (Badler et al., 1993), ErgoMan (Schaub et al., 1997), 3DSSPP (Chaffin, 1969), OSKU (Helin et al., 2007) and Santos (VSR Research

Group, 2004). These have been employed chiefly in automotive, aerospace and military contexts and in later years also in production system design (Lind et al., 2008).

In many cases, production engineering involves modeling of the planned working environment in a virtual 3D environment. Here, different setups of machines that automate parts of the manufacturing process are combined with models of human operators, greatly facilitating the evaluation of task allocation strategies. Frequently, the DHMs can be animated to show work postures and give an idea of time consumption for work tasks. These animation schemes can be manipulated by the production planning engineer building the simulation, either using manual adjustments or kinematic motion prediction models, which are frequently based on databases of 'realistic' movements that approximate motion paths of a specific goal (e.g. moving an object). Also, thanks to three-dimensional recording technology allowing motion capture, it is possible to simulate realistic movements by recording the limb-posture of a moving human subject in real time. Many DHMs incorporate a variety of analysis tools for ergonomics; the most common implemented tools and guides tend to be static and posture-based, such as RULA (McAtamney and Corlett, 1993), OWAS (Karhu et al., 1977) and the NIOSH lifting equation (NIOSH WPG, 1981 and Waters et al., 1993).

According to Chaffin (2005), it is vital that DHMs are based on posture and motion prediction models that are valid for various populations, and that the basis of analysis must be real motion data. Also, as stated in the introduction of this thesis, few models for continuously evaluating the effects of ergonomic load exposure over time exist that can readily be implemented to 'follow' an animated flow of dynamic movements. Successful efforts of implementing real-time readouts of the RULA method (McAtamney and Corlett, 1993) in virtual environments have been reported (Jayaram et al., 2006; Helin et al., 2007).

In some cases the focus of using a virtual planning tool is not so much on ergonomics as on production flow simulation, disturbance modeling and other process factors, which on one hand emphasizes the importance of the time aspect, but at the same time constitutes a reason why the DHMs' capabilities regarding ergonomics analysis may vary. Also, virtual tools may at present predominantly appear as part of the production design process in large-scale corporations who are able to make a large-scale investment in virtual tools, rather than small- or middle-sized enterprises. This is often dependent on factors such as the ability of the company to allocate personnel and economic investments towards education and use of virtual tools (e.g. large automotive corporations, as described by Lämkull, 2006), and the perceived usefulness of virtual evaluation before making machine-park investments. A framework for judging whether virtual environment tools are a feasible option in a production planning context has been suggested by Chung et al. (2002).

A number of researchers (Chaffin, 2005; Dukic et al., 2007; Högberg et al., 2007; Wells et al., 2007; Chiang et al., 2008; Laitila, 2005) have stated that while virtual tools have proven very useful and contain many well-developed functionalities, there is substantial improvement potential in many areas having to do with ergonomics. Chaffin (2005) argues that appropriate motion modelling is a must for valid prediction of ergonomics implications, and that *Inverse Kinematics* (one of the main driving algorithms of human motion simulation) involves time-consuming calculations that may be inaccurate.

3. RESEARCH QUESTIONS AND DELIMITATIONS

This chapter summarizes the aims and objectives of the research as a whole in light of the theoretical background.

3.1 RESEARCH QUESTIONS

The aim for this research is to explore how the ergonomics evaluation needs of *production system designers*[4] relate to the tools and methods that have been developed so far by the scientific community, with special regard to how time aspects are addressed.

The objectives of the research in this thesis are to explore:

- which contextual aspects influence industrial choices and use of tools and methods,
- which aspects need to be covered by analysis to make methods relevant for modern-day production system designers' demands, and
- (from a theoretical angle) how current ergonomics evaluation methods take consideration of time aspects.

These considerations can be operationalized by the following research questions:

RQ1 *Which ergonomics evaluation considerations are evident in methods used by industrial manufacturing corporations?*

RQ2 *Which time-related ergonomics concepts have been sufficiently explored by ergonomics research to be implemented into Digital Human Models?*

---

[4] Regardless of whether they are a single person or a collaborative team

Potential benefactors of this research are developers of DHM software with animation capabilities, as well as all corporate actors in the production design process who work together as a team to achieve the balance between factors that make up a healthy and effective production system.

3.2 DELIMITATIONS

The research carried out in this compilation thesis is mainly focused on *physical load* exposures and the identification of risk for MSDs resulting from physically unhealthy work design. Although the risks of injury are certainly influenced by environmental factors, subjective experiences and psychosocial factors, those issues are excluded from the considerations of this thesis.

4. METHODOLOGY

This chapter presents the general research approach and the specific methods used in the appended papers.

4.1 GENERAL RESEARCH APPROACH

It can be said that the problem area has been approached from two different angles in this thesis; one practical and one theoretical. Taking Digital Human Modelling software to the next level needs to be anchored in conscientiously balancing a duality of challenges:

- firstly, ensuring that relevant industrial DHM user needs and priorities are in focus, and
- secondly, augmenting the simulation capacity of DHMs by making use of scientific findings regarding time-related ergonomics evaluation.

As the thesis author's work has progressed, the research has by necessity gone from its initially intended quantitative, algorithm-focused point of departure to one that concerns social sciences, corporate contexts and skill-based evaluation. Also, many evaluation method choices may be pragmatic rather than methodologically motivated, and such pragmatic factors need to be weighed into the picture.

Therefore, by virtue of the problem area's multiple actors and stakeholders, there is a rationale for combining *quantitative* and *qualitative* research methods in the research domain. *Qualitative* methods are difficult to summarize, but can be described as focused on processes and the contextual study of phenomena occurring in 'natural settings'. They tend to aspire to provide rich, detailed descriptions and increase holistic understanding for the studied phenomena (Bryman and Bell, 2007 p. 426).

Q*uantitative* methods are described by Danermark et al. (2003) as being frequently focused on "statistical causal analysis, variable analysis and aggregates of units where mathematics play a major role, and that empirical observations are given priority" (p. 281). Quantitative methods tend to use instruments as a medium for data collection (e.g. scales, tests, surveys) and are concerned with 'impersonal', precise, detailed reductionistic results, while qualitative research results are mediated through the researcher (observations, interviews) and are geared towards holistic descriptions which can be further elaborated upon (Danermark et al. 2003, p. 286). Qualitative vs. quantitative strategies is the classical distinction between methods used in social sciences-related research. For the work in this thesis it becomes important to assume a standpoint that can combine these methods, since the ultimate goal is to use research results regarding industrial needs combined with a holistic knowledge of which ergonomics methods exist, in order to develop credible algorithms and functions for DHMs. Such a goal must per definition be able to appreciate both qualitative and quantitative data.

Interestingly, Danermark et al. (2003) offer an alternative categorization of research design into *intensive* or *extensive* empirical procedures, meaning that the research can be either geared towards causal, contextual explanations of how a specific phenomenon arises (*intensive*), or towards descriptive 'representative' generalizable results that are not necessarily explanatory (*extensive*). The former tends to incorporate a greater proportion of qualitative data collection and analysis methods, while the latter uses formalized (quantitative) structured instruments for data collection and statistical analysis.

This alternative distinction rests upon the assumption that the general research question is of the nature "What produces a specific occurrence?" (Danermark et al. 2003, p. 290) and that the phenomena being studied are determined by their context, which at least for the work in Paper I is a relevant assumption. While Papers II and III do not explore how a specific phenomenon occurs contextually, each studied literature contribution has been produced in a specific research context influencing its objectives.

4.2 DATA COLLECTION METHODS

Paper I was a *case study* consisting of a *secondary analysis* of *unsolicited* company-internal *running records* that were produced as part of ongoing ergonomics monitoring. Since it turned out that the results were not easy to interpret in themselves, the document study was combined with collection of *primary* data in the form of *interviews*. Papers II and III are based on a *literature review,* which can be considered a collection and analysis of *secondary* and *tertiary* data (chiefly other research articles). What these methods involve is explained in the following sections.

4.2.1 Case Study

Inasmuch as the research in Paper I can be considered a *Case study*[5], it displays the following characteristics (Bryman and Bell, 2007): it studies a single organization (Volvo Car Corporation), a single location (a specific factory in Sweden) and a single event (the succession of two ergonomics evaluations). According to Bryman and Bell, a *case study* implies "intensive examination of the setting" (2007, p. 62). Yin, (2003) distinguishes between different types of cases, of which the one in question can be called a *revelatory* case, since it provides "an opportunity to observe and analyse a phenomenon previously inaccessible to scientific investigation" (Yin, 1984 p. 44, cited by Bryman and Bell, 2007).

4.2.2 Document Analysis and Data Types

According to Flick (2006), the research performed in all the appended papers includes something that can be called *document analysis.* A 'document' is defined as a standardized artefact that is produced as part of an ongoing development. Most often they come in a pre-determined format (e.g. case reports, notes, PMs, certificates, letters, judgments etc.). Prior (2003, in Flick, 2006) adds that they must be considered in light of the context ("fields of action") they are produced and used in. Documents can be either *solicited* (i.e. requested from the studied actors by a researcher, in order to draw conclusions) or *unsolicited* (i.e. they are produced as part of ongoing routine regardless of the researcher's objectives). A further classification is that between *running records*, which are produced continuously as a result of administrative processes, and *episodic* or *private records,* which are produced occasionally (Webb et al., 1966 and Lee, 2000; both in Flick, 2006). The important point (according to Flick, 2006) is that documents are *contextualized* information, since the context influences the quality, representativeness and

---

[5] The thesis author would like to emphasize that 'Case Study' is actually a methodology and research approach in itself, rather than a data collection method; however since it constitutes a rather small yet important portion of the appended research, the concepts relevant for this *particular* case study are briefly mentioned.

meaning of the documents. As suggested by Scott (1990, in Flick, 2006) it is important to keep in mind that the circumstances (who, when and where) under which the documentation was produced affects its quality.

Furthermore, these exists a distinction between *primary* and *secondary* (sometimes also *tertiary*) documents or data (Flick, 2006; Bryman and Bell, 2007). Although the exact boundaries between the types are not always clear, *primary* data tends to signify a scenario where the data stems from an 'eyewitness account', i.e. the collector of data and producer of the document are one and the same, while *secondary* data is generally generated by study of primary documents (and not the actual object or event of study). Tertiary documents tend to be sources to find other documents (Flick, 2006). Thus, *secondary analysis* is "the analysis of data by researchers who will probably not have been involved in the collection of those data, for purposes that in all likelihood were not envisaged by those responsible for the data collection." (Bryman and Bell, 2007 p. 326)

4.2.3 Interview

In Paper I, two interviews with company actors who had experience of the two studied ergonomics evaluations were conducted. They were carried out as *focused interviews* (Merton, Fiske and Kendall, 1956 in Bryman and Bell, 2007, p. 213), meaning that the interrogator asked predominantly open questions having to do specifically with the focus area (i.e. the two factory evaluations). Furthermore, the interviews can be labelled as *unstructured* (i.e. a list of topics and issues to discuss was used instead of formal questions) and a *group* interview (Bryman and Bell, 2007, p. 213), since the interviews were carried out more than one person at a time, both times. The interviews were recorded on-site via note-taking and some preliminary tables and charts of the study's quantitative results were shown to the interviewees during the interview as a 'prompt' for eliciting comments. After the interviews, a preliminary version of the paper was shown to respondents for further corroboration.

It may be prudent to emphasize that the goal was specifically to gain a rich, detailed understanding of the interviewees' points of view and explore aspects that the interrogator could not deduce from the quantitative analysis. This is called qualitative interviewing (Bryman and Bell, 2007 pp. 473 – 474).

4.2.4 Literature Review

The objective of the literature study in Papers II and III[6] (the second 'line of research') was to be evaluative, establishing what is known within the research area and identifying relevant concepts and theories, relationships, gaps, contradictions and inconsistencies between the contributions (Psychology Writing Center, 2005; Bryman and Bell, 2007). Such a review provides support for defining and refining research questions and research designs. Many theoretical research outlooks exist in parallel in this research field, and many of these can be distinguished through comparison of assumptions of research questions, experimental methods, data analysis and conclusions drawn (Psychology Writing Center, 2005).

The literature is reviewed and discussed regarding these aspects in Paper II, and Paper III embodies an effort to 'suggest the next research step'. Since the review also interpretively analyzes multiple aspects of production ergonomics (which has been extensively studied from several different points of departure) starting from a DHM development theme, the approach may be considered a form of *meta-ethnography* (Bryman and Bell, 2007 p. 102-103).

Additionally, the review has provided plenty of input towards this thesis' *Frame of Reference* chapter and suggested further research, as suggested by Bryman and Bell (2007).

---

[6] Papers II and III are described together since they were originally one paper that was split into two – therefore they are based on the same research activities. The reason for describing 'Part II' before' Part I' is that this follows the actual workflow: the literature review was performed first and resulted in the proposed framework. However, in keeping with journal publications praxis, in the submitted manuscripts the framework is presented as 'Part I' and the scientific base (the review) as 'Part II'.

4.3 DATA ANALYSIS

4.3.1 Statistical Treatment

Paper I incorporates a comparison between the quantitative (or semi-quantitative) data that was collected in two factory-wide ergonomics evaluations, chiefly consisting of ratings on a workstation-level where each station was ranked as red (not acceptable), yellow (needing further attention) or green (acceptable). This means that there existed *ordinal* data (i.e. belonging to categories that can be rank ordered but are not necessarily equal distances apart; see Bryman and Bell, 2007 p. 355) on three levels, which could be subjected to bivariate descriptive statistics (Bryman and Bell, 2007 p. 360) and tested for agreement using the software SPSS 15.0 for Windows.

There was also *nominal* data (i.e. categories with no internal order) on a *dichotomous* level (signifying only two possible categories; Bryman and Bell 2007 p. 365-357), since the two evaluations were also compared in terms of whether or not they pointed out one of four body segments (back, shoulder, neck or hand) as being at risk for unhealthy exposure. This data was also subjected to bivariate descriptive statistics.

In general, all data was crosstabulated and subjected to built-in applicable mathematical tests for agreement in the SPSS software. The *odds* of either method identifying risk for a body segment were calculated manually. A significance level of 5% (α= 0.05) was used.

4.3.2 Hermeneutical Approach to Data Categorization

In Paper II, the collected data was subjected to a hermeneutical approach when it was gradually arranged into different categories, explored further and re-arranged into new, more meaningful categories that emerged as the literature was amassed and processed. Although this is not so much a method as a theory of understanding, the concept of the *hermeneutic circle* (Smith, 1998 p. 161) can be used to describe the gradual processing of the collected literature by alternately interpreting and understanding the whole in relation to its parts, and the parts in relation to the whole.

4.4 QUALITY CRITERIA

The research presented can, to some extent, be scrutinized using classical criteria of reliability and validity[7] (Yin, 2003), since its content is partly quantitative; this will be attempted, however it becomes quickly apparent that for certain issues, alternative criteria are more suitable. In these cases Lincoln and Guba's alternative naturalistic quality criteria for trustworthiness in qualitative research (Lincoln and Guba, 1985 pp. 301 – 327; Bryman and Bell, 2007 pp. 410-415) are consulted, addressing *transferability, credibility, dependability* and *confirmability* instead. Rather than explain the meaning of the terms here, this will be done 'in context' in the Results chapter.

---

[7] Internal/external validity, generalization, objectivity and reliability, as described by Yin, 2003.

5. RESULTS (SUMMARY OF PAPERS)

This chapter provides a summary of the appended papers, describing the procedure, results and an evaluation of the research quality.

5.1 PAPER I

5.1.1 Procedure

The starting point of Paper I was a retrospective case study where two different ergonomics evaluation procedures (methods) had been used to evaluate the same factory of a Swedish automotive manufacturer. The situation was such that the company had invested a great effort into first using a method called *BME*, where factory teams assigned to a line of workstations were tasked with arriving at a consensual rating of acceptability for each workstation, according to a highly specified corporate protocol with clearly defined criteria of acceptability. The evaluation teams had received a 3-week company training course to certify them as users of the method. After the factory had been evaluated using the BME method, the entire procedure was replaced with evaluation by two Occupational Health Service professionals (OHS ergonomists) who were assigned to evaluate each workstation again, this time using the Swedish national standard provision *AFS 1998:1* as acceptability criteria. Rather than follow a specified rating protocol, the ergonomists performed an 'expert' evaluation based on their knowledge and experience, and evaluated ergonomics individually on a substantial number of workstations.

For both procedures, the common main principle for evaluation was that each individual workstation was given a rating expressed by a 'stoplight'-configuration: stations were classified as *red* (unacceptable ergonomics), *yellow* (needing further evaluation) or *green* (acceptable). Furthermore, both methods reported specific body segments considered at risk for injury at each rated workstation.

Post-completion of the two evaluations, a document study was commenced based on the corporate evaluation records. The working hypothesis being tested was that the two evaluation procedures were equally effective at identifying ergonomically problematic workstations. This was investigated by comparing how the BME method and the national standard (AFS) had rated each workstation respectively. Also, the specific body segments reported by either procedure were compared, to see to what extent there was agreement. The comparison was carried out using descriptive statistics, chiefly using simple statistical tests of agreement.

Since it was not immediately obvious what caused the differences in ratings, the statistical comparison was followed up by a semi-structured interview with the team of pre-production ergonomists that had been present when the BME evaluations were performed, and a second one with the two OHS ergonomists who carried out the AFS 1998:1 national standard evaluation.

5.1.2 Results

Though the methods were believed to be similar enough to be interchangeable, they differed significantly in how they rated workstations, and it was observed that the national standard tended to rate more severely (more classification into yellow and red) than the BME procedure. As for body segment reporting, the overall propensities for BME and the national standard to identify a workstation as a risk for a particular body segment are significantly different, although conclusions cannot be drawn with confidence regarding the hand category and the neck category is also doubtful.

Both interviewed groups stated that there were differences mainly in how the BME and national Standard methods considered the middle ‘yellow’ rating; it transpired that there were other corporate-cultural contextual factors not evident from the quantitative results that also affected the interpretation of the yellow level.

Some ambiguities remain due to the study setup; among other things, it was not possible to determine whether the differences in ratings were specifically correlated to the methods or the persons who performed the evaluations. Inter-rater reliability testing is fraught with confounding factors, since a) the testing involves comparing the performance of one individual with that of a team of three people, and b) the relative difference between the levels of ergonomics expertise among raters was not known, apart from the assumption that the OHS ergonomists had considerably greater experience. Intra-rater reliability was not applicable for testing, since each person or team had only given stations a rating once. Furthermore, although it had been assumed by the paper authors that the two evaluations had been carried out sufficiently close in time (with a gap of three months) to assume that no major remodelling of the workstations had been done, there is some uncertainty that cannot be completely accounted for.

Summarily, Paper I proposes that large-scale corporations might inadvertently exchange one ergonomics evaluation method for another that has a different criteria basis, thus getting different results on the same workstations and not capturing the same ergonomics problems.

5.1.3 Evaluation

In Paper I, the research design evolved in an emergent fashion, with the qualitative part 'added on' as the insufficiencies of the studied material revealed that a purely quantitative comparison would be difficult to justify. Although the quality of the material itself has not been questioned in Paper I, it should be mentioned again that the two evaluations were performed by two very different actor configurations (multiple teams vs. one team). Thus, there is reason to suspect that the evaluation data from either method, although similar in output, were collected for different end users AND different purposes because of *who* collected them. In this case, documentation quality was not discussed in the paper (since there was no other viable alternative source of information).

The quantitative analysis was actually preceded by qualitative preparation work, in the sense that the material needed to be categorized and filtered in order to be numerically compared. For example, only workstations that had been evaluated by both methods were taken into account in the qualitative comparison (i.e. no random sampling) and since both methods arbitrarily reported specific body segments under load, the four most prevalent 'complaint segments' were compared and the remaining segment categories discarded, leading to further elimination of stations in the sample.

The qualitative element of Paper I, the interviews, were considered essential by the authors in order to make sense of the quantitative results, which were permeated with constructed (context-specific) meaning that was not accessible to an outsider.

The strength of Paper I, method-wise, is that the combination of quantitative and qualitative methods gives added insight into a quantitative result that by itself is no indicator of a clear tendency. In all, the usefulness of the results increased thanks to the combination of methods. However, the basic criteria for evaluating reliability and validity regarding this study must take into account that the study itself is very context-specific (unique for both company and country). The paper itself gives a *thick description* of the studied evaluation methods, the circumstances at the factory, the personnel involved and also directs the reader to source material that tells more about the context, which hopefully fulfils the quality criteria of enabling future researchers to determine transferability to another context.

The *external reliability* (i.e. the study's replicability) in Paper I can be said to be low in the sense that the context and material made the results very situation-specific. However the *procedure* for the actual quantitative comparison is richly described in the paper, as well as the context, actors and methods involved in the comparison. This aspect leads us to Lincoln and Guba's quality criteria of *Transferability* – with the aid of the supplied *thick description*, future authors should be able to decide whether other case contexts readily lend themselves to what was done in this study and can at least replicate the same principles for sampling and comparison categories as in the paper.

On the downside, the description of the *qualitative* work offers no direction as to what manner of questions were asked – to put it harshly, *replicability* of the interviews for anyone other than (indeed, including) the interrogator is minimal. Three great disadvantages (attributable to the interrogator's inexperience) were that the interviews were: performed by one interrogator alone; not audio-recorded, but type-written as the interview progressed; and unstructured. In a sense, the on-site note-taking made the subsequent analysis easier, as some of the filtering and categorization of answers was performed simultaneously with the data collection. However, due to these circumstances, the *replicability* of this data collection has been reduced significantly as a result.

The possibility of ensuring *dependability* and *confirmability* of the interviews is not impressive, since the interview records are not appended, the work performed by one individual, and the accessibility of the 'raw' data is low. On the other hand, the strong influence of the corporate context and personnel involvement was the major reason for allowing the interview to progress in an unstructured manner, making replicability virtually impossible to attain at the outset. Additionally, the results were affected by group dynamics between the interviewer and the interviewees, the corporate context and the fact that the results were 'filtered' by the method of notation. This means that it is impossible to separate context and the interviewer's interpretation from the findings, and hence to entirely replicate the method used.

As for *internal validity*, or the match between what is observed and the theories developed, the degree to which this is fulfilled could be considered both high and low in Paper I – mostly because the authors have been very cautious about drawing conclusions based on the quantitative material, opting instead for basing conclusions on the synthesized results of the two data collections (and doing this very cautiously as well, stating that explanations for the quantitative results *in this particular context* arose from the qualitative interviews). In line with Lincoln and Guba's (1985) suggested criteria amendments to ensure *credibility*, one might say that the research design involved at least a small element of triangulation (by combining quantitative and qualitative data collection; Bryman and Bell, p. 412). Also, one of the interview respondents was involved in proofreading the paper and giving corroboration feedback before submission – a form of *respondent validation*.

5.2 PAPERS II AND III[8]

5.2.1 Procedure

The starting point for Paper II was to explore how the aspect of *Time/Dynamics* ergonomics concepts that are directly related to time factors (such as continuous exposure, repetition, frequency etc.) has been defined and treated in ergonomics literature. The long-term objective was to use the literature review as a basis for developing a framework for how to incorporate time-related ergonomics aspects into a DHM software process. The framework was

---

[8] Papers II and III will still be described and evaluated together. See footnote 6.

presented separately in Paper III and Paper II constitutes the scientific basis for the framework.

A literature review was carried out starting with a keyword search using words such as *time, ergonomics evaluation, dynamic, repetitive* and *cumulative*. Most sources were found in databases Scopus, Ingentaconnect, Google Scholar, Inderscience, ScienceDirect and similar services. It was decided that in order to retain a focus that would be applicable to DHM, the initial search was limited to literature from 1990 and onwards. Additional literature outside of this time frame was added for one of two reasons – either they were found in the reference lists of the collected contributions and deemed relevant enough to include, or they were suggested as additional input by colleagues who audited the review as it progressed.

After initial reading and sorting of the material, the author used a chiefly hermeneutic approach to categorize the material in different ways.

5.2.2 Results

An initial categorization of the found time-related ergonomics terminology into functional groups led to reflections on time perspectives that influence the range of applicability for different terms and concepts. It was found that for some time-related terms, there was a lack of consensus regarding how to use them, or relate them to each other in a hierarchical manner. Figure 3 shows the initial categorization round of the identified concepts:

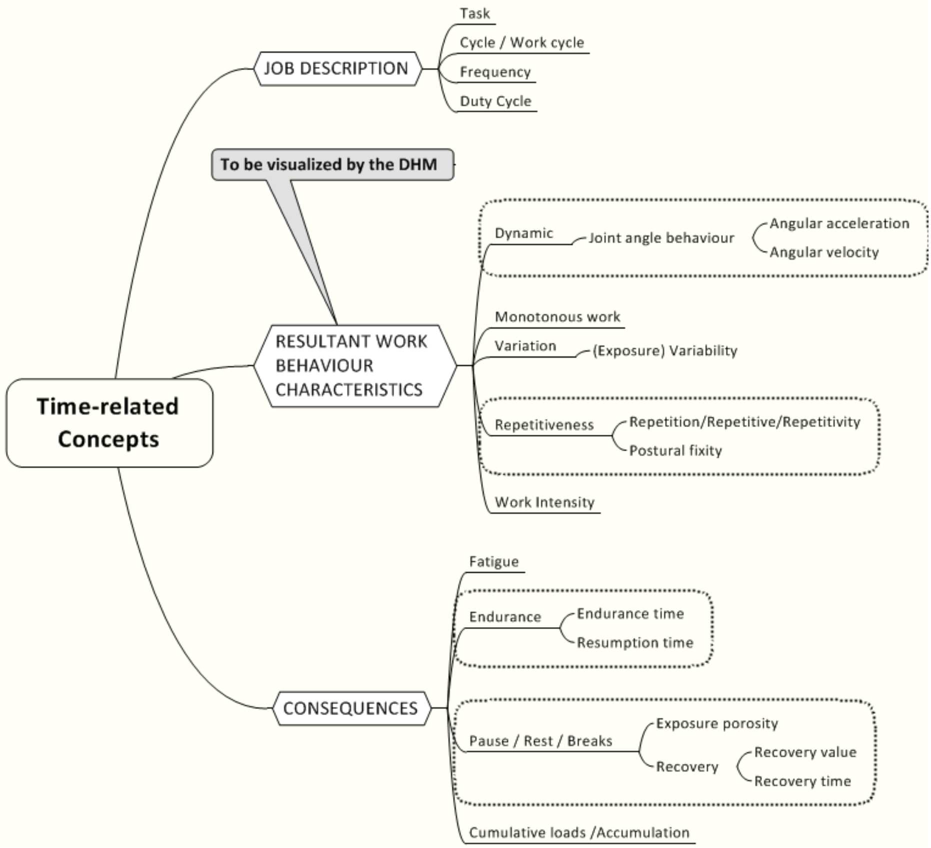


Figure 3 – A functional classification of time-related concepts (From Paper II)

The results show that the time-related ergonomics terms can be sorted into functional groups and related to each other as part of a chronological process relevant for implementation into DHM workflows. Also, the review made an effort to organize the found terms and methods into hierarchies and arrange them along a time-scale continuum, thus illustrating that the intended scope of usefulness varies for different concepts depending on the time scale they are intended for.

5.2.3 Evaluation

In Paper II, the subject of analysis has been a collection of literature that has touched upon the subject of *dynamic* or *time-related* terms and concepts in ergonomics evaluation. All of the selected material was obtained through database searches and consists entirely of scientific research publications (conference papers, journal articles and books). The *external reliability / replicability* of the literature review is satisfactory in the sense that the author describes which keywords were used in the search, which search engines yielded results; the only dubious elements are why some of the found literature was eventually discarded (and for what reasons – this is not discussed), and those literature contributions that were 'suggested by colleagues' as stated in Paper II; however all the used material is obvious from the reference list.

Paper II assumes a stance that by necessity must be tolerant, or at least aware, of several different research paradigms to understand the value and possible interrelations of different contributions. While it is hardly meaningful to call the review anything other than a qualitative study, issues of replicability for the analysis part could constitute a point of criticism. The actual literature review was performed using a hermeneutical approach, aspiring to do justice to the individual contributions and clarify a 'big picture' of the literature corpus. Regarding *internal validity*, and *credibility*, these aspects are difficult to evaluate fairly since the results are largely a result of the author's reflection and categorization of the material and thus not adherent to a 'strict' method for arriving at those conclusions. Since *triangulation* is not really a viable way to get around this problem, an explicit auditing process would (in retrospect) probably have been helpful in improving the paper's issues of reliability and validity, although such a quality control process is decidedly easier to implement when there are more than one author.

The possibility of ensuring *dependability* and *confirmability* of the study is high mostly due to the high quality of the peer-reviewed material used. The accessibility of the used documents is fairly high and can be examined (given access to the referenced scientific journals).

6. SYNTHESIS AND DISCUSSION

This section brings up insights that are the result of reflection on the contributions made in the papers and how they interrelate.

6.1 TIME PERSPECTIVES – OR ‘WHAT IS DYNAMIC?’

Bringing the insights from the case study into the literature review resulted in an increased awareness on the part of the thesis author of contextual matters. These influence whether different evaluation capabilities are perceived as ‘useful’ for potential DHM users.

One of the main lessons learned from this research is perhaps that it is not enough to ask what ‘dynamic’ ergonomics evaluation is. It would appear that the term itself could represent a number of time-related strategies for ergonomics evaluation, but the term is used carelessly and can signify the continuous readout of a static evaluation method’s score values over a time-line, as well as a strictly defined situation where the influence of muscular fatigue, recovery, joint motions and overcompensated weight handling are in focus.

What characterizes these different variants of ‘dynamic’ analysis is that they all pertain to a certain *time perspective.* Some methods are geared at high-resolution analysis ranging over very short time scales, often in matters of seconds or minutes. Other time perspectives with longer ranges (hours, shifts, months) tend to include a more holistic point of view in order to be applicable, at the cost of being at a lower resolution and measurement dependability (e.g. assessing the cumulative workload over a lifetime using interviews).

In order to find the ‘right’ time scale for any evaluation method, it is important to recognize how time is treated in production system ‘culture’ and thus realize *who* will be interested in using them for their professional purposes.

As a segue into the section that follows, the next section will bring up time factors as they are treated in production system contexts, which will lead naturally into who the actors in the process are.

6.1.1 Treatment of Time Factors in Production Systems

Van Lingen et al. (2002) argue that producers of manually assembled goods must balance increased productivity with maintaining good workforce health, using an integratory approach bringing together the disciplines of assembly engineering and ergonomics. Neumann et al (2006) second the notion that ergonomics and productivity can be improved simultaneously, and also recommend that design teams should be held accountable for ergonomics. At another angle, Bao et al. (1997) conclude that positive ergonomics effects run the risk of being counteracted by simultaneous work rationalization measures (particularly in assembly line balancing, i.e. trying to even out task durations over workstations).

One widely recognized strategy for improving ergonomics in production system design is to implement job enlargement, i.e. rotation between tasks (e.g. Möller et al., 2004). This is expected to increase variation and thereby reduce MSD risks associated with repetitiveness. While the approach has been lauded, other incentives or goals in production engineering may end up counteracting this strategy (e.g. reducing operator learning time or improving specific skills).

The needs of production system developers regarding ergonomics analysis methods are thus determined by a number of optimization goals that are sometimes in conflict. Time-related factors of interest are identification of repetitive work patterns, lack of variation, fatigue effects, work enlargement effects, distributions of activity/rest, etc.

6.1.2 Actors Involved with Production Ergonomics

A production system is seldom the result of one single person’s design; thus, it is important to understand that the outcomes of ergonomics interventions are seldom purely at the hands of ergonomics experts (Bao et al., 1997; Wells et al., 2007; Dempsey and Mathiassen, 2006). Depending on the size of the company and the type of products being produced, the team of people (called *Actors* here) who have a professional task or objective related to the design of a production system may vary in number, degree of collaboration, allocation of responsibility for certain design aspects and information needs.

Depending on the focus and aspirations of researchers, the more non-scientific active parties have at times been labelled ‘practitioners’ (e.g. according to the definition by Kilbom, 1994, see Table 2). However, practitioners have at times also been defined as a separate group from ‘experts’ (Li and Buckle, 1999), or as an interchangeable name for “professional ergonomists” (Dempsey et al., 2005). In yet other cases, contradictory professional relations like ‘engineer vs. ergonomist’ (Wells et al., 2007) have been described. This indicates that there seems to be some variation in literature regarding the use of the different terms. The author of this thesis has therefore chosen the more neutral term ‘Actors’ (in line with Dukic et al., 2007) to collectively signify individuals or organizational units (groups) who may in some way become involved with ergonomics evaluation at different stages of the process (from production design to implementation). The author also wished to differentiate from the term ‘stakeholders’ (e.g. as in Neumann, 2004) to emphasize the potential each individual or group could have on actively influencing the process. Some of them are listed in Table 2:

Table 2 - Taxonomy of different types of Actors involved in ergonomics issues in the production design process. Classification into 'Primary' and 'Marginal' actors has been made by the thesis author:

Primarily affected/involved actors	*Marginally affected/involved actors*
• Production engineers * • Industrial designers * • Supervisors * • Occupational Health and Safety professionals * • Ergonomists * • Labour inspectors * • Product Development ** • Pre-production Engineering ** • Production Engineering ** • Logistics ** • Affected workforce representative(s), operators • Personnel managers • Union representatives • Simulation engineers (if the company uses virtual tools to evaluate planned production layouts)	• Purchasing ** • Economic executive(s) • Higher-level corporate executives • Research actors (e.g. scientists wishing to perform studies in an ongoing production setting) • National directives and laws (not necessarily a physical person, but may be personified by a labour inspector or legal representative) *(actors marked with * are defined as "Practitioners" according to Kilbom, 1994 and those with ** are brought up in Neumann, 2004)*

The different actors listed above have different roles, objectives and degrees of involvement and/or influence on the production process. In smaller enterprises, some personnel may sometimes be invested with more than one of the roles mentioned above, leading to a different objectives basis for design decisions. Therefore, the information needs (and interest level) of each actor may vary greatly, depending on what data detail level they need to execute their work tasks. Sometimes these role differences can result in conflicts of interests and different preferences regarding evaluation tools and procedures.

According to Wells et al. (2007), one such issue that may diverge between actors is how time is addressed in production system ergonomics interventions. One of the main points made is that contradictory objectives between engineers and ergonomists may occur when the two actors attempt to manipulate time aspects of production. Tools used by engineers are geared towards time-efficient production and minimizing non-value-adding time, while ergonomists' tools describe more physiological factors such as work-rest patterns, movement velocities or exposure durations. Kazmierczak et al. (2005) describe how the usage of work time has been given different positive or negative connotations for the perspectives of business (*value- added/non-value-added* time), flow simulation (*utilized/non-utilized* time), video analysis (*direct work / unplanned breaks*) and ergonomics (*activity / recovery opportunities*).

With regard to ergonomics issues, some actors are more actively affected and involved than others. The level of knowledge brought into the process by the actors also varies in degree and kind. Production workers, union representatives and engineering personnel may have great knowledge and experience of production work and the associated problems, while an ergonomist (working reactively or pro-actively) may have a great deal of experience and training in recognizing unhealthy work postures and activities. However; the degree of involvement of an actor may not be proportional to the influence they have over final decisions regarding the production design. According to Dempsey and Mathiassen (2006, p. 33), "other considerations may take precedence (…) work conditions for the individual are created in a negotiation between different parties".

Neumann (2004, p.66) recommends the following solution to bridging the conflicting objectives of different actors:

> "Chains of responsibility, linking decision makers to decision consequences, should be established and formalised. This accountability should begin with risk factor indicators and extend to pain and injury rates in operational systems (make engineering responsible for MSDs – not the Health and safety resource personnel). Ideally this performance will be connected to employee evaluation and remuneration processes."

6.2 META-THEORETICAL ASPECTS

To a great extent, the research field of ergonomics evaluation has been dominated by epidemiology, biomechanics, logic and mathematics, all of which are strongly quantitative disciplines. Researchers frequently 'start' from one of these approaches and strive to attain credibility for their research using statistical evidence – normally empirical or clinical study results. For many, statistical evidence is the heaviest form of justification. The emphasis on empirical and/or experimental validation suggests that *empiricical realism* and *objectivism* (Bryman and Bell, 2007 pp. 18 - 22) are the dominating strains of the field. Most examples of this place heavy emphasis on clinical testing and on relating findings to epidemiology.

However, ergonomics researchers with a psychosocial point of departure have shifted the focus of 'what knowledge is' to qualitative materials, focusing on organizational issues surrounding ergonomics evaluation and thereby requiring categorization and interpretative approaches. Increasingly, it is acknowledged that the perceptions, behaviours and experiences of humans are strongly intertwined with perceived physical strain and load exposure. Therefore, standpoints of *constructionism* and *interpretivism* (Bryman and Bell, 2007 pp. 19-23) manifest themselves in such cases, meaning that context and interpretation of the results are central.

Thus, it becomes clear that this interdisciplinary research field can harbour researchers of many epistemological outlooks, whose different points of departure shape their research design in different ways.

Paper I begins with the assumption that the results from two different ergonomics evaluation methods used in the same factory can be compared in a quantitative manner, since both methods generate results on the same type of colour-zone scale.

Also, the method of comparison in Paper I rests heavily on categorization and reduction of data from the two (rather large) result sets. The whole study is clearly presented at the outset as a corporate-specific case study, where a) the comparison results cannot be directly generalized per se and b) the sample upon which the quantitative results are based is highly representative, but NOT selected at random. In other words, a purely quantitative comparison cannot be interpreted or explained. To address these drawbacks, the comparison was subsequently ventilated in two group interviews with selected actors from the company who had insight into the usage of the two different methods. Thus, the quantitative approach has been laced with an interpretive outlook from the beginning, since the authors assume that they cannot ‘trust’ the justification from the statistical results per se.

Paper II is a literature review whose purpose is to ‘construct a corpus’ on how researchers during the past two decades have addressed the subject of time-consideration in ergonomics evaluation. The basic criterion for selection of the material was that time is emphasized somehow as an important and previously underestimated factor in ergonomics evaluation. Regarding meta-theory, an interpretivistic standpoint is once more present (to distinguish the users and developers of ergonomics evaluation methods from the methods); however, there is simultaneously an underlying objectivistic standpoint which assumes that actors are able to use developed methods (and concepts) ‘reliably’; otherwise, the rationale for developing evaluation methods for implementation into generalizable DHMs would fail.

7. CONCLUSIONS AND FURTHER RESEARCH

This concluding section answers the research questions and summarizes the most important findings, as well as proposing further potential areas of continued research.

7.1 CONCLUSIONS FROM THE PAPERS

7.1.1 Paper I

It appears that different actors in the case study context had different professional objectives and information needs, which influenced their interest, involvement and need for ergonomics evaluation data (especially regarding level of detail). The choice of switching from one evaluation method to another in this case appears to have been pragmatic and influenced by contextual factors rather than an active selection geared at achieving comparable results. One mentioned historical argument for switching evaluation methods was complaints of heavy workload from the actors performing evaluations. Although the two methods were assumed (at a managerial level) to be similar, the quantitative comparison has shown that the results on the same workstations are significantly different. Additional qualitative investigation revealed that the involved actors were aware of some differences between the methods, chiefly regarding contextual factors.

While this case study in itself may not provide a justifiable basis for suggesting industrial needs on ergonomics evaluation methods, it has resulted in interesting episodical evidence to learn from and possibly use to construct further investigations on needs-related themes. It is strongly recommended to industrial corporations that any changes in ergonomics evaluation routines should be carefully planned, and that any such changes should be preceded by careful method criteria comparison, as well as background interviews of affected personnel. These interviews should focus on the professional objectives of each evaluating actor, to ensure that the interpretation of rating levels is understood by all involved professional groups and that output data needs are met by the chosen procedure.

7.1.2 Papers II and III

The author has identified some useful categorizations for a number of time-related ergonomics terms and has suggested organizing the found time-related concepts into a ‘process-flow’ framework based on an *input-throughput-output* concept. Doing this can give DHM tool developers an overview of which time-related aspects interact and which combinations are suited to different analysis goals. In this framework the different time-related concepts are identified as descriptive, resultant or consequential (input - throughput - output) and some additional factors discovered in the study (such as interacting effects of experience on physical exposure tolerance) are suggested. The author would like to acknowledge that some concepts may arguably belong ‘in between’ the three process stages, and that the process may even be considered in a reversed direction (i.e. the suggested outputs may be used to intellectually deduce the parameters suggested as inputs).

7.1.3 Synthesis

As this research has progressed, the author found that insight from the first study (Paper I) were carried over into the second (Papers II and III), influencing the recognized value of what was found and opening up for additional insights that were not necessarily within the scope of the final paper. A general tendency was that the aspect of user needs on evaluation methods led to insight regarding different actors in the process that influence what kind of information is considered ‘relevant’ for different objectives, as well as the differences in time perspectives that arise within the context of a production system.

7.2 ANSWERS TO RESEARCH QUESTIONS

At this stage it is possible to attempt to answer the research questions posed in the introduction chapter:

RQ1 *Which ergonomics evaluation considerations are evident in methods used by industrial manufacturing corporations?*

It appears that clear criteria of acceptability on a reasonably simple type of rating level (e.g. a stoplight-scale) are a popular option to ensure that results are understood by several actors. However, implicit factors may still cause differences in interpretation of such scales. Management should be aware of such risks when selecting an evaluation procedure, and especially when changing from one procedure to another. Depending on who performs evaluation and/or uses the resultant data to achieve intervention goals, corporate-internal methods are at liberty to tailor evaluation methods to suit the 'units for improvement' considered the most relevant target for improvement, e.g. individual workers, workstations or product construction details.

RQ2 *Which time-related ergonomics concepts have been sufficiently explored by ergonomics research to be implemented into Digital Human Models?*

It is possible to introduce a number of time-related ergonomics concepts into DHM analysis tools. The most rewarding first step is probably to employ analysis methods that use joint angle motion data as inputs, since this can be easily supplied by a DHM. Furthermore, it would probably increase the scope of usefulness for DHMs if methods for assessing work–rest distributions over a day's work could be implemented; several algorithms exist for determining endurance times and recovery times, such principles could probably be combined to create a feasible analysis tool that evaluates planned work patterns against recommended limits based on such algorithms.

The obvious advantage of carrying out virtual simulations of work is that long-term exposure effects can be modelled much faster than in real time; in such cases, the evaluation method employed must be deemed relevant for such a long-term time perspective. DHM developers need to carry out development in dialogue between with users, i.e. industrial practitioners, scientists and professional ergonomists, to ensure that the information requirements of both industrial developers and decision makers are met.

7.3 FURTHER RESEARCH

The researched performed within the bounds of this thesis was described earlier as two perspectives of the same problem. It can also be added that these two sides are not the only two sides. There are many other facets to further developing Production Ergonomics Evaluation, some of which have already been touched upon by some of the research described here. The insights described in 7.2.3 have provided the author with a realization about the imagined path of research shown in Figure 1 (at the beginning of this thesis). It may not be sufficient to generate knowledge for improving DHMs if the two outer fields are traversed only once; therefore, the author feels it may be prudent to revisit that figure and describe a more likely research path:

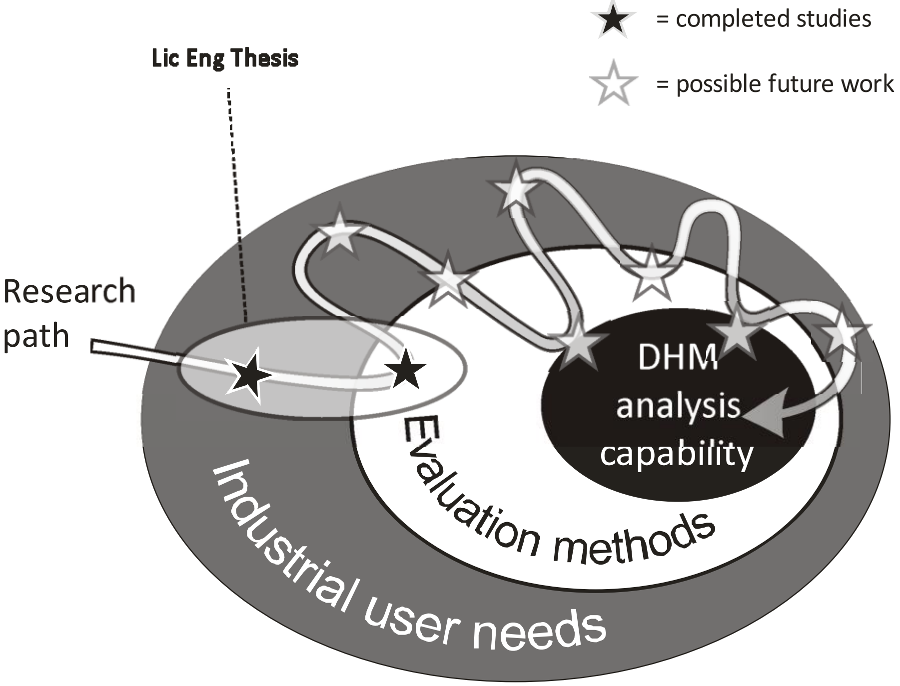


Figure 3 – The path toward DHM development; probably not a straight line. The transparent stars suggest possible future research in the form of alternating case studies, theoretical method studies and DHM development. Continually revisiting the different fields and bringing knowledge from previous work into the next is likely to generate feasible knowledge that will improve the usefulness of DHM tools.

As shown, continually bringing knowledge from empirical cases into theoretical studies, and then back again for validation, appears to be a more progressive strategy for addressing improvement of DHMs while making sure that improvements are firmly anchored in user needs and current scientific developments. Also, venturing into DHM development may provide useful knowledge to bring back into other fields.

For example, one domain of research is to explore further the role of corporate actor perspectives on ergonomics responsibility. This is intended to be examined in a series of future case studies examining different actors' views and collaborative needs regarding ergonomics evaluation. Also, the DHM time-framework developed in Papers II and III could very well become the object of 'artefact research', where the suggested workflow and functions could be implemented in a DHM and tested on different simulation cases.

In this way, it is hoped that the sum of the contributions presented in this thesis (and the lessons learned in the process) will be a good foundation for continued research towards improving DHM tools for production ergonomics, and understanding the considerations that determine whether they will be used or not.

REFERENCES

AFS (1998). ERGONOMICS FOR THE PREVENTION OF MUSCULOSKELETAL DISORDERS - Provisions of the Swedish National Board of Occupational Safety and Health on Ergonomics for the Prevention of Musculoskeletal Disorders, together with the Board's General Recommendations on the Implementation of the Provisions. Solna, Sweden: Arbetarskyddsstyrelsen. Legal provision.

Badler, N.I., Phillips, G.B., Webber, B.L. (1993). Simulating Humans: Computer Graphics Animation and Control. Oxford University Press, USA.

Bao, S., Winkel, J., Mathiassen, S. E., & Shahnavaz, H. (1997). Interactive effect of ergonomics and production engineering on shoulder- neck exposure - A case study of assembly work in china and sweden. International Journal of Industrial Ergonomics, 20(1), 75-85.

Bao, S., Spielholz, P., Howard, N., & Silverstein, B. (2009). Application of the strain index in multiple task jobs. *Applied Ergonomics, 40*(1), 56-68.

Berlin, C. (2007). ON THE DEVELOPMENT OF A TIME-SENSITIVE ERGONOMICS EVALUATION METHOD. Proceedings of the 39th NES Conference, Lysekil, Sweden. CD

Bryman, A. & Bell, E. (2007, 2nd ed.). Business Research Methods. Oxford University Press Inc, New York

Chaffin, D. (1969). A computerized biomechanical model: Development and use in studying gross body actions. *J. Biomechanics*, **2**, 429–441.

Chaffin, D. B. (1997). Development of computerized human static strength simulation model for job design. *Human Factors and Ergonomics in Manufacturing, 7*(4), 305-322.

Chaffin, D. B. (2005). Improving digital human modelling for proactive ergonomics in design. Ergonomics, 48(5), 478-491.

Chiang, J., Stephens, A., Potvin, J., 2008. Automotive Manufacturing Task Analysis: An Integrated Approach. In: Proceedings of the 2008 Digital Human Modeling for Design and Engineering Conference and Exhibition, June 17-19, Pittsburgh, Pennsylvania, USA. SAE 2008-01-1897.

Chung, K. H., Shewchuk, J. P., & Williges, R. C. (2002). An analysis framework for applying virtual environment technology to manufacturing tasks. *Human Factors and Ergonomics in Manufacturing, 12*(4), 335-348.

Dahl, R.A. (1982). Dilemmas of Pluralist Democracy: Autonomy Versus Control. New Haven, CT, Yale University Press.

Danermark, B., Ekström, M., Jakobsen, L., Karlsson, J. Ch. (2003, 2nd ed.). Att förklara samhället. Studentlitteratur AB, Sweden. ISBN: 9789144027722

Dukic, T., Rönnäng, M., & Christmansson, M. (2007). Evaluation of ergonomics in a virtual manufacturing process. Journal of Engineering Design, 18(2), 125-137.

Dempsey, P. G., McGorry, R. W., & Maynard, W. S. (2005). A survey of tools and methods used by certified professional ergonomists. Applied Ergonomics, 36(4 SPEC. ISS.), 489-503.

Dempsey, P. G., & Mathiassen, S. E. (2006). On the evolution of task-based analysis of manual materials handling, and its applicability in contemporary ergonomics. Applied Ergonomics, 37(1 SPEC. ISS.), 33-43.

Flick, Uwe (2006, 3rd ed.). An Introduction to Qualitative Research. SAGE Publications: London.

Garg, A., Chaffin, D. B., & Herrin, G. D. (1978). Prediction of metabolic rates for manual materials handling jobs. *American Industrial Hygiene Association Journal, 39*(8), 661-674.

Grant, K. A. (1994). Evaluation of grip force exertions in dynamic manual work. Proceedings of the Human Factors and Ergonomics Society 1, pp. 549-553.

Helin, K., J. Viitaniemi, S. Aromaa, J. Montonen, T. Evilä, S-P. Leino, T. and Määttä. 2007. OSKU Digital Human Model in the Participatory Design Approach. A New Tool to Improve Work Tasks and Workplaces. VTT Working Papers VTT-WORK-83.

Hignett, S., & McAtamney, L. (2000). Rapid entire body assessment (REBA). *Applied Ergonomics, 31*(2), 201-205.

Högberg, D., Bäckstrand, G., Lämkull, D., De Vin, L.J., Case, K., Örtengren, R., Hanson, L. and Berlin C. (2007). Towards Dynamic Ergonomics Analysis of Work Sequences in Virtual Environments. Proceedings of the 17th International Conference on Flexible Automation and Intelligent Manufacturing (2007 FAIM), Philadelphia, USA, June 2007, pp 581-588, ISBN 978-1-4276-2092-7.

Jayaram, U., Jayaram, S., Shaikh, I., Kim, Y., Palmer, C. (2006). Introducing quantitative analysis methods into virtual environments for real-time and continuous ergonomic evaluations. Computers in Industry 57, 283-296.

Juul-Kristensen, B., Fallentin, N., & Ekdahl, C. (1997). Criteria for classification of posture in repetitive work by observation methods: A review. International Journal of Industrial Ergonomics, 19(5), 397-411.

Karhu, O., Kansi, P., & Kuorinka, I. (1977). Correcting working postures in industry: A practical method for analysis. *Applied Ergonomics, 8*(4), 199-201.

Kazmierczak, K., Mathiassen, S. E., Forsman, M., & Winkel, J. (2005). An integrated analysis of ergonomics and time consumption in swedish 'craft-type' car disassembly. Applied Ergonomics, 36(3), 263-273.

Kilbom, A. (1994). Repetitive work of the upper extremity: Part II - the scientific basis (knowledge base) for the guide. International Journal of Industrial Ergonomics, 14(1-2), 59-86.

Kuorinka & Forcier (eds) (1995) Work Related Musculoskeletal Disorders (WMSDs): A Reference Book for Prevention

Laitila, L. (2005). Datormanikinprogram om verktyg vid arbetsplatsutformning - En kritisk studie av programanvändning. Doctoral Thesis. Luleå Technical University, Luleå.

Lämkull, D. (2006). Computer Manikins in Evaluation of Manual Assembly Tasks. Research series from Chalmers University of Technology, Department of Product and Production Development: report no. 14. ISSN 1652-9243. Lic. Eng. Thesis.

Laring, J., Christmansson, M., Kadefors, R., & Örtengren, R. (2005). ErgoSAM: A preproduction risk identification tool. Human Factors and Ergonomics in Manufacturing, 15(3), 309-325.

Laring, J., Forsman, M., Kadefors, R., & Örtengren, R. (2002). MTM-based ergonomic workload analysis. International Journal of Industrial Ergonomics, 30(3), 135-148.

Lee, R. M. (2000). Unobtrusive methods in social research. Open University Press: Buckingham.

Li, Guangyan & Buckle, Peter (1999). Current techniques for assessing physical exposure to work-related musculoskeletal risks, with emphasis on posture-based methods. Ergonomics, 42 (5), 674-695.

Liberty Mutual (2004). Liberty Mutual Manual Materials Handling Tables. Retrieved September 21, 2007, from: http://libertymmhtables.libertymutual.com /CM_LM TablesWeb.

Lincoln, Y.S. and Guba, E.G. (1985). *Naturalistic Inquiry.* Sage Publishing, Thousand Oaks, USA.

Lind, S., Krassi, B., Johansson, B., Viitaniemi, J., Heilala, J., Stahre, J., Vatanen, S., Fasth, Å., Berlin, C. (2008). SIMTER: A Production Simulation Tool for Joint Assessment of Ergonomics, Level of Automation and Environmental Impacts. *Proceedings of the 18th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM 2008)*, Skövde, Sweden, Jun. 30 - Jul. pp. 1025-1031

Ma, L., Chablat, D., Bennis, F., & Zhang, W. (2009). A new simple dynamic muscle fatigue model and its validation. *International Journal of Industrial Ergonomics, 39*(1), 211-220.

Marras, W.S. (1992) Toward an Understanding of Dynamic Variables in Ergonomics. In: M.R. Cullen, Editor, Occupational Medicine: State of the Art Reviews, Hanley and Belfus, Inc., Philadelphia, pp. 655-677.

Mathiassen, S. E., & Winkel, J. (1991). Quantifying variation in physical load using exposure-vs-time data. Ergonomics, 34(12), 1455-1468.

McAtamney, L., & Corlett, E. N. (1993). RULA: A survey method for the investigation of work-related upper limb disorders. *Applied Ergonomics, 24*(2), 91-99.

Merton, R. K., Fiske, M., Kendall, P.L. (1956). The Focused Interview: A Manual of Problems and Procedures. Free Press, Glencoe, USA

Möller, T., Mathiassen, S. E., Franzon, H., & Kihlberg, S. (2000). Relationships between cycle time and mechanical exposure within and between individuals in repetitive assembly work. Paper presented at the 162-165.

Neumann et al (1999) 4D WATBAK: Adapting research tools and epidemiological findings to software for easy application by industrial personnel (Intl Conference on Computer-aided ergonomics and safety)

Neumann, W. P., Winkel, J., Medbo, L., Magneberg, R., & Mathiassen, S. E. (2006). Production system design elements influencing productivity and ergonomics: A case study of parallel and serial flow strategies. International Journal of Operations and Production Management, 26(8), 904-923.

Neumann, W.P. (2004). Production Ergonomics Identifying and Managing Risk in the Design of High Performance Work Systems. Department of Design Sciences, Lund University, Sweden. ISBN 91-628-6287-1. Doctoral Thesis

NIOSH WPG (1981). Work Practices Guide for Manual Lifting. NIOSH Technical Report No. 81-122. U.S. Department of Health and Human Services. National Institute for Occupational Safety and Health, Cincinnati, OH 45226.

Norman, R., Wells, R., Neumann, P., Frank, J., Shannon, H., Kerr, M., et al. (1998). A comparison of peak vs cumulative physical work exposure risk factors for the reporting of low back pain in the automotive industry. Clinical Biomechanics, 13(8), 561-573.

Occhipinti, E. (1998). OCRA: A concise index for the assessment of exposure to repetitive movements of the upper limbs. *Ergonomics, 41*(9), 1290-1311.

Prior, L. (2003). Using Documents in Social Research. Sage Publications Ltd: ISBN: 9780761957478

Psychology Writing Center (2005). Writing a Psychology Literature Review. University of Washington, Washington, USA.

Schaub, K., Landau, K., Menges, R., Grossmann, K. (1997). A computer-aided tool for ergonomic workplace design and preventive health care. Human Factors and Ergonomics in Manufacturing 7, 269–304.

Seidler, A., Bolm-Audorff, U., Heiskel, H., Henkel, N., Roth-Küver, B., Kaiser, U., et al. (2001). The role of cumulative physical work load in lumbar spine disease: Risk factors for lumbar osteochondrosis and spondylosis associated with chronic complaints. Occupational and Environmental Medicine, 58(11), 735-746.

Snook, S. H., & Ciriello, V. M. (1991). The design of manual handling tasks: Revised tables of maximum acceptable weights and forces. *Ergonomics, 34*(9), 1197-1213.

Scott, J. (1990). A Matter of Record: Documentary Sources in Social Research. Polity: Cambridge. ISBN: 978-0-7456-0070-3

Smith, Mark J. (1998). Social Science in Question. SAGE Publications: London.

Van Lingen, P., Van Rhijn, G., De Looze, M., Vink, P., Koningsveld, E., Tuinzaad, G., et al. (2002). ERGOtool for the integral improvement of ergonomics and process flow in assembly. International Journal of Production Research, 40(15 SPEC.), 3973-3980.

VSR Research Group, 2004. Technical report for project virtual soldier research. Center for Computer-Aided Design, The University of IOWA. Technical report.

Waters, T. R., Putz-Anderson, V., Garg, A., & Fine, L. J. (1993). Revised NIOSH equation for the design and evaluation of manual lifting tasks. *Ergonomics, 36*(7), 749-776.

Webb, E. J., Campbell, D. T., Schwartz, R. D., Sechrest, L. (1966). Unobtrusive measures: Non-reactive research in the social sciences. Rand McNally and Company: Chicago.

Wells, R., Mathiassen, S. E., Medbo, L., & Winkel, J. (2007). Time-A key issue for musculoskeletal health and manufacturing. Applied Ergonomics, 38(6), 733-744.

Yen, T. Y., & Radwin, R. G. (2000). Comparison between using spectral analysis of electrogoniometer data and observational analysis to quantify repetitive motion and ergonomic changes in cyclical industrial work. Ergonomics, 43(1), 106-132.

Yin, R.K. (1984). *Case Study Research: Design and Methods.* Sage Publications Inc., Beverly Hills, CA. ISBN 0803920571

Yin, R.K. (2003). *Case Study Research: Design and Methods.* Sage Publications Inc., New York, USA.

APPENDED PAPERS

Paper I: Berlin, C., Örtengren, R., Lämkull, D. & Hanson, L. (2009*) Corporate-internal vs. National Standard – A comparison study of two ergonomics evaluation procedures used in automotive manufacturing.

Paper II: Berlin, C. (2009**)
Time-Related Factors in Ergonomics Evaluation Part II: a Literature Review and Scientific Basis for the Framework

Paper III: Berlin, C. (2009**)
Time-Related Factors in Ergonomics Evaluation: Part I - a Development Framework for Digital Human Modelling

---

** Submitted for approval to International Journal of Industrial Ergonomics. Manuscript version.*

*** Submitted for approval to Applied Ergonomics. Manuscript version.*

Paper I: Berlin, C., Örtengren, R., Lämkull, D. & Hanson, L.

Corporate-internal vs. National Standard – A comparison study of two ergonomics evaluation procedures used in automotive manufacturing.

Manuscript version.

Submitted for approval to *International Journal of Industrial Ergonomics (2009)*

Corporate-internal vs. National Standard – A comparison study of two ergonomics evaluation procedures used in automotive manufacturing

(Manuscript version)

Cecilia Berlin [a, 1], Roland Örtengren [a], Dan Lämkull [a, b], Lars Hanson [c]

[a] Department of Product and Production Development, Chalmers University of Technology, SE-412 96 Göteborg, Sweden

[b] Volvo Car Corporation, Manufacturing Engineering Dept. 81022, SE-405 31 Göteborg, Sweden

[c] Department of Design Sciences, Lund University, SE-221 00 Lund, Sweden

Abstract

Manufacturing corporations sometimes use corporate-internal procedures to evaluate and monitor the ergonomic status of the workplace. This article describes an industrial case study in the Swedish automotive sector, where an internally developed evaluation procedure was compared with a procedure based on a Swedish national standard provision.

It was found that the national standard procedure tended to give more severe ratings and statistical support shows that the two evaluation procedures are not equivalent. The ability of the methods to identify body segments at risk was also compared.

The quantitative comparison was followed up with interviews, where the influence of professional tasks and objectives became evident, as well as the fact that evaluation criteria are quantified differently by the two procedures. The main finding is that unforeseen differences in analysis procedure, criteria of acceptability and levels of detail can cause use-related difficulties for different professional groups when methods are used interchangeably.

Relevance to industry: Industrial corporations wishing to monitor ergonomics consistently are advised by the authors to ensure that ratings from internal evaluations are interpreted the same way by all involved personnel, and that they at least have criteria levels equivalent to those of a national standard.

Keywords: Comparison case study; Ergonomics evaluation methods; Production ergonomics; Physical ergonomics; Automotive manufacturing; National ergonomics standards

1. Introduction

There exists a number of scientifically developed and validated ergonomics evaluation methods aimed at workplace analysis (such as RULA (McAtamney and Corlett, 1993), Strain Index (Moore and Garg, 1995), REBA (Hignett and McAtamney, 2000), the Cube model (Kadefors, 1994; Sperling et al., 1993), OCRA (Occhipinti, 1998) etc.). Studies of their application in industrial settings have been performed (Drinkaus et al., 2003; Bao

---

[1] Corresponding author. Tel: +46-31-772-1290
E-mail address: cecilia.berlin@chalmers.se (C. Berlin)

et al., 2006; Jones and Kumar, 2007), but the reality is that industrial corporations often develop their own internal methods for evaluation, or use a national provision as pass-or-fail criteria. Consequently, research articles that address corporate-internal or national standard ergonomics evaluation procedures are few and far between.

The work of Li and Buckle (1999) acknowledges that "most of the existing methods developed so far (…) are research-orientated. In other words, they are based on the experts' view of what occupational risk factors should be considered". Li and Buckle further state that research studies from a practitioner's viewpoint - as opposed to an expert's - are rare in ergonomics literature and that different levels of analysis detail are demanded by practitioners and researchers respectively. Törnström et al. (2008) have addressed corporate-internal evaluation procedures to some extent, focusing on "factors supporting and hindering the implementation and application" of the corporate-internal procedure.

This observation of how a corporate-internal procedure was replaced by a national standard-based procedure illustrates the consequences of switching between two vastly different evaluation models – such a change affects output data, which in turn has consequences for personnel who require a specific type of data to fulfil the objectives of their work with ergonomics. From the academic point of view, the study fuels interesting questions regarding how such different procedures can be compared and characterized in spite of possibly different acceptability criteria.

The aim of the case study is to determine whether the two methods (which will henceforth be referred to as *procedures*) can be considered equivalent (and thus, interchangeable) in terms of how they rate workstation-level ergonomics. A further purpose is to explore whether contextual and company-specific factors affect the use and results of the procedures.

2. Method

2.1. Research Approach and Material

This article describes an observation of how a corporate-internal procedure at a Swedish automotive manufacturing corporation (Volvo Car Corporation, VCC) was replaced by a national standard-based procedure. The research is based on retroactive analysis of collected company documentation from the time periods that the two procedures were applied to the factory.

Comparison of the corporate-internal and national standard evaluation procedures was made using two approaches. First, the evaluation results were compared in a quantitative manner, tallying levels of agreement and using graphic plotting to explore any visible evaluation tendencies. This was followed by unstructured group interviews with personnel who were actively involved at different stages of the two evaluations. The main purpose of this qualitative study was to gain knowledge and insight regarding the background history and purposes of each procedure, and to focus on the needs of the users and the structure of the procedures, rather than the evaluation records.

2.2. The Two Compared Evaluation Procedures

In 2004, VCC made a decision to assign the responsibility of factory ergonomics evaluation to the production personnel. To this end, an observation-based evaluation procedure called BME, short for *Beräknings Modell Ergonomi* (which translates roughly to 'Ergonomic Assessment Model', see Amprazis, 2005; Björk, 2006; Törnström et al., 2008) was developed and implemented in VCC's final assembly plant in Torslanda, Sweden (Törnström et al., 2008) as a tool for continuous ergonomics improvement in ongoing production. However, three years later, the factory management made a new decision to cease using the BME procedure to monitor factory ergonomics. In its place, a national standard-based evaluation was performed on the factory, this time carried out by two professional ergonomists from an externally contracted occupational health service (OHS). The 'method' used for evaluation was the Swedish provision AFS 1998:1, abbreviated in this article as AFS-98 (AFS, 1998).

The BME evaluation was carried out during a two-month period in 2006, and the AFS-98 evaluation was carried out three months later during two months.

2.2.1. BME

BME is a Volvo-internal, quantitatively based observation method described by Amprazis (2005) that identifies risks for musculoskeletal disorders in production (Törnström et al., 2008). Its input structure is a highly detailed protocol with rating scales based on pre-specified boundary conditions. BME was developed for use by production personnel in teams consisting of one Local Manufacturing Engineer and one Worker Safety Representative working at the assembly line being analyzed, thereby having first-hand experience of performing the work tasks (Björk, 2006). These teams evaluated their 'home' assembly line segment, using BME on each workstation, where there is a well-defined task instruction of 'best practice' for carrying out the assembly work. Judging from the calendar week values reported in the protocols, the evaluation of each production line was completed by the teams within weeks, in most cases, during a total time span of two months. Using BME requires evaluators to attend a compulsory three-week certification course. The course covers Volvo's corporate standards for physical ergonomics, basic physical ergonomics knowledge and how to use the BME procedure (Björk, 2006).

For each work station, three factors - posture, forces and frequency - are rated for each work step or task. The theoretical basis for this principle stems from a biomechanical evaluation model described by Sperling et al. (1993), which is visualized as a three-dimensional 'cube' with posture, force and time as its axial dimensions. Each dimension is rated as low, moderate or high in demand (corresponding to a score between 1 and 3), and the scores are multiplied to give an aggregated score called the "Cube value", (i.e. $1 \leq \text{Cube value} \leq 27$) which signifies a total rating of the work. Depending on where acceptability criteria levels have been determined, the Cube value translates into one of the three assessments "acceptable", "conditionally acceptable" and "unacceptable".

In the BME protocol and course guide (Amprazis, 2005), these dimension boundary conditions for posture, force and frequency/time are given scores between 1 and 3. This Cube value score is then translated via the BME-specific boundary criteria into a three-zone colour code – green meaning "OK", yellow "may require action depending on time or frequency" and red "always requires action if the time in this zone exceeds a total of 2 hours/day or 100 times/day" (Amprazis, 2005). The scoring in BME is based on a SAM-based approach (see Luthman et al., 1990), taking consideration of individual actions in the work sequence, and scores are in practice based on boundary values for body posture angles, work duration, tool-specific forces/impacts and frequencies of specific tasks.

2.2.2. Provision AFS 1998:1 (AFS-98)

The Swedish Work Environment Authority issues legal documents regulating corporate work environments. In 1998 they released the provision AFS 1998:1 (AFS-98), targeted specifically at physical ergonomics. It is stated explicitly in the provision that an employer is responsible for continually maintaining a healthy workplace for the employees. The appendix to the provision contains guidelines for assessment of work posture, duration of work cycles, lifting requirements and relevant conditions which worsen or improve the harmfulness of the work posture (e.g. duration of postures, repetitiveness, spatial dimensions of the workplace, weight of handled objects and possibilities of gripping them, freedom to autonomously decide when to take breaks, etc.).

At VCC, two OHS ergonomists evaluated the factory on a workstation basis, looking at individual assembly workers, observing work flows and basing evaluations on observed high-risk postures, frequency of occurrence and relevance to the work task. They also took job rotation into consideration when evaluating stations. Each workstation was commented verbally in a results protocol and given an AFS-98 rating of red, yellow or green based on the OHS ergonomist's judgment. As in the case of BME, evaluations were performed within a time span of two months, although this time the evaluations took place full-time for the two ergonomists during that period.

Time spent on evaluation of each workstation varied from case to case, depending on whether the ergonomists needed to test weight loads, interview operators etc.

The AFS-98 provision (AFS, 1998) has most of its specified boundary conditions for acceptability levels explicitly stated in its appendix. These boundary conditions determine whether a working circumstance is to be rated as red (unsuitable), yellow (needs review) or green (acceptable) by the AFS-98 model with regards to situations such as sitting/standing/walking work, lifting tasks, and factors that affect the risks for harmful ergonomic loads. Factors that have been quoted as risks and have been given criteria values are:

- body segment postures (neck, back, shoulder/arm and legs), [no measurement units] for which positions or scenarios are described verbally
- Lifting distances from lumbar back region, [cm]; either acceptable (green-yellow) or not suitable (red)
- Weight of lifted burden, [kg], weight intervals that are adjusted to the distance from lumbar back region, as these factors interact
- Pushing and pulling limits [N], with force levels specified for initiation of push/pull and continuous push/pull
- Work cycle characteristics [no measurement units], verbally described with regards to repetitiveness, posture, influence over work and work content/learning aspects (psychosocial factors)
- Worsening affective conditions related to the task, the object being handled, the workspace and the worker [no measurement units], verbally described characteristics.
- Time aspects [no measurement units], although these are non-specified and not really treated as separate criteria since they cover frequency, distribution of tasks over the shift, repetitiveness, static work etc. and therefore appear in all the criteria categories mentioned above.

The values for boundary conditions in the AFS-98 appendix are stated to be valid for work shifts of four to eight hours in duration and are based on models from a publication called TemaNord 1994:541[2] (TemaNord, 1994), a collaborative report documenting the work and assessment models of Nordic health authorities regarding

---

[2] This resource has since been made unavailable; in its place an updated version called TemaNord 1997:516 is available.

ergonomics monitoring and improvement. The Appendix states explicitly that the models for assessment do not take into consideration if the work as a whole demands large force exertions or not, and that work cycle characteristics are to be considered the superior risk factor for unhealthy workplace ergonomics.

To summarize, it may be safe to say that all the guideline boundary values serve as a checklist rather than a strict evaluation protocol to be filled in. Using such a guide for evaluation demands great maturity of judgment, ergonomics competence, knowledge of evaluation principles, observational skill and experience in order to identify potential risks successfully - as is recommended in AFS-98 (AFS, 1998), especially when further investigation is needed. Being a legal provision, the guidelines in AFS-98 are intentionally vague to increase the scope of application. Intended or preferable users are therefore OHS personnel, physiotherapists etc.

2.3. Descriptive statistics

This section describes the quantitative/statistical approaches used to compare the documented evaluation results. Statistical calculations were made using SPSS 15.0 for Windows. The built-in software modules for Pearson χ^2, Kendall's tau-c and Kolmogorov-Smirnov testing were applied to the colour-rating data (ordinal by ordinal) and Pearson χ^2, Fisher's Exact tests were applied to the body segment comparisons (nominal by nominal). Odds were calculated manually. A significance level of 5% (α= 0.05) was used.

2.3.1. Three-zone (Rating Colour) Comparison

The BME and AFS-98 evaluation results for each work station were first compared on the output data they have in common – the red-yellow-green ratings. Statistical treatment of the data was comprised of crosstabulation, followed by applicable tests for agreement.

There are a total of 283 listed workstations, grouped into 18 assembly line segments. After filtering out all stations that had been evaluated by only one of the procedures BME or AFS-98 and stations with invalid protocol values (due to input errors), a sample of 163 stations remained.

2.3.2. Body segment comparisons

The second statistical comparison studied which body segments are explicitly reported by either procedure as being at risk for musculoskeletal injury. Here, the input protocols differ. The BME protocols report a maximum of two body segments, one being the 'primary' limb at risk and the other 'secondary'. In contrast, the AFS-98 had no upper limit to the number of mentioned body segments built into the protocol. Also, there was no evident ranking of which was considered 'at greatest risk'.

In order to compare the body segment results, some gradual simplifications were made. First, the order of ranking in the BME reports was disregarded, and the reported body segments were hence weighted equally (for example, the primary-secondary combination pairs "hand-neck" or "neck-hand" would be considered equal). The segments Hand, Wrist and Finger(s) were all grouped into a collective 'Hand' category.

This reductive approach led to pairwise comparisons of the Shoulder, Hand, Back and Neck categories for the BME and AFS-98 evaluations, as these were the most numerous in occurrence. For various reasons, not all workstation evaluations reported body segments at risk. In a pairwise comparison, there is a risk that such absences of reported body segments could be misinterpreted statistically as one procedure missing a specific body segment that is identified by the other. To eliminate this risk, only stations with body segment reports from both procedures were compared, making the comparison a pure hit/no hit - test. Following this strategy, the body segment comparisons were performed on a sample of 120 stations and applicable tests of agreement were made.

2.4. Supplementary Interviews

In order to gain insight regarding the historical background of BME and AFS-98, the intended users and pragmatic issues concerning use, two unstructured group interviews were carried out, first with a group of three Pre-production ergonomists who were in charge of factory ergonomics evaluations before the introduction of BME, then the two OHS ergonomists who were in charge of subsequently evaluating the factory using AFS-98. The interviews were recorded on-site via note-taking and a preliminary version of the article was made accessible to the interviewees for corroboration afterwards. The interviewees were selected by recommendation and their experience provided insights about the working climate, requirements and historical context of the change of evaluation procedure.

3. Results

3.1. Comparison of Green-Yellow-Red Evaluations

The colour-zone ratings were crosstabulated and some statistical tests of agreement were performed. Results are shown in table 1.

Table 1: Comparison of green – yellow – red evaluations for BME and AFS-98. Numbers in boldface indicate agreement.

		BME rating			
		GREEN	YELLOW	RED	*Total*
AFS-98 rating	GREEN	**47**	18	2	*67*
	YELLOW	33	**50**	2	*85*
	RED	3	8	**0**	*11*
	Total	*83*	*76*	*4*	*163*

The number of stations with matched ratings constitutes 59.5% of all ratings. One tendency made apparent by table 1 is that there is no agreement in the red rating category. In general, the red ratings found in the BME study are considerably fewer than in the AFS-98 study (4 as opposed to 11). In the station layout sequence, all the red ratings are spread throughout the factory with no noticeable concentrations. In five occurrences, one procedure rated the station as red while the other rated it as green.

The calculated Pearson $\chi^2 = 18.797$ yields a significance of $p = 0.001$, however with three cell counts less than 5, alternative testing is recommended. Since the matrix is ordinal-by-ordinal, calculation of Kendall's tau-c is relevant, yielding $\tau = 0.238$ with a $p < 0.005$, indicating with confidence that BME and AFS-98 ratings are significantly different.

Perhaps the most interesting tendency in table 1 is the fact that the values outside of the agreement diagonal show a clear tendency below the diagonal, i.e. there are twice as many instances where the AFS-98 rates more severely than BME (44 occurrences as opposed to 22). Moreover, there are more 'severe' ratings by AFS-98 in the yellow-red range than by BME; 41 occurrences as opposed to 20. Running a Kolmogorov-Smirnov test on the difference frequencies confirms that the differences are *not* normally distributed, but skewed towards a more severe rating tendency by AFS-98.

What is not made visible by table 1 is that some station areas displayed 'clustered' rating differences, i.e. several consecutive workstations had non-matching ratings. A more detailed version of the chart, where each individual station was specified by name and shown in consecutive order, was generated for the interview sessions as discussion material.

The colour-zone comparison was commented by both interview groups, who explained the differences in ratings by emphasizing that the two procedures have different interpretations of the middle 'yellow' level. Traditionally in the automotive industry, the yellow level has been considered a non-critical level that merely signals room for improvement, but the OHS ergonomists maintained that following the criteria for 'yellow' in the AFS-98, yellow should be considered a more severe rating. Furthermore, both groups mentioned that during the time that BME was implemented, the evaluation on a strict task-by-task basis resulted in some stations being labelled 'green' in spite of their work sequences containing some possibly significant 'red' activities. The OHS ergonomists acknowledged that during observations, they only consider 'relevant' actions in their ergonomics assessments that bring about physical risks, thus disregarding non-harmful or non-value-adding activities such as walking, pressing buttons or tearing off order sheets (as one of the interviewees stated, "How can I pay attention to that, when back doors are being lifted in extreme postures?").

As a rule, BME bases the entire evaluation on sequential tasks, and would count work rotation simply as an ameliorating factor, while the OHS ergonomists rate rotation specifically (sometimes resulting in an entire station being rated red because of an unacceptable job rotation). Anecdotal examples such as these were offered by the OHS ergonomists as possible examples of how some red-green rating differences arose. This illustrates how differently factors are weighed into the assessment by either procedure, depending on the occupational role of the evaluators and the formality of the tool they use.

3.2. Pairwise comparisons of reported body segments

The BME protocols reported a maximum of two body segments while the AFS-98 tables reported all body segments considered at risk, in one case reporting as many as five body segments with no evident ranking. Table 2 shows the agreement counts for Back, Shoulders, Hands[3] and Neck.

---

[3] Including reports of finger, wrist and hand exposure

Table 2: BME-AFS-98 comparison of body segment reports, with statistical probability calculations. Numbers in boldface indicate agreement between both methods.

		BME			
		BACK	NO BACK	*Total*	Matches: 64.1%
AFS-98	BACK	**32**	12	*44*	
	NO BACK	31	**45**	*76*	Pearson χ^2 = 11.398
	Total	*63*	*57*	*120*	Two-sided significance level p= 0.001
		SHOULDER	NO SHOULDER	*Total*	Matches: 67%
	SHOULDER	**59**	24	*83*	
	NO SHOULDER	16	**21**	*37*	Pearson χ^2 = 8.464
	Total	*75*	*45*	*120*	Two-sided significance level p= 0.004
		HAND	NO HAND	*Total*	Matches: 58.3%
	HAND	**39**	29	*68*	
	NO HAND	21	**31**	*52*	Pearson χ^2= 3.394
	Total	*60*	*60*	*120*	Two-sided significance level p= 0.065
		NECK	NO NECK	*Total*	Matches: 78.3%
	NECK	**5**	4	*9*	
	NO NECK	22	**89**	*111*	
	Total	*27*	*93*	*120*	Fisher's Exact test, two-sided p= 0.027

The calculated *p* values for the Back and Shoulder comparisons imply that we may safely assume that the results are not due to chance; however the match percentages of 64.1% and 67% have to be discussed in light of what constitutes a satisfactory agreement level for the company. The *p* value calculated for Hand (*p* = 0.065) exceeds the significance level set by the present paper; the Fisher's exact value for the Neck results (*p* = 0.027) does not exceed the significance level, but the substantial differences in cell counts lead the authors to conclude that the Hand and Neck agreements should be interpreted with reservation. For the Neck, there are three times as many neck reports from BME as from AFS-98, and the great majority of agreements are in the “no neck / no neck” cell.

The odds for a workstation to be identified by either procedure as risky for a particular body segment have been calculated manually (as the ratio between the total number of ‘hits’ by one method and the total number ‘missed’ by the same). The odds of a station being labelled a ‘back-risk’ by BME are almost twice as high as being identified by AFS-98 (1.1 for BME, versus 0.58 for AFS-98). For Shoulders, the odds of being labelled a risk by AFS-98 are 1.35 times those of BME. In the Hand category, AFS-98 again labels stations as a risk 1.31 times more often than BME and in the Neck category, a station is 3.6 times more likely to be identified as a risk by BME than by AFS-98 (however, the previous reservations regarding the Neck results still apply).

Summarily, it appears that the overall propensities for BME and AFS-98 to identify a workstation as a risk for a particular body segment are significantly different, although conclusions cannot be drawn with confidence regarding the Hand category and the Neck category is also doubtful.

3.3. Contextual and Pragmatic Factors (Interview results)

Historically, a recurring reason for dissatisfaction with evaluation procedures has been that the assessment work load and time consumption have been too great on the evaluators, prompting switches of evaluation procedures also prior to the one studied in this observation. Both interviewed groups identified advantages with BME; the Pre-production Ergonomists had been very satisfied with the fact that the ratings from the BME reports were on such a detailed level that they were able to work on changes on a car-model level. The OHS ergonomists felt that BME provided a preliminary tool for production personnel to make an initial ergonomics judgement and later decide whether to request further aid from the OHS. At present, the OHS ergonomists acknowledge that using the AFS-98 carries weight in discussions with other professional groups (such as production line personnel) since evaluations are based on legal requirements.

According to the interviews, the quantitative nature of BME historically led to a tendency to ‘conceal’ red tasks in an assembly sequence in a station that might be rated as green overall. Both groups felt that this was a result of not having impartial ergonomists perform the analysis – assessments were made on a less extensive ergonomics knowledge basis, and the time-study philosophy of basing the total station rating on an activity-related ‘sum’ of red, yellow or green actions has little congruency with an experienced ergonomist’s ability to judge postures and activities in relation to how frequently they occur and how harmful they are.

The concern of Pre-production ergonomists is to change the product on a “bolt-and-nut level” rather than the process, in order to address ergonomics problems proactively. When BME was introduced, responsibility for evaluating ergonomics was assigned to local technical personnel, and the evaluation detail was on the level the Pre-production team required. This advantage has since been lost in the AFS-98 evaluations, and the Pre-production ergonomists feel that the need for more detailed analyses obliges them to ask the OHS ergonomists for re-evaluations (or they independently perform their own complimentary evaluations). Both interviewed groups mention that there was a role-based conflict of interests inherent within the BME teams; while the Local Manufacturing Engineers’ interest was to preferably get an acceptable (green) rating for their assembly line segment, the Worker Safety Representatives had as an objective to find whatever unacceptable working conditions were present.

The main assignment of the OHS ergonomists who performed the AFS-98 evaluation is to rate the work stations on a holistic level, in order to get an idea of the accumulated physical load over a prolonged working period. Also, they stressed that much of their knowledge is deeply internalized and that their judgments were performed with ‘gut feeling’ and were limited to a simplified, holistic level due to time and personnel restrictions.

One issue brought up by the OHS ergonomists was that since they are from an externally contracted OHS provider, there has been a shift of responsibility regarding ergonomics monitoring. Prior to and during the use of BME, it was VCC who internally took responsibility for ergonomics work (via the Pre-production team or the BME teams), but since all evaluation assignments are now ‘outsourced’ to the OHS as a consultancy, they feel there is a risk that the ‘internal follow-up’ procedures may suffer. The Pre-production ergonomists brought up similar concerns.

4. Discussion

The situation ‘observed’ in this comparison study has occurred as a reality in the manufacturing industry - one procedure is chosen, on a management level, to entirely replace another, despite the fact that the underlying methods yield data that solve different problems. This implies that studying such strategy changes and the consequences thereof are a valid concern for industry. However, since this comparison rests very much upon the retrospective analysis of corporate documentation that has sometimes been incomplete or difficult to interpret, the statistical approach has by necessity been explorative and some aspects have not been possible to study (for instance, the multiple actors involved in using BME and AFS-98 respectively, along with the frequent omission of evaluators’ names in the BME documentation greatly hampered the plausibility of performing inter- and intra-rater reliability analyses.) In light of some findings that have come from the interviews, a different quantitative approach may have been more suitable were this methods comparison to be made again.

From the quantitative comparison (specifically that which is shown in Table 1), it becomes clear that there is a large proportion of non-agreement between station ratings. It has been established that much of the non-agreement is most likely due to differences in rating definition between AFS-98 and BME, while other 'covert' causes may include undocumented local station/work changes implemented between evaluations, inexplicit agendas on the part of evaluators and criterial differences in what 'unit of improvement' is being observed (e.g. entire task sequences vs. specific postures and rotations). The proportion of non-agreement that is caused by these three factors is at this stage unclear and may merit a methodology of its own; a more qualitative approach may prove fruitful in order to conceptualize such ‘hidden’ influences, although it would most likely alter the objective of the study. Further work along these lines is certainly needed in order for corporate ergonomics directives to be able to develop internal methods that at least match a mandatory national standard.

A point that was brought up in the interviews is that the historical definition of the yellow level at Volvo (prior to the introduction of BME) has been ‘acceptable’, to the point where yellow has on occasion been considered a 'target value' for some employees. In contrast, the OHS ergonomists view a yellow rating from AFS-98 as far more severe. This has and may continue to cause misunderstandings between professional groups if colour-zone results are used ‘at face value’ to follow up the ergonomic status of the factory, as the evaluations are based on diametrically different observation principles (task-based approach vs. holistic judgment-approach). Therefore, if strategic ergonomics decisions are to be made on the basis of the red-yellow-green categorization on a management level, it is vital that all concerned parties have clearly understood the meaning of what the colour zones imply. This is also significant in the discussion of whether the two procedures are 'successful' in identifying and ranking ergonomic risks.

Both interview groups acknowledged that keeping workstation ergonomics evaluation data updated is a constant problem, regardless of the procedure used.

One main aspect in common between BME and AFS-98 is that they both demand a minimum level of specialized competence from the evaluators (completed internal certification training or long-term professional experience, respectively). This implies that evaluation results in both cases are dependent on the ability of the evaluators to correctly assess postures, forces and time aspects of the work under study, according to the guidelines of either BME or AFS-98. In other words, the issue of ergonomics expertise is significant to the user's ability to make an assessment.

The purpose of the study is not to endorse or promote either procedure as superior to the other, as there is no available unbiased 'benchmark' measurement to rate ergonomics by in this case. Indeed, this comparison should be regarded as an observed example case highlighting the pragmatic differences that arise when two different methods are used interchangeably for the same end purpose. It has been suggested by the results that discrepancies between the evaluations may be caused not only by workstation-specific differences, but also by differences in boundary conditions within the two evaluation procedures. The methods were assumed to be similar at the time they were used, but since neither BME nor AFS-98 are strictly scientifically developed, it is not immediately evident where the underlying theory for boundary/acceptability levels is taken from in either procedure's documentation. The authors would therefore like to stress that this comparison study does not conclusively answer the question of whether BME or AFS-98 is more accurate or successful at identifying risky work tasks. This is very difficult to judge without having an additional 'gold standard' source of information regarding the ergonomics status of the workplace for comparison (such as work injury records).

5. Conclusions and Recommendations

The two procedures BME and AFS-98 were compared using a quantitative approach followed by a complementary group interview. It was found that the two procedures differ significantly in station ratings, with AFS-98 tending to give more severe ratings. There is no evident pattern aside from some consecutively clustered differences, and many differences can be explained 1) by the method-inherent differences in boundary conditions for what is considered acceptable, and 2) by the differences in focus and work objectives of the personnel evaluating the assembly line.

Changes in ergonomics evaluation procedures in a production system need to be carefully thought out. Changes affect the time consumption for data collection, the level of input detail, the desired or required level of competence (ergonomics-related and industry-specific) of the observers, and the nature and usefulness of the output data for different stakeholders (production developers, OHS personnel, production personnel). The consequence of having changed from BME to AFS-98 has been a change in problem-solving focus (partially a result of the shift in personnel allocation for the assignment).

The shift from a 'bolt-and-nut' technical focus to a holistic level is a rationalization issue – the OHS ergonomists lack the time to complete their contractual assignments at the former, highly detailed level.

The long-term results of this change are that the ergonomics focus has shifted, and that different professional groups within the organization have had their supply of data for continued work altered, which in turn alters the discussion between the different professional groups on ergonomics issues in the production system.

Neither BME nor AFS-98 can be considered an absolute measure of exposure, and therefore, the accuracy of the measurement results is not the main target of interest for this comparison study. Also, their relative success at identifying ergonomically hazardous work cannot be concluded from this study, as this would have required additional comparison of the results with a 'gold standard' measurement of ergonomics status.

It is strongly recommended to industrial corporations that any changes in ergonomics evaluation routines should be carefully planned, and that any such changes should be preceded by careful method criteria comparison, as well as background interviews of affected personnel. These interviews should focus on the professional objectives of each evaluating actor, to ensure that the interpretation of rating levels is understood by all involved professional groups and that output data needs are met by the chosen procedure.

Acknowledgements

This paper is partly a result of the research project 4D Ergonomics which is carried out within Virtual Ergonomics Centre (http://www.vec.se) and is financially supported within the MERA (Manufacturing Engineering Research Area) program under grant no. 2005-01998 by VINNOVA (the Swedish Agency for Innovation Systems) and the participating organizations (Alviva, Dassault Systèmes, Etteplan, SAAB Automobile Siemens/UGS and Volvo Car Corporation). This support is gratefully acknowledged. The authors also would like to express their gratitude to European Ergonomists Ann-Christine Falck, Kristina Troedsson and production ergonomist Sari Rosenström. Thanks also go to the ergonomists from the occupational health service organization in the studied factory.

Many thanks to Oscar Person, Marita Christmansson, Lars-Ola Bligård, Annki Falck, Dan Högberg and two anonymous reviewers for useful and constructive insights and comments regarding the contents and structure of the article.

References

AFS. ERGONOMICS FOR THE PREVENTION OF MUSCULOSKELETAL DISORDERS - Provisions of the Swedish National Board of Occupational Safety and Health on Ergonomics for the Prevention of Musculoskeletal Disorders, together with the Board's General Recommendations on the Implementation of the Provisions. Solna, Sweden: Arbetarskyddsstyrelsen; 1998.

Amprazis J. BME. Beräknings Modell Ergonomi Volvo Car Torslanda, utg. 03.1, 2005-01-10 (internal Volvo BME education material, in swedish); 2005.

Bao S, Howard N, Spielholz P and Silverstein B. Quantifying repetitive hand activity for epidemiological research on musculoskeletal injuries—Part II: comparison of different methods of measuring force level and repetitiveness. *Ergonomics* **49** (4) 2006; p. 381–92.

Björk E. The BME Model of Calculation and its Connection to Quality and Productivity. LITH-IKP-EX--06/2349—SE. Linköping: Linköping University (Master Thesis in Swedish; abstract in English); 2006.
Drinkaus P, Sesek R, Bloswick D, Bernard T, Walton B, Joseph B et al. Comparison of ergonomic risk assessment outputs from Rapid Upper Limb Assessment and the Strain Index for tasks in automotive assembly plants. Work 2003 21: 165–72.

Falck, A. Virtual and Physical Methods for Efficient Ergonomics Risk Assessments - A Development Process for Application in Car Manufacturing. Göteborg; Chalmers University of Technology, 2007. ISSN 1652-9243

Hignett S, McAtamney L. Rapid Entire Body Assessment (REBA). Applied Ergonomics 2000; 31: 201–5.

Jones T, Kumar S. Comparison of ergonomic risk assessments in a repetitive high-risk sawmill occupation: Saw-filer. International Journal of Industrial Ergonomics 2007; 37, Issues 9-10: p. 744-53.

Kadefors, R. An ergonomic model for workplace assessment. Proceedings of the IEA'94, 1994, Vol. 5. International Ergonomics Association, Toronto, Canada, pp. 210–212.

Li G, Buckle P. Current techniques for assessing physical exposure to work-related musculoskeletal risks, with emphasis on posture-based methods. Ergonomics 1999; 42 (5): 674-95.

Luthman G, Bohlin H., Wiklund A. MTM i Sverige 1950–1990, Teknik och praktik (in Swedish). Stockholm: Sveriges Rationaliseringsförbund; 1990.

McAtamney L, Corlett, NE. RULA: a survey method for the investigation of work-related upper limb disorders. Applied Ergonomics 1993; 24: 91–9.

Moore JS, Garg A. The strain index: a proposed method to analyze jobs for risk of distal upper extremity disorders. American Industrial Hygiene Association Journal 1995; 56: 443–58.

Munck-Ulfsfält U, Falck A, Forsberg A, Dahlin C, Eriksson A. Corporate ergonomics programme at Volvo Car Corporation. Applied Ergonomics 2003; 34: 17-22.

Occhipinti E. OCRA: a concise index for the assessment of exposure to repetitive movements of the upper limbs. Ergonomics 1998; 41:1290–311.

Sperling L, Dahlman S, Wikstrom L, Kilbom A and Kadefors R. A cube model for the classification of work with hand tools and the formulation of functional requirements, Applied Ergonomics 1993; 24 (3): 212–20.

TemaNord. Vägar till färre arbetsskador (TemaNord 1994:514) - utveckling av nordisk ergonomitillsyn, modeller för ergonomisk riskvärdering (Nordic health ministry report, in Swedish) Nordic Council of Ministers; 1994. ISBN 92-912-0421-8

Törnström L. Beständig förbättring?: om en företagsutvecklad belastningsergonomisk modell. (Dissertation thesis, in swedish) Linköping: Linköping University; 2007. ISBN: 978-91-85831-31-9

Törnstrom L, Amprazis J, Christmansson M, Eklund J. A corporate workplace model for ergonomic assessments and improvements. Applied Ergonomics 2008; 39 (2): 219-28.

VCS 8003-29. Ergonomics requirements – Application. Volvo Corporate Standard 8003,29. Volvo Car Corporation, Göteborg, Sweden. 2006.

Paper II: Berlin, C.

Time-Related Factors in Ergonomics Evaluation Part II: a Literature Review and Scientific Basis for the Framework

Manuscript version.
Submitted for approval to *Applied Ergonomics*. (2009)

Time-Related Factors in Ergonomics Evaluation Part II: a Literature Review and Scientific Basis for the Framework

(Manuscript version)

Cecilia Berlin

Dept. Of Product- and Production Development, Div. of Production Systems, Chalmers University of Technology, Göteborg, Sweden

Address: Dept. Of Product- and Production Development, Div. of Production Systems, Chalmers University of Technology, SE-412 96, Göteborg, Sweden.

Tel: +46-31-772-1290.

E-mail address: cecilia.berlin@chalmers.se

Abstract

Ergonomics problems in production systems are of a multi-causal nature. It has been established in ergonomics literature that combinations of posture, force, and time-varying factors like activity duration, repetitiveness, work-rest distribution and dynamic muscle reactions to physical loads can all influence the occurrence of work-related musculoskeletal disorders (MSDs). The point of departure for this literature review is to compile and examine time-related ergonomics terms for the benefit of introducing such concepts into Digital Human Models (DHMs). The implementation of the terms is described in a sibling article (Part I). This article brings up how time-related factors in ergonomics evaluation have been addressed, conceptualized, measured, and given acceptability criteria in ergonomics literature from 1990 to date. It discusses ambiguities regarding how terms have been used and the influence of time-scale perspectives on the usefulness of different concepts.

Statement of relevance

Developers of Digital Human Models can benefit immensely from an overview of available scientific findings regarding how to take consideration of time-related factors of physical workload. The scientific community benefits from identification of ambiguities and gaps in ergonomics research, to enable further development of prognostic analysis methods.

Keywords: Ergonomics evaluation; Time aspects; Dynamic evaluation; Digital Human Modeling

1. Introduction

Ergonomics evaluation of production systems (especially with regard to manual assembly tasks) is chiefly geared towards identifying and eliminating risks for work-related musculoskeletal disorders (MSDs) among human workers. As a rule, the physical behaviour of the human operators is regarded as the main measurable causal factor for MSDs, whenever the behavioural patterns (work movements) are identified as unhealthy. Due to the fact that there is much well-accepted research regarding evaluation of body *postures*, the main focus of most widely-accepted methods is to identify isolate postures that are considered extreme, unbalanced or physically strenuous. Most such methods analytically assume that the posture can be considered as an inert (static) load situation.

However, posture and static loading are not the only culprits behind MSDs. It has been widely suggested by several researchers that time-varying aspects of work behaviour, such as repetitiveness, monotony, durations of exposure etc. contribute at least as much (if not more) to the potential risk for work-related injury. Therefore, many researchers have called for a need to shift focus away from pure posture analysis in favour of more time-related ergonomics analysis. (Wells et al., 2007; Chiang et al., 2008)

As the computational capability and accessibility of computers has increased dramatically over the last two decades, software tools for simulation of human work and ergonomics evaluation (known as Digital Human Models, DHMs) have been successfully developed and employed in some industries already at the production planning stage. However, the analysis tools available in most DHM software reflect the status of the research field of today; according to a recent overview by Lämkull et al. (2008), the most widespread DHM software developers chiefly supply posture-based analysis tools that assess identified risks as if they were a static loading situation. This is an unfortunate mismatch with the increased capability of DHMs to visualize animated movement sequences. With recent developments both in *Motion Capture* technology and Motion databases, DHM movement simulations are becoming more relevant and visually convincing.

What is missing today in the selection of well-established ergonomics evaluation methods (and consequently, DHM software) is a way of addressing time-related components of workload exposure. Many researchers have made advancements in conceptualizing time-related factors, in some cases presenting ways to quantify them, but there appears to be great diversity in how different lines of research take time factors into consideration. Therefore, this literature review contributes to an overview of how time-related ergonomics exposure factors have been addressed and how they may interact.

2. Method

2.1. Data Collection

The material for this literature study has been collected primarily via database searches, using a number of combined key terms[1] such as *time, ergonomics evaluation, dynamic, repetitive*

---

[1] Some found by using truncated entries, e.g. "repeti*" or "evalua*"

and *cumulative*. Most sources were found in databases Scopus, Ingentaconnect, Google Scholar, Inderscience, ScienceDirect and similar services.

It was decided that emphasis should be placed on literature from 1990 and onwards. Unquestionably, the issue of evaluating human work in a time-related, non-static manner has been brought up in ergonomics literature before then, but it was presumed by the author that literature from this limited period would contain more DHM-relevant contributions. If deemed within the scope of interest, additional material was obtained from the reference lists of selected contributions and through suggestions by colleagues.

2.2. Analysis

The contributions were screened by the author after an initial read-through so that the final material was comprised of case studies, literature reviews, experimental descriptions, relevant doctoral theses, proposals of terminology definitions and time-related practitioner methods. Once established, the material was subjected to categorization using a principally hermeneutical approach (Smith, 1998). A number of guides for scientific literature reviews were consulted and the one described by Psychology Writing Center (2005) was chiefly adhered to.

3. Results

3.1. The Reviewed Material as a Whole

After an initial scan of the material, a number of recurring concepts relevant to time aspects were discovered. Some contributions describe a specific evaluation method, others address contexts of application/strategies/production-related issues etc. from a socio-organizational perspective, yet others establish classification criteria on an epidemiological/clinical basis, and some discuss practitioner needs and preferences.

Certain review contributions are especially noteworthy. The first indicative review contribution is Kilbom's (1994) review "Repetitive work of the upper extremity (Part II)", which strives to define which measurable parameters[2] should be used to describe repetitive work. Kilbom's review has a pronounced focus on exposure-effect relationships. The major contribution is Kilbom's comprehensive compilation of definitions for the term 'repetitive' and suggested quantifications of it.

Li and Buckle's (1999) review of posture-based methods makes some interesting points regarding the capacity of certain methods to perform dynamic recordings of movement in real time (although some of the technology may be considered outdated today, or limited to laboratory use). They note that besides posture, other risk factors such as force, frequency and/or repetitiveness of movement, task duration etc. are believed to be important contributors to MSDs, although little is known about the relative importance of each factor. Li and Buckle also emphasize that different risk assessment tools have been developed with very specific types of work in mind and that they can be used 'wrongly' if applied to a different situation.

---

[2] The term 'parameters' is used verbatim from Kilbom, 1994

Wells et al. (2007) is the most recent review found in the search. They state that the time concepts established by ergonomics literature “map poorly onto the known quantitative risk factors” (p. 741). Their review also identifies a number of common concepts, variables and metrics that could facilitate the exchange of time-related information between engineers and ergonomists. This is presented in a number of tables bringing up time-related concepts (related to specific body regions) and risk factors as found in ergonomics literature. Wells et al. also suggest that modern-day conditions and tendencies in production systems will cause *lack-of-variation* to surpass *peak loads* and *extreme postures* in relative importance as a biomechanical risk factor for MSDs.

3.2. Time-related Evaluation Terminology

Several authors in this review (Kilbom, 1994; Wells et al., 2007; Kazmierczak et al., 2007) have independently brought up the point that time-related terms are used and interpreted differently by different readers, stakeholders or actors, depending on the context in which the terms are used and the person’s professional discipline. As shown by this review, several time-related terms used by the research community lack uniform definition. Not many standard glossaries seem to exist regarding time-related ergonomics terminology, so many concepts have been explored by different lines of research with an unstated, implicit definition. How successfully each concept embodies risk factors is therefore not easy to judge, since inconsequential definitions can lead to ‘losses in translation’ between literary contributions. At the same time, it is not easy to determine who has the authority to finally decide the strict definition of any of these terms, as many definitions may be closely associated with criteria limits for acceptability, which in turn may be specific to different types of physical work. Kilbom (1994) illustrates this dilemma by presenting tables with numerous definitions and quantitative definition limits of repetitive work.

These ambiguities aside, it is possible to categorize the found terms and concepts into functional groups. A first useful categorization is to show the reported MSD ‘Risk symptoms’, i.e. physiological mechanisms that may lead to MSDs, and where they are distributed across a number of associated time perspectives (short- and long-term). The time scale varies in the literature, from very small increments such as EMG gaps (fractions of seconds) to the entire working life (years).

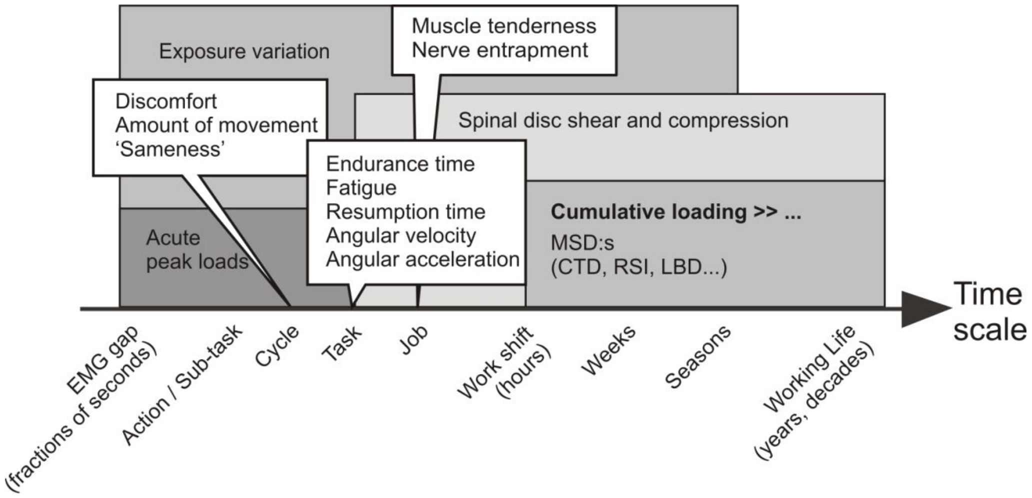


Figure 1 – Expressions of MSD Risk 'Symptoms' Across Different Time Scales (Marras, 1992; Rose et al., 2001; Rose, 2001; Moore and Wells, 1992; Kee and Karwowski, 2001; Juul-Kristensen et al.,1997; Gilad, 1995; Wells et al., 2007; Norman et al., 1998; Seidler et al., 2001 and Kumar,1990.)

In *Figure 2,* another explorative categorization is used, where the terms have been grouped under the headings *Job Description, Resultant Work Behaviour Characteristics,* and *Consequences.*

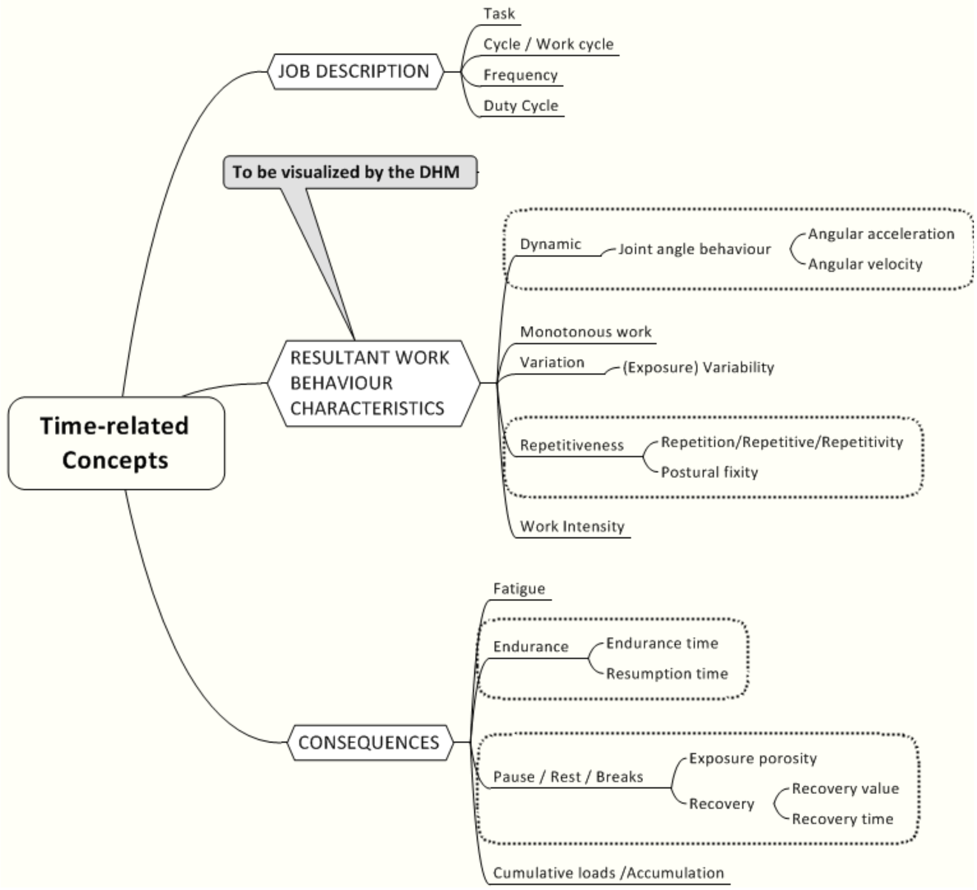


Figure 2 – A functional classification of Time-related concepts

3.2.1. Job Description

Certain terms relate to the basic elements of describing a job activity, and many of them interrelate. The job description includes some basic time-related inputs that are significant contributors to MSD risks. For instance, the relationship between job, *task* and *cycle* needs to be clear in each description. This brings up the meaning of related terms such as *frequency* and *duty cycle*. Also, the *speed of work* (which is related to frequency) can be included as part of the job description.

What constitutes a *task* has been conceptualized in different ways – Colombini (1998) states that a task is a “Specific working activity whose objective is the attainment of a specific operational result” (p. 1264). Norman et al. (1998) divide jobs into tasks for the purpose of calculating accumulated load (as the ‘peak load’ of each task times its duration). Kilbom (1994) argues that a task should be defined in terms of the parameters *static loads, external force* and p*osture*, and also that “the engaged body region and duration of exposure should be specified". Kilbom's (1994) definition of *task* implies that it is clear when a task activity begins and ends. This definition is focused on repetitive work, and emphasizes the notion that the repetitive work is concentrated to a specific body segment.

Dempsey and Mathiassen (2006) assert that the usefulness of classical task analysis techniques may be limited in the context of ergonomics evaluation due to modern work being very complex (e.g. in the presence of job rotation, seasonal variations or flexible manufacturing strategies). They also state that task-analysis approaches may be more useful for identifying peak loads for individual tasks, but are not as successful when cumulative exposures or exposure variation patterns are in focus.

A *cycle* is defined by Colombini (1998) as "a sequence of technical, mainly mechanical, actions of relatively short duration, that repeats itself over and over, always the same". In this way, Colombini has incorporated the concept of repetitiveness into the definition of a cycle, stating that tasks made of cycles are per definition repetitive - however, this definition seems to be rather unusual. Gilad (1995) states that *work cycles* are "composed of short, frequent motion elements, non-frequent and forceful motion elements" (p.94) and should be broken down into sub-activities consisting of tasks. This implies that there is some ambiguity in the literature regarding the name of the lowest-level activities that constitute work; both *task* and *cycle* appear in different contributions as the label for lowest-level activities.

In conjunction with this, some contributors have used the term *frequency* differently. Moore and Wells (2005) define it as the inverse of cycle time (i.e. increased frequency equals decreased cycle time). The *speed* at which work is performed is rarely uniformly quantified in literature, although it is sometimes mentioned as a risk component (Bao et al, 2006; Moore and Garg, 1995; Escorpizio and Moore, 2007; Kilbom, 1994). Colombini (1998) brings up the term *action frequency,* measured as the number of (mechanical) actions per time unit (minute, cycle or shift). This arguably captures situations where workers can choose to speed up or slow down their working rhythm, e.g. when producing a fixed number of pieces per shift (Colombini 1998, p.1268). In the *Strain Index* model (Moore and Garg, 1995; Bao et al., 2009) two different concepts are used to capture the phenomenon; the work is characterized by the number of 'Efforts per Minute', which is rated according to criteria levels, and 'Speed of work' which is rated subjectively (on an ordinal scale) based on observation.

Moore and Wells (2005) have described the concept of *duty cycle* as the proportion of stipulated work cycle time actively working, expressed as a percentage of cycle time. Bao et al. (2006a) word it differently, as the percentage of a cycle spent in exertion (as in relation to forceful hand exertions). From a physiological perspective, Mathiassen and Winkel (1991) state that the original definition of *duty cycle* is only applicable to work oscillating between two load levels (of which one can be equal to zero), although the term can be expanded to state the relative distribution of load over time (p. 1460).

Bao et al. (2009) summarize the situation quite succinctly by stating that the breakdown terms *job, task, work element* and *exertion* have all been defined inconsistently in literature, and thus it is important in each individual case to define what each respective research team means by the terms and how they relate to each other hierarchically. Bao et al. (2009) do so by stating that a *job* (which is understood to be what is done during a *shift*) can be broken down into several *tasks*, and from there into several *work elements* which are each characterized by *exertions* (p. 57).

3.2.2. Resultant Work Behaviour Characteristics

The DHM needs to be able to generate a model of the work sequence based on the input, and as such must be able to visualize and evaluate what is happening - i.e. there must be time-related, quantitative criteria of acceptability built into the tool. What the DHM can do is to visualize the time-driven work characteristics in such a way that the DHM user is made aware of their role as risk factors that may impede on good work performance. What is meant by *dynamic* work or analysis techniques must first be established, as must the related terms *monotony* and *variation.* The most widely discussed concept in the literature concerns *repetitiveness*.

According to Marras (1992), the term *dynamic* generally signifies how motion influences force exertion(from an EMG-related perspective) and that it “may increase greatly the predicted loading experienced by a joint” (Marras, 1992 p. 65) due to increased muscular co-activation. Dynamic activity further implies that body segments are subject to motion velocities, in combination with flexion, torques and lift rates. Marras’s study supports that increased motion may increase the risk of *Lower Back Disorder* (LBD). Kilbom’s definition of *dynamic* is somewhat more intuitive, signifying that “movements around a joint are easily distinguished” (Kilbom 1994, p.153). Grant’s (1994) description relates to grip force requirements during manual handling of loads; in this case, *dynamic* implies that grip force requirements vary during motion, resulting in a peak hand exertion at some point. Högberg et al. (2007), from a more DHM-oriented perspective, let *dynamic* ergonomics evaluation signify animated work simulations, where the objective of the DHM is to compute aggregated loads over entire work sequences.

It follows that *dynamic* movement is closely related to movements of the body’s joints, which is discussed in terms of *angular velocity* and *angular acceleration* in some contributions. In their review of classification criteria for joint angles, Juul-Kristensen et al. (1997) suggest that angular velocity and acceleration combined with force have greater importance as risk factors than posture. According to Marras (1992), body segments differ in sensitivity to the two movement components; for example, Marras found the trunk to be more sensitive to angular velocity, while the wrist was more sensitive to angular acceleration. From a production system perspective, Wells et al. (2007) point out that angular velocities and accelerations are closely related to the human operators’ interactions with the production system and are therefore not so predictable.

Some terms are in themselves descriptors of undesirable conditions, such as the concept of *monotonous work (*see *repetitiveness).* Wells et al. (2007) quote two definitions of the term that are both related to EMG readouts: “High autocorrelation of posture or EMG time history” (according to Moore and Wells, 1992) and “Low within work task variance, low between task variance of EMG or posture” (Mathiassen et al., 2003). Both definitions thus relate monotony to the repeated use of the same muscular structures.

An antonym to the above expression is *variation*, implying that actions vary to such a degree that the strain of one particular muscular load is relieved by switching to other activities, even if they do not involve rest ‘by design’. It is commonly suggested that mechanical exposure variation can be used as an intervention strategy against MSDs (Mathiassen, 2006; Möller et al., 2004). However, Wells et al. (2007) argue that little consensus exists regarding metrics for variation, largely due to the fact that variation of exposure can be measured over very different time scales ranging from very short (EMG gaps <1 s) to very long (e.g. variations over work seasons).

The term *exposure variability* sometimes also appears (e.g. Mathiassen, 2006 and Möller et al., 2004); in general it signifies a descriptive statistical measure of biomechanical exposure variation and appears frequently in studies of occupational epidemiology. The term may also describe “dispersion within days within subject, between days within subject, between subjects, between tasks, between jobs” (Mathiassen, 2006 p. 423). In the case of Möller et al. (2004) the time perspective is shorter – the term here signifies cycle-to-cycle statistical variance of exposure parameters level, frequency and duration (using ANOVA algorithms). As a side note, Dempsey and Mathiassen (2006) express skepticism towards the lack of studies that corroborate positive effects of job rotations; and indeed, Möller et al. (2004) found in their job-rotation case that job enlargement generally increased variability, but could also lessen the cycle-to-cycle variability for some workstations.

This in turn leads to the definition of what is meant by *repetitiveness*[3], a widely discussed term. There are chiefly three definition types present in the studied literature; the first concerns physiological definitions, the second relates to tasks, and the third concerns quantification attempts.

Physiological definitions focus chiefly on use of muscular or skeletal structures. An early definition by Moore and Wells (1992) suggests that *repetitiveness* of a job should be defined in terms of amount of tissue movement, cycle time and estimate of 'sameness' (from the point of view of postural changes). Moore and Wells specifically note the importance of identifying repetitiveness as repeated or sustained applications of force, and that lack of movement (“*postural fixity*”) is a special case of repetitiveness. This stance is repeated in a later contribution, defining similarity of movements specifically as “use of the same tissues over and over” (Moore and Wells 2005, p.861). Kilbom (1994) writes that repetitive work involves frequent repetition of physically similar work cycles. Escorpizio and Moore (2007) implicitly express repetition as a task involving near-identical muscular movement similarity under the same external load (in their case, transferring a weight in a pick-and-place experiment). Bao et al. (2006a) compare two different definitions of how to quantify repetitive hand activity, concluding that the two definitions capture different exposure phenomena. Gilad (1995) emphasizes the contribution of jobs which are “frequent in [...] appearance, short in duration and cyclic in performance” (p. 92) towards acquiring *Cumulative Trauma Disorders*, characterized early on by lack of recovery time, muscle tenderness/overuse and nerve entrapment. Approaching the matter from another angle, Occhipinti (1998) suggests that high-frequency actions (exceeding 40 actions per minute)

---

[3] Also referred to as repetition, repetitivity, *repetitive work* etc. in literature

"necessarily shorten the time available for contraction and decontraction of muscles" (p. 1294), thus linking repetitiveness to pause distribution and duration.

Task-related definitions of repetitiveness also occur; they assume that work can be divided into identifiable sub-units. Gilad (1995) uses a hierarchical breakdown of jobs into tasks, which are in turn broken down into elements of non-cyclic and cyclic work which are investigated further. Rather uniquely, Colombini (1998) defines the term *cycle* as being a repetitive occurrence per se, and Occhipinti (1998) shares this definition.

Quantifications of repetitive work have been attempted numerous times in order to establish acceptability limits (assuming that repetitive work is a risk factor for MSDs). Fallentin et al. (2001) quantify repetitiveness as number of movements of joints in a unit time. Kilbom (1994) lists numerous criteria definitions of repetitiveness (p. 154), expressed in cycle time lengths where the majority propose the threshold value < 30 seconds. Many of the criteria in Kilbom's (1994) table and/or article are used by other contributors (Gilad, 1995; Colombini, 1998; Occhipinti, 1998; Möller et al., 2004). Colombini (1998) and Occhipinti (1998) both quantify repetitiveness in terms of "technical actions", stating that more than 30 technical actions per minute constitute repetitive work.

Bao et al. (2006a) employ a two-part conditional definition of repetitive work (based on Silverstein et al., 1987 and Keyserling et al., 1993) where basic cycle times are <30 seconds and/or more than 50% of the job consists of similar upper extremity motion patterns. They also suggest a multi-factorial quantification of repetition[4] in terms of frequency and duty cycle of hand exertion, repetitive muscle activity (classified by time study methods), hand activity level, duration of exertion, number of efforts per min and speed of work (Bao et al., 2006a; p. 366). Thus, it should be clearly expressed in DHM evaluation work which quantification criterion of repetitiveness is used in any circumstance.

3.2.3. Consequences

Once the time-related job characteristics have been visualized by the DHM, what is left is to bring to attention the resultant effects of physical exposure that may infringe work performance (such as pain, discomfort, limited *endurance*, *fatigue*) and provide recommendations of how to handle them (e.g. using *pause* strategies to ensure *recovery*).

One mechanism indicating that work performance may suffer is the onset of *fatigue*, which is defined by Ma et al. (2008) as "the point at which the muscle is no longer able to sustain the required force or work output level". According to Konz (1998a), fatigue appears as either cardio-vascular, skeletal-muscular or mental fatigue and is likely to be reflected in an increased number of (performance) errors rather than a decrease of units produced per time unit, and relates the problem to factors such as lack of sleep, insufficient rest, too many daily work hours and/or work hours at an inappropriate time of day. Rose (2001) explores fatigue

---

[4] Specific to the case of forceful hand activity

reactions[5] such as *endurance time*, *recovery time*, *resumption time* and pain reactions in awkward postures.

Related to fatigue is the concept of *endurance.* Evidence in Rose et al. (2001) suggests that work experience influences endurance and resumption time after fatigue; experienced workers have longer endurance times and shorter resumption time than inexperienced workers. This 'training effect' is also supported by Grant et al. (1996). Interestingly, Rose et al. (2001) conclude that endurance time is not influenced by loading occurring at the ends of the worker's range of motion. However, an observed effect was that when loading was resumed directly after rest, the second endurance time was shorter and the ensuing (voluntary) recovery time was longer.

The 'antidote' to fatigue is usually termed *pause, rest, breaks, muscular relaxation* or *recovery* in different contributions. A related term, *exposure porosity*, is defined by Wells et al. (2007) as the occurrence of restorative work breaks and pauses. Konz (1998b) organizes "resting time" into the following categories:

1. Off-work resting time
2. Formal breaks, such as coffee breaks
3. Informal breaks (work interruptions, training)
4. Microbreaks (short breaks of a minute or less)
5. Working rest (performing another task using a different part of the body)

(adapted from Konz, 1998b)

Hopefully, resting leads to *recovery.* Konz describes the *Recovery Value* of a rest as a function of how fatigued the muscle is when rest begins, the length of the rest, and what happens during the rest, which can be regarded as a dose/response relationship (Konz, 1998b). Thus, the recovery value is a measure of the 'effectiveness' of the rest. *Recovery time* has been described in Rose et al. (2001) as a term with varying meanings depending on which aspect of recovery is in focus; for example, the recovery time can be related to critical pulse frequency levels or mean power frequencies of EMG signals (pp. 501 – 502). Rose et al. coined the term *resumption time* in their contribution to avoid confusion as to which aspect of recovery was studied. Colombini (1998) defines *recovery* as a period within a working shift or cycle where no repetitive mechanical actions take place, allowing for "metabolic and mechanical recovery of the muscle" (p.1264).

---

[5] In Rose et al. (2001), *endurance time* was experimentally measured as the time between application of a physical load until the participant requested to have the load removed due to discomfort or pain. *Resumption time* signifies the time between load removal and when the participant was willing to resume the loading task.

Konz (1998a) lists several strategies for preventing fatigue (general, muscular or mental fatigue) in a guideline, as summarized below:

1. Revise work-scheduling policy (to avoid too many consecutive hours or hours at the wrong time)
2. Optimize stimulation at work (to avoid mental over- or understimulation)
3. Minimize the fatigue dose (by lessening work intensity and establishing a work/rest schedule)
4. Use work breaks
5. Use frequent short breaks
6. Maximize recovery rate (by removing environmental stressors and muscle stressors)
7. Increase the *recovery/work* ratio (by increasing recovery time OR decreasing work time)

(adapted from Konz, 1998a)

Gilad's (1995) recommendation regarding recovery is that recovery time must be at least twice as long as the duration of a forceful motion and occur between two such forceful motions. According to Gilad, insufficient recovery time between forceful acts (especially repetitions) is a risk factor leading to *cumulative trauma disorder.*

Finally, one of the most sought-after consequences is how to describe the *cumulative* effects of physical work exposure. Buckle and Devereux (2002) speak of cumulative reduction of capacity[6] as a result of overexertion of the muscles or frequent high muscle load, either mechanism leading to muscular fatigue which in turn contributes to MSDs.

Definitions of *cumulative* differ conceptually in the literature, among other things regarding which time perspective the physical load is related to. Kumar (1990) integrates biomechanical load and exposure time over entire working lives (spanning several years) – this was assessed by interviews and by calculation of compression and shear at spinal discs using a biomechanical model. Seidler et al. (2001) also assume a long-term exposure profile, focusing on the risk of contracting Lumbar Spine Disease. Seidler et al. use a modified Mainz-Dortmund dose model (a retrospective estimate based on overproportional weighting of the lumbar disc compression force relative to the respective duration of the lifting process; see Jager et al., 1999) to calculate cumulative forces to the lumbar spine over an entire working life. Other approaches assume a shorter time span and more of a task division focus. For instance, Norman et al. (1998) calculate cumulative loads based on daily work shifts, advocating an approach where task peak loads in a task are multiplied by the number of times the task occurs over the shift and by the duration of exposure for each task (measured in Newton-seconds) and then added to the spinal loading between work tasks (which is estimated as the loading in an upright standing position multiplied by the time spent waiting). In this way, cumulative load is calculated as the consequence of a particular task, and the total shift load is thus the sum of all task load integrals and the 'pause loads'.

---

[6] of muscles

Gilad's (1995) definition is specifically tied to C*umulative Trauma Disorders*[7]. Gilad characterizes *cumulative loads* as the result of a repetitive job with limited recovery time between cyclic jobs, suggesting that frequency of hazardous movements per cycle and the pause/recovery mechanism is an important factor in avoiding CTD.

3.3. Some Time-Related Evaluation Methods

As an update to the method overview compilations that can be found in many of the studied literature reviews, below is a listing of some methods for ergonomics evaluation (some software-based) that in some way considers time aspects. The methods can be distributed across a time scale as shown in *figure 3*.

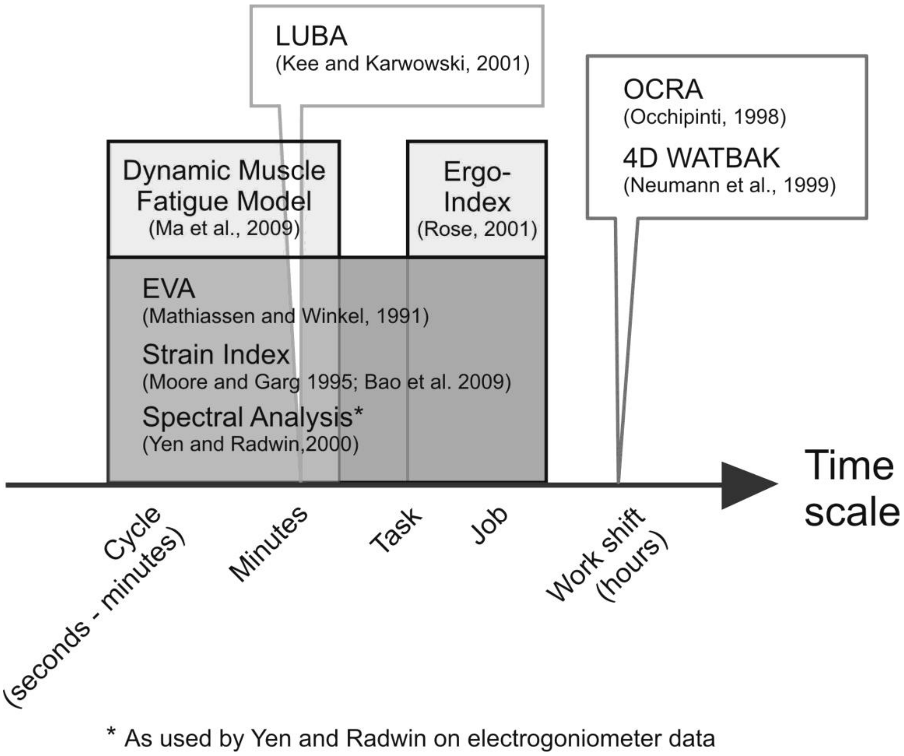


Figure 3 – Time-related Ergonomics Evaluation Methods and Their Applicable Time Scales. Methods contained in blocks are applicable to a range of time units, while those contained in captions are suited to one specific time unit (*Kee and Karwowski, 2001; Ma et al., 2009; Mathiassen and Winkel, 1991; Moore and Garg, 1995; Bao et al., 2009; Neumann et al., 1999; Occhipinti, 1998; Rose et al., 2001; Van Lingen et al., 2002;).*

---

[7] which is equated to the terms Repetitive Strain Injuries and Repetitive Motion Injuries (Gilad, 1995).

LUBA (Kee and Karwowski, 2001) is an assessment technique for postural upper-body loading, based on discomfort caused by joint motion and maximum holding time. The time scale relevant to this technique is stated to be short-time exposures (minutes). It is in effect a subjective method based on perceived discomfort, expressed as a ratio or *postural load index* for joint motions by the hand, arm, neck and back and the corresponding maximum holding times in static postures. The different indexes obtained for varying postures allow for comparison of stress es and perceived discomfort levels across postures. In the process of developing LUBA, Kee and Karwowski developed a posture classification scheme based on joint angle data.

Ma et al.'s (2009) *Dynamic Muscle Fatigue Model* operates on the premise that the influence of external load, workload history and individual differences are of major importance to fatigue development. The model's parameters include maximum voluntary contraction[8], current exertable maximum force and the external load of the muscle (i.e. how much force it need to generate). Ma et al. emphasize that fatigue is a growth function with time, that is reciprocal to muscle force capacity (i.e., the greater the fatigue, the less capacity for force generation, and the longer a load is applied, the greater the fatigue). Calculation of the *Fatigue Index* is a data reduction excluding the influence of time. The model has been validated against 24 static maximum endurance time models and three dynamic models according to various literature, where each model is specific to a particular body region (Table 2, Ma et al. 2009) such as upper limbs, elbows, hands and back. The model also assumes that there is no recovery during the duration of work. Ma et al. have also expressed an ambition to apply the model to a 'virtual reality framework', presumably involving a DHM (pp. 218 - 219).

EVA (Exposure Variation Analysis) was developed by Mathiassen and Winkel (1991) to quantify variation in observed physical work. It applies to work movements up to entire job durations, where a job is a subset of a shift. EVA is based on the assumption that physiological response to the working load changes as a function of exposure time and can be administered to any continuously recorded signal (such as EMG measurement of muscle activity). The graphical representation of EVA includes a three-dimensional bar diagram showing the percentage of working time a person spends at different percentages of maximum voluntary contraction and the time durations that these contractions are held. Instead of showing a loading sequence, EVA thus shows how (sustained) loads are distributed over the working period, allowing for comparison of distribution profiles between different jobs. However, as it is a data-reduction method, EVA does not provide a real-time dispersion of exposure levels and leaves out duration of exposure.

The *Strain Index* is a scoring system based on observation of work. Originally developed in 1995 by Moore and Garg, it has been extended from a single-force scenario model to be applicable to multiple-task jobs (Bao et al., 2009) which is the subject for this time-related review. The Strain Index is calculated for exposure over a day, i.e. a shift, but is based on a task breakdown. With regards to time factors, the Strain Index rates a number of exposure parameters with qualitative and quantitative criteria levels (Table 1, Moore and

---

[8] Of an individual muscle without fatigue

Garg, 1995). Each parameter score corresponds to a multiplier factor (Table 3, Bao et al., 2009) which, when all are multiplied together, result in the Strain Index. Time-relevant aspects taken into consideration are duration of exertion, efforts per minute, speed of work and duration per day. There are several different strategies of varying 'exactness' for calculating the Strain Index, where approaches differ depending on how many of the exposure parameters are measured rather than estimated (Table 4, Ma et al., 2009). The calculated *Strain Index* places the work in one of three categories; Safe, Action or Hazard, indicating whether alteration of the job is necessary.

One 'observation' method that deserves special attention in this context is Yen and Radwin's (2000) use of *Spectral Analysis* on electrogoniometer data (in a time series). The main rationale for this method is that compared to any observation method[9], it offers considerably greater sampling resolution and precision of posture classification. The reason why it is brought up here is that its calculation algorithm could be very easily implemented in a DHM, and would probably be greatly simplified (in terms of time- and resource requirements) as a result. Its main output is a quantification of posture magnitude, repetition rates, posture amplitude differences and repetition frequency. Its main potential in a DHM would be to describe joint motion and characterize repetitive behaviours, joint angle deviations and sustained postures (although the time-study breakdown of the observed jobs into cycles was performed manually in Yen and Radwin's (2000) study).

Ergo-Index (Glimskär et al., 1987; Rose, 2001) is a model that can be used to analyse continuous readouts of data recorded during work, e.g. EMG measurements or subjectively reported fatigue or discomfort. The original model (described by Glimskär et al., 1987), applicable for comparing different work task methods regarding symmetrical static work with both hands, consists of four components:

- Relations between load level and endurance,
- Relations between load level, loading time and recovery need,
- Estimation of a task's production time, (loading time + recovery time),
- Estimation of the compression force on the lumbar spine and alert if it exceeds 3400N.

(adapted from Rose, 2001)

The original model (Appendix 1 of Glimskär et al., 1987) requires input data in the form of population percentile, load as a percentage of the specified population's maximum force exertion, load distances in the sagittal plane, load type (lifting, pushing or pulling), load magnitude, operation time (in minutes). Outputs that can be calculated are recovery time,

---

[9] The latter method has a great disadvantage according to Yen and Radwin – since sample rates tend to be low, observational "posture classification tends to classify small motions as sustained postures" (Yen and Radwin 2000, p. 130).

production time (i.e. operation time + recovery time) and risk of back injury (based on NIOSH levels; Waters et al., 1993).

Rose's (2001) improvements on the model include the use of experimentally determined resumption times in the calculation of recovery, plus a general validation and extension of the original model's scope. Rose also suggests taking the influence of worker experience into account (experienced workers have longer endurance times), that endurance-limiting pain arises in muscular rather than joint structures, and that the difference between sexes in endurance can be disregarded for the same relative load (% of MVC). Rose cautions that the model is still not entirely reliable for all types of EMG readouts, since the readouts tend to vary greatly when loads are low. Ergo-Index also exists as a software program (BELAB, 1992).

OCRA (Occhipinti, 1998) is a quantification index for MSD risk assessment targeted specially at repetitive motions of the upper limbs. Its main function is to sort repetitive tasks into problematic and non-problematic in order to steer priority of interventions. In effect an observation tool, OCRA calculates an index of exposure, based closely on the procedure for the NIOSH Lifting Index (Waters et al., 1993). The OCRA Index is based on a relationship between the actual number of actions performed in one day (or shift) and a 'recommended' (maximum) number of actions. Under 'optimal' conditions, the recommended number is 30 actions per minute, and the constant is diminished gradually as a function of the presence and characteristics of a number of risk factors (force, posture, recovery periods etc.). The OCRA Index is fairly easy to calculate and requires the number of repetitive tasks over the shift and the duration of each repetitive task (in minutes). It also takes into account the effects of insufficient recovery time and perceived effort. Occhipinti provides an OCRA data collection sheet with the necessary observation inputs and suggests OCRA Index value thresholds (p. 1294) that may be interpreted as green (fully acceptable), amber (borderline / uncertain) or red (definitely significant). It therefore appears fairly easy to integrate as a module in a DHM application. However, it is to be noted that differentiations must be made between left and right limbs. Also, Occhipinti emphasizes that at the time the article was written (1998), the OCRA Index had not yet been validated.

4D WATBAK (Neumann et al., 1999) is an assessment software targeted at risks for Lower Back Pain and based on an epidemiological database of risk factors. 4D-WATBAK allows for calculation of shift-long cumulative load (force-time integrals) on the spine, peak forces in the hands and on the spine. The software includes a biomechanical link segment model (a simplified form of DHM). The user enters different work actions and specifies their duration. If the durations do not add up to a full shift period, the remaining time is labelled as 'unaccounted for' and a low 'resting' load value is assigned to enable full-shift load calculation (similar to Norman et al. 1998). Model outputs include peak force instants and levels as well as the cumulative load. The user can then compare generated values with 'threshold limit values' to assess acceptability of ergonomics for the shift. Although 4D WATBAK may be considered technologically outdated today, its 'principles' can easily be implemented onto a more modern manikin. Another advantage is that it operates from a task-breakdown stance, which makes it compatible with many other analysis tools.

4. Discussion

In this review, time-related ergonomics terminology has been studied, mostly with the conclusion that differing implicit time scale perspectives lead to a variety of definitions and near-synonymous uses. It appears that while the potential of incorporating time-related aspects into DHMs has been applauded, there is no strict consensus on what many of the concepts mean. The implicit definitions vary between different lines of research, leading to ambiguity when comparisons are made of different results. Thus, it appears that DHM developers are pretty much at liberty to define the input, throughput and output terms based on literature of their choice. As long as this is stated clearly and the terms are used consistently, the author sees no immediate problems.

To appreciate the width of the contributions, it is important to recognize that there are some basic paradigmatic differences between the viewpoints of the different authors. Li and Buckle (1999) note that "in epidemiological studies, different exposure variables are rarely considered simultaneously" (p. 687) since little is known about the interaction between risk factors. In a similar manner, many authors in the review have acknowledged that isolated findings always have the caveat that a real work situation implies numerous other influential factors. For example, Kilbom (1994) notes that tolerance for repetitiveness has been known to be reduced by psychosocial work factors such as work control, time pressure and training. This multifactorial problem has been increasingly addressed in later contributions, e.g. the effects of operator experience on endurance (Rose et al., 2001) or the aspiration by Ma et al. (2009) to extend the Strain Index to be valid for dynamic, multi-task jobs. Thus, DHM developers are increasingly obliged to use research findings that take heed of multifactorial inputs.

Many sources indicate that the (gradual) injury mechanisms that may lead to MSDs are different for different body parts (e.g. Juul-Kristensen et al., 1997; Marras, 1992; Ma et al., 2009; Yen and Radwin, 2000). As mentioned before, it has been found that different body segments may be sensitive to different motion/load components and in order to make use of the available research findings, it would be wise to take consideration of the existing body-specific models and use the acceptability criteria that exist for different segments.

Implementation into DHM software should be based on joint angle data over time; data which an animated DHM could very well supply. At the same time, in concurrence with the scientific community's guidelines for how tasks should be described (with regard to posture, forces, durations, cycle times), DHM tools need to further develop analysis models to represent dynamic loads (i.e. loading during motion) and especially the case of muscular overexertion over prolonged time periods. While algorithms exist which can recognize and automatically segment repetitive actions from motion data without a previous definition of tasks, the author would recommend a continued use of task breakdowns in order to involve more actors within the production system design process. A DHM process failing to encourage participative ergonomics work is not recommended, for this reason the added detailing of tasks should be incorporated to increase understanding for involved actors. The experiences of Dukic et al. (2007) suggest that there is also substantial improvement potential regarding the actual process of using virtual tools. Their case study results illustrated that virtual simulation results run a risk of becoming very dependent on the knowledge and interests of the person who carries out a simulation. To remedy this, Dukic et al. (2007) advocate that the results of the computer manikin simulations can be made even more reliable with the aid of participative ergonomics and better documentation.

One problematic aspect of time-related ergonomics evaluation that has been focused upon in this review is that of time *perspectives* - explicitly or not, the terms used to define time-exposures to physical work all have their implied long- or short-term perspective when it comes to judging the risk for MSDs. The range of perspectives varies from short-term exposures lasting seconds or minutes, via mid-level perspectives (exposure over one or several work shifts), to extreme long-term exposure perspectives (years or an entire working life). This should be emphasized in the selection of analysis methods in a DHM context, in order to obtain results that are valid for the time period being simulated.

The ergonomics evaluation methods brought up in the review are presumably not an exhaustive compilation; however they do display some very different ways of incorporating time aspects, and although some are observation-based methods and others are software-based, they all have potential to contribute to better time-relevance in DHM analysis tools. Most of the methods already based in software appear to be easily transferable, while the observation methods offer ways of handling data that could be supplied by the DHM (e.g. joint angle motion data) that could provide the DHM user with higher-resolution classification of postures (diminishing the problem of subjective observation judgments), more dependable characterization of joint velocity and acceleration, and elimination of calibration/disturbance problems inherent in real-life joint angle motion measurements (e.g. using electrogoniometers).

This review has chiefly focused on how to take into account the small, gradually accumulating components of body loading that contribute to MSD development in a long-term perspective. It is, however, important to realize that a spectrum of ‘warning signs’ (i.e. injury mechanisms) exists. In this review, the focus has been on non-acute injury mechanisms that add up with time until the body region under stress reaches a ‘critical state’. What has been excluded from the discussion is that MSDs may also be contributed to by acute pain or discomfort; indeed, many of the contributions have specifically emphasized the role of repeatedly experiencing pain as a major contributor, and thus the avoidance of acute pain or discomfort equals avoiding at least one very tangible mechanism for developing MSDs.

Finally, some additional reflection should be given to the fact that different actors in a production design process may not just have different objectives with time manipulation, but may also have different propensities for using DHM tools and thus express varying degrees of interest in additional developments of time-related tools in software. The continued challenge for DHM developers will therefore be to carry out development in dialogue with users, i.e. industrial practitioners, scientists and professional ergonomists, deciding in collaboration with these actors how to get the most out of improved time-consideration in DHM software.

5. Further Work

Some additional work (not addressed by this review) is needed to establish the relationships between different time-related ergonomics aspects. Among other things, the author feels that the following research questions deserve continued efforts:

- The importance of time scale perspectives and what their different levels imply should be further investigated (in terms of which of exposure measurement resolution is deemed feasible for each level). Also, the longer the time perspective, the more important it becomes (presumably) to account for additional influencing factors such as work control, psychosocial and environmental conditions, worker health profiles, etc. What is a good strategy for selecting a relevant 'sampling resolution' for time scales ranging from less than a second up to entire working lives, and at what levels does the importance of additional factors (such as work experience) come into play?
- It has been acknowledged by several sources that posture classification criteria, sensitivity to motion components and fatigue developments are unique for specific body parts. How can the different existing body-specific models be brought together in a functional framework with uniform input and output parameters?
- The relative importance of the injury mechanism components that may add up to a contracted MSD is at present unclear; are the acute 'warning signs' and the gradually accumulating 'ignorable' ones of equal importance?

Acknowledgements

This article is written as part of the 4D Ergonomics research project which is carried out within Virtual Ergonomics Centre (www.vec.se) and is financially supported by VINNOVA (the Swedish Agency for Innovation Systems) within the MERA (Manufacturing Engineering Research Area) program under the grant no. 2005-01998 and by the participating organizations (Alviva, Dassault Systèmes, Etteplan, SAAB Automobile, Siemens / UGS and Volvo Car Corporation). This support is gratefully acknowledged.

Sincere thanks go to Dan Lämkull, Lars-Ola Bligård, Roland Örtengren and Johan Stahre for support and constructive help with this article, and to Roland Örtengren, Ann-Christine Falck and Patrick Neumann for helpfully supplying and suggesting additional sources to the study.

References

Bao, S., Winkel, J., Mathiassen, S. E., & Shahnavaz, H. (1997). Interactive effect of ergonomics and production engineering on shoulder- neck exposure - A case study of assembly work in China and Sweden. International Journal of Industrial Ergonomics, 20(1), 75-85.

Bao, S., Spielholz, P., Howard, N., & Silverstein, B. (2006). Quantifying repetitive hand activity for epidemiological research on musculoskeletal disorders - part I: Individual exposure assessment. Ergonomics, 49(4), 361-380.

Bao, S., Spielholz, P., Howard, N., & Silverstein, B. (2009). Application of the strain index in multiple task jobs. *Applied Ergonomics, 40*(1), 56-68.

BELAB, Byggergolab AB (1992). Ergo-Index Software.

Buckle, P. W., & Jason Devereux, J. (2002). The nature of work-related neck and upper limb musculoskeletal disorders. *Applied Ergonomics, 33*(3), 207-217.

Chaffin, D. B. (2005). Improving digital human modelling for proactive ergonomics in design. Ergonomics, 48(5), 478-491.

Chiang, J., Stephens, A., Potvin, J., 2008. Automotive Manufacturing Task Analysis: An Integrated Approach. In: Proceedings of the 2008 Digital Human Modeling for Design and Engineering Conference and Exhibition, June 17-19, Pittsburgh, Pennsylvania, USA. SAE 2008-01-1897.

Chung, K. H., Shewchuk, J. P., & Williges, R. C. (2002). An analysis framework for applying virtual environment technology to manufacturing tasks. *Human Factors and Ergonomics in Manufacturing, 12*(4), 335-348.

Colombini, D. (1998). An observational method for classifying exposure to repetitive movements of the upper limbs. Ergonomics, 41(9), 1261-1289.

Dempsey, P. G., & Mathiassen, S. E. (2006). On the evolution of task-based analysis of manual materials handling, and its applicability in contemporary ergonomics. *Applied Ergonomics, 37*(1 SPEC. ISS.), 33-43.

Dempsey, P. G., McGorry, R. W., & Maynard, W. S. (2005). A survey of tools and methods used by certified professional ergonomists. Applied Ergonomics, 36(4 SPEC. ISS.), 489-503.

Docherty, P., Forslin, J., Shani, A.B. (2002). Creating Sustainable Work Systems: Emerging Perspectives and Practice. Taylor & Francis, London.

Dukic, T., Rönnäng, M., & Christmansson, M. (2007). Evaluation of ergonomics in a virtual manufacturing process. Journal of Engineering Design, 18(2), 125-137.

Escorpizo, R., & Moore, A. (2007). The effects of cycle time on the physical demands of a repetitive pick-and-place task. Applied Ergonomics, 38(5), 609-615.

Fallentin, N., Juul-Kristensen, B., Mikkelsen, S., Andersen, J.H., Bonde, J.P., Frost, P. and Endahl, L. (2001). Physical exposure assessment in monotonous repetitive work – the PRIM study. Scandinavian Journal of Work, Environment and Health, 27, 21–29.

Glimskär, B., Höglund, P.-E. & Örtengren, R. (1987). Ergo-Index En beskrivning av ergonomiska effekter. Report in Swedish, TRITA-BEL 0036, LiTH-IERG-R-9, The Royal Institute of Technology, Stockholm, Sweden.

Gilad, I. (1995). A methodology for functional ergonomics in repetitive work. International Journal of Industrial Ergonomics, 15(2), 91-101.

Grant, K. A. (1994). Evaluation of grip force exertions in dynamic manual work. Proceedings of the Human Factors and Ergonomics Society 1, pp. 549-553.

Grant, S., Hynes, V., Whittaker, A., & Aitchison, T. (1996). Anthropometric, strength, endurance and flexibility characteristics of elite and recreational climbers. *Journal of Sports Sciences, 14*(4), 301-309.

Högberg, D., Bäckstrand, G., Lämkull, D., De Vin, L.J., Case, K., Örtengren, R., Hanson, L. and Berlin C. (2007). Towards Dynamic Ergonomics Analysis of Work Sequences in Virtual Environments. Proceedings of the 17th International Conference on Flexible Automation and Intelligent Manufacturing (2007 FAIM), Philadelphia, USA, June 2007, pp 581-588, ISBN 978-1-4276-2092-7.

Jager, M., Luttmann, A., Bolm-Audorff, U., Schafer, K., Hartung, E., Kuhn, S., et al. (1999). The Mainz-Dortmund dose model (MDD) for appraisal of stress to the lumbar spine from lifting or carrying heavy loads or by working postures with highly inclined trunk in suspicion of occupational disease no. 2108: Part 1: Retrospective determination of strain in work associates with risk. [Mainz-Dortmunder Dosismodell (MDD) zur beurteilung der belastung der lendenwirbelsaule durch heben oder tragen schwerer lasten oder durch tatigkeiten in extremer rumpfbeugehaltung bei verdacht auf berufskrankheit nr. 2108: Teil 1: Retrospektive belastungsermittlung fur risikobehaftete tatigkeitsfelder] *Arbeitsmedizin Sozialmedizin Umweltmedizin, 34*(3), 101-111.

Juul-Kristensen, B., Fallentin, N., & Ekdahl, C. (1997). Criteria for classification of posture in repetitive work by observation methods: A review. International Journal of Industrial Ergonomics, 19(5), 397-411.

Karhu, O., Kansi, P., & Kuorinka, I. (1977). Correcting working postures in industry: A practical method for analysis. Applied Ergonomics, 8(4), 199-201.

Kazmierczak, K., Neumann, W. P., & Winkel, J. (2007). A case study of serial-flow car disassembly: Ergonomics, productivity and potential system performance. *Human Factors and Ergonomics in Manufacturing, 17*(4), 331-351.

Kee, D., & Karwowski, W. (2001). LUBA: An assessment technique for postural loading on the upper body based on joint motion discomfort and maximum holding time. Applied Ergonomics, 32(4), 357-366.

Keyserling, W.M., Stetson, D.S., Silverstein, B.A. and Brouwer, M.L. (1993). A checklist for evaluating ergonomic risk factors associated with upper extremity cumulative trauma disorders. Ergonomics, 36, 807–831.

Kilbom, A. (1994). Repetitive work of the upper extremity: Part II - the scientific basis (knowledge base) for the guide. International Journal of Industrial Ergonomics, 14(1-2), 59-86.

Konz, S. (1998a). Work/rest: Part I - guidelines for the practitioner. International Journal of Industrial Ergonomics, 22(1-2), 67-71.

Konz, S. (1998b). Work/rest: Part II - the scientific basis (knowledge base) for the guide. International Journal of Industrial Ergonomics, 22(1-2), 73-99.

Kumar, S. (1990). Cumulative load as a risk factor for back pain. *Spine, 15*(12), 1311-1316.

Lämkull, D., Berlin, C., Örtengren, R. (2008). DHM - Evaluation Tools. Handbook of Digital Human Modeling: Research for Applied Ergonomics and Human Factors Engineering. Duffy, V.G. (Ed.). Taylor & Francis, CRC Press, pp. 24-1—24-23. ISBN/ISSN 0805856463.

Laring, J., Christmansson, M., Kadefors, R., & Örtengren, R. (2005). ErgoSAM: A preproduction risk identification tool. Human Factors and Ergonomics in Manufacturing, 15(3), 309-325.

Li, G. & Buckle, P. (1999). Current techniques for assessing physical exposure to work-related musculoskeletal risks, with emphasis on posture-based methods. Ergonomics, 42 (5), 674-695.

Ma, L., Bennis, F., Chablat, D., & Zhang, W. (2008). Framework for dynamic evaluation of muscle fatigue in manual handling work. IEEE International Conference On Industrial Technology (ICIT 2008).

Ma, L., Chablat, D., Bennis, F., & Zhang, W. (2009). A new simple dynamic muscle fatigue model and its validation. *International Journal of Industrial Ergonomics, 39*(1), 211-220.

Marras, W.S. (1992) Toward an Understanding of Dynamic Variables in Ergonomics. In: M.R. Cullen, Editor, Occupational Medicine: State of the Art Reviews, Hanley and Belfus, Inc., Philadelphia, pp. 655-677.

Mathiassen, S. E., & Winkel, J. (1991). Quantifying variation in physical load using exposure-vs-time data. Ergonomics, 34(12), 1455-1468.

Mathiassen, S.E., Möller, T., Forsman, M., 2003. Variability in mechanical exposure within and between individuals performing a highly constrained industrial work task. Ergonomics 46, 800–824.

Mathiassen, S. E. (2006). Diversity and variation in biomechanical exposure: What is it, and why would we like to know? *Applied Ergonomics, 37*(4 SPEC. ISS.), 419-427.

Möller, T., Mathiassen, S. E., Franzon, H., & Kihlberg, S. (2004). Job enlargement and mechanical exposure variability in cyclic assembly work. Ergonomics, 47(1), 19-40.

Moore, J. S., & Garg, A. (1995). The strain index: A proposed method to analyze jobs for risk of distal upper extremity disorders. *American Industrial Hygiene Association Journal, 56*(5), 443-458.

Moore, A. E., & Wells, R. (1992). Towards a definition of repetitiveness in manual tasks. In: Mattila, M., Karwowski, W. (Eds.), Computer Applications in Ergonomics, Occupational Safety and Health, Elsevier, New York,, 401-408.

Moore, A., & Wells, R. (2005). Effect of cycle time and duty cycle on psychophysically determined acceptable levels in a highly repetitive task. Ergonomics, 48(7), 859-873.

Neumann et al (1999) 4D WATBAK: Adapting research tools and epidemiological findings to software for easy application by industrial personnel. International Conference on Computer-aided Ergonomics and Safety.

Neumann, W. P., Winkel, J., Medbo, L., Magneberg, R., & Mathiassen, S. E. (2006). Production system design elements influencing productivity and ergonomics: A case study of parallel and serial flow strategies. International Journal of Operations and Production Management, 26(8), 904-923.

Norman, R., Wells, R., Neumann, P., Frank, J., Shannon, H., Kerr, M., et al. (1998). A comparison of peak vs cumulative physical work exposure risk factors for the reporting of low back pain in the automotive industry. Clinical Biomechanics, 13(8), 561-573.

Occhipinti, E. (1998). OCRA: A concise index for the assessment of exposure to repetitive movements of the upper limbs. Ergonomics, 41(9), 1290-1311.

Psychology Writing Center (2005). Writing a Psychology Literature Review. University of Washington, Washington, USA.

Rose, L. (2001). Models and methods for analysis and improvement of physical work environments. Ph.D. thesis. Chalmers Tekniska Hogskola, (1741), iii+1-50.

Rose, L., Ortengren, R., & Ericson, M. (2001). Endurance, pain and resumption in fully flexed postures. Applied Ergonomics, 32(5), 501-508.

Seidler, A., Bolm-Audorff, U., Heiskel, H., Henkel, N., Roth-Küver, B., Kaiser, U., et al. (2001). The role of cumulative physical work load in lumbar spine disease: Risk factors for lumbar osteochondrosis and spondylosis associated with chronic complaints. Occupational and Environmental Medicine, 58(11), 735-746.

Silverstein, B., Fine, L.J. and Armstrong, T.J. (1987). Occupational factors and carpal tunnel syndrome. American Journal of Industrial Medicine, 11, 343–358.

Smith, M. J. (1998). Social Science in Question. The Open University, SAGE Publications, London. ISBN 0 7619 6041-1

Van Lingen, P., Van Rhijn, G., De Looze, M., Vink, P., Koningsveld, E., Tuinzaad, G., et al. (2002). ERGOtool for the integral improvement of ergonomics and process flow in assembly. International Journal of Production Research, 40(15 SPEC.), 3973-3980.

Waters, T. R., Putz-Anderson, V., Garg, A., and Fine, L. J. (1993). Revised NIOSH equation for the design and evaluation of manual lift ing tasks. Ergonomics, Vol. 36, No. 7, pp. 749–776.

Wells, R., Mathiassen, S. E., Medbo, L., & Winkel, J. (2007). Time-A key issue for musculoskeletal health and manufacturing. Applied Ergonomics, 38(6), 733-744.

Yen, T. Y., & Radwin, R. G. (2000). Comparison between using spectral analysis of electrogoniometer data and observational analysis to quantify repetitive motion and ergonomic changes in cyclical industrial work. *Ergonomics, 43*(1), 106-132.

Paper III: Berlin, C.

Time-Related Factors in Ergonomics Evaluation: Part I - a Development Framework for Digital Human Modelling

Manuscript version.

Submitted for approval to *Applied Ergonomics (2009)*

Time-Related Factors in Ergonomics Evaluation Part I: a Development Framework for Digital Human Modelling

Cecilia Berlin

Dept. Of Product- and Production Development, Div. of Production Systems, Chalmers University of Technology, Göteborg, Sweden

Address: Dept. Of Product- and Production Development, Div. of Production Systems, Chalmers University of Technology, SE-412 96, Göteborg, Sweden.

Tel: +46-31-772-1290.

E-mail address: cecilia.berlin@chalmers.se

Abstract

It has been established in ergonomics literature that combinations of posture, force, and time-related factors like activity duration, repetitiveness, work-rest distribution etc. can all influence the development of work-related musculoskeletal disorders (MSDs). However, most ergonomics analysis tools found in computer-based Digital Human Models (DHMs) do not address time-related issues such as variation, load accumulation, repetitiveness, endurance – thus, the time-related aspect of work health problems is excluded from analysis in most DHMs.

Based on a literature including relevant contributions from 1990 to date, this paper proposes a guideline framework directed at DHM developers wishing to include time-related analysis factors in their DHM's analysis toolkit. The different time-related concepts found by the review (which is described in a sibling article, Part II) are arranged in a flow (input – throughput – output) and additional considerations are suggested.

Statement of relevance

Developers of Digital Human Models can benefit immensely from an overview of available scientific findings regarding how to take consideration of time-related factors of physical workload. This contributions suggests a strategy for implementing them.

Keywords: Ergonomics evaluation; Time aspects; Dynamic evaluation; Digital Human Modeling

1. Aim of the Framework

This framework is based on a major literature review regarding different time-related ergonomics terms and concepts, and places these terms in a context relevant to work simulation software, specifically Digital Human Models (DHMs). It is aimed at DHM developers wishing to incorporate time aspects into DHM software, and recommends where each concept belongs in an *input-throughput-output* DHM workflow process.

In light of the time-related terms, concepts and evaluation methods that were found, some additional considerations that appear to be motivated by the findings are also proposed. Gaps in research needing more work are also identified. Thus the framework contains a guideline-mannered suggestion of how to capture the different time-related concepts and where in the process they should appear, based on the present literature review. Also, comments are made on the rationale of implementing the evaluation methods found by the review in a DHM.

2. Input – Job Descriptors

The DHM should offer the user a clearly structured division of the job description into hierarchical levels. There are many supported ways of doing this, of which the recommendation below is one possibility.

2.1. Describing a Job

The recommended breakdown of the different levels (with definitions) is as in Bao et al. (2009[1]). At the level of *Motion Elements*, breakdown goes into parallel classification with Gilad's (1995) characterization of the motion elements as being cyclic (recurring) or not, and additional characterization of the motion *per body segment.* Using the term 'cyclic' as a characteristic rather than breaking down a multi-task job into 'cycles' diverts terminological confusion. Specifying body segments under exposure at an early stage allows for more specific analysis later, using relevant acceptability criteria. Also at the level of *Motion Elements*, application of external forces should be specified, as well as their duration. The breakdown is shown in *Figure 1.*

It is understood that the DHM should be able to self-generate many of these characteristics once the simulation has been run, though for recorded motions, sophisticated equipment may be required (e.g. a motion tracking system and haptic force recording devices).

Waiting, resting or any form of 'non-work' should also be accounted for on the level of *Tasks*, to enable calculations of duty *cycle* and *frequency* for those evaluation methods that require it.

---

[1] The lowest level in the breakdown described by Bao et al. (2009), exertion, has been included after the Motion Element level as one of several characteristics to be specified.

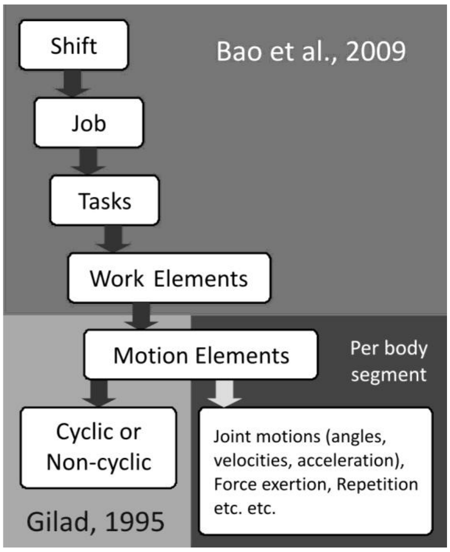


Figure 1 – Recommended breakdown principles as suggested in the combined literature.

For each stage of breakdown, the duration time should be specified so as to enable analysis of work-pause distributions. (Konz, 1998a and 1998b)

2.2. Additional Considerations and Research Gaps

2.2.1. Person-specific inputs

To ensure validity of the simulation, especially when the motion data is from a motion recording, it should be very clearly stated which individual-specific characteristics might influence the outputs. For example, specifying the population percentile that the studied worker belongs to allows for several analysis methods to give suitable criteria levels at a later stage.

2.2.2. Worker experience /training effects

As an example of the above, experienced workers (Rose, 2001) have been found to have longer endurance times, therefore input of worker experience levels could be used to analyze planned work and pauses for novices/experts. In cases where a new 'best practice' for a job is being tested, the DHM user can test for job duration differences between when the job is first implemented and when the worker has had substantial experience and has developed a routine.

3. Throughput – Resultant Work Behaviour to be Visualized by the DHM

The ability of the DHM to initially identify the simulated work as characterized in some way means that criteria levels must be built-in from the beginning. The throughput section can be considered a kind of ‘preliminary output’, although it operates more as a ‘labelling’ stage in the workflow.

3.1. Dynamic Motion Elements

Should be identified by the DHM so as to alert the DHM user of motions that involve a risk of muscular overexertion /over-compensation (Buckle and Devereux, 2002; Grant, 1994). This characterization should be related to joint angle motion properties (velocity and acceleration), with alerts shown for the importance of different motion components with regard to specific body regions (Juul-Kristensen et al., 1997; Marras, 1992). The same characterization model could alert the DHM user of the possibility of planning ‘*working rest’* activities[2] (Konz, 1998b), suggesting job variation as a main risk avoidance strategy.

3.2. Repetitive/monotonous work

Should be identified (using categorization criteria) to highlight the consecutive risk distribution over the work sequence. The DHM developer is at liberty to select repetition criteria (or perhaps allow the DHM user to select from a number of options), for which Table 1 in Kilbom (1994) is recommended reading. For the DHM, it is recommended that the ‘amount of sameness’ at the *Motion Elements* level should be quantified to indicate the degree of repetition per body segment. Lack of movement could be considered a special case of repetitiveness (see Moore and Wells, 1992).

3.3. Variation

As an inverse to repetition, variation is an indication of consecutive muscular activities not following a non-cyclic behaviour. Increasing the (muscular) variation should be suggested as an improvement strategy whenever *repetitive* or monotonous work is identified by the DHM. Could appear as a warning alert for simpler software, or be expressed through more sophisticated variation analysis tools such as *EVA* (Mathiassen and Winkel, 1991).
Frequency can be used as an indicator per job task of the work intensity, i.e. interpreted as number of similar *Motion Elements* (muscular activities) in succession. Relates to the highlighting of repetitiveness (see above) and can serve as a short-term criterion for avoiding monotonous task design.

3.4. Exposure

Can be expressed/ quantified in terms of a work-to-rest ratio, as in Konz (1998b). However, it is understood that all previously discussed factors are part of the ‘exposure’ that will be analyzed by the DHM’s analysis tools and that the outputs are expressions of that exposure in terms of its outcomes.

---

[2] I.e. letting the worker switch to another type of work activity involving other muscle groups

3.5. Additional Considerations and Research Gaps

3.5.1. Dynamic 'overcompensation'

Since dynamic activity tends to 'amplify' the joints' experience of loading (Marras, 1992), the DHM could include an 'overexertion function' to simulate the additional muscular force generated by the worker in dynamic loads handling. However, more substantial research is probably needed.

3.5.2. Time perspectives

The resulting effects of the simulated exposure could be 'zoomed' between different time perspectives, giving a possibility of readouts at:

- short-term level (muscular, cycle-to-cycle),
- shift level (one day's work)
- mid-level (exposure over a shift)
- long-term (prognosis from short-term via
- shift-daily basis, to
- career-term (lifetime)

Specifying both short- and long-term risks for each time span could be coupled with suggested strategies at each level for avoiding the risk factor.

4. Output – Consequences of Work Exposure

The outputs of the DHM should bring to the user's attention the risk of effects that may infringe the work performance. These 'warning signs' are part of a spectrum ranging from acute, short-term reactions (such as acute pain, discomfort or fatigue) to long-term developments such as work-related musculoskeletal disorders[3].

4.1. Fatigue

Fatigue appears in different forms (cardio-vascular, skeletal-muscular, mental) and generally diminishes or disables the ability to continue working until a recovery has been made. Fatigue can be greatly accelerated by muscular pain.

4.2. Endurance

Endurance is an expression of how long a worker can continue performing a job without a conscientious break. Endurance time can be calculated, and many body segment-specific models exist (see Table 2, Ma et al., 2009) although the majority of these are static.
For implementation in the DHM, see Dynamic Muscle Fatigue Model and Ergo-Index below.

---

[3] Sudden injury is left out of the discussion here.

4.3. Pause / Rest /Recovery

The purpose of a pause or rest is to achieve recovery, i.e. a fatigued muscle is allowed "metabolic and mechanical recovery" (Colombini, 1998). Calculation of recovery times has been attempted or experimentally determined; The DHM could employ a built-in alert that appears whenever the analysis tools identify too much fatiguing work in succession. The alert could also present recommended pause/break patterns to the DHM user, in the form of a checklist. The guidelines suggested by Konz (1998a) could be implemented as a recommended risk avoidance strategy. Also, Konz's (1998b) concept of Recovery Value can be used to give the DHM user an idea of the effectiveness of the rest (which depends on the initial fatigue when rest begins, the rest duration and what happens during the rest).

4.4. Accumulation/ Cumulative Loading

The way to calculate accumulated loading still requires additional research; calculating load integrals over time has been done before, but the recovery component (i.e. the effect of rests and pauses) of complex, varying work has seldom been taken into account. With the detailed data available from the DHM, those integrals can be calculated with greater precision, but one of the main findings of this review presents the caveat that resting and recovery affects the 'adding up' of cumulative loading.

Judging from the literature, it seems that cumulative loading is very much affected by exposure porosity, i.e. the presence of restorative breaks as part of the work schedule. Also, how to take loading experience in the long term into account is yet unclear. However, some approaches towards quantifying the cumulative load are described below (see 4D WATBAK and EVA below).

4.5. Additional Considerations and Research Gaps

4.5.1. Body-segment specific outputs

In many cases, the most detailed and robust descriptions of 'consequence developments' (such as fatigue / endurance time calculations, etc.) are specifically designed for a particular body part. Rather than opting for generalized models, letting the DHM evaluate the simulated motions against specific body-part criteria should give a better idea of the specific 'warning signs' and potential injury types that the work may result in. For example, endurance-limiting pain arises in muscular rather than joint structures, according to Rose (2001).

4.5.2. Customization towards specific professions

It has been suggested by previous research that different specific vocations entail different repetition and force exertion profiles that criteria for acceptability should be 'tailored' to the situation at hand. The reasons for specific criteria levels would probably become more intuitive for DHM users to understand.

Thus, an area for further work is to enable the DHM to select profession-specific acceptability criteria, which should also help to determine more plausible work-rest distributions that are suitable to the nature of the job.

4.6. Plausible Ergonomics Analysis Methods for DHM Implementation

- Calculation of the *Strain Index* (Moore and Garg, 1995; Bao et al., 2009) for jobs can be made more 'precise' thanks to the data generated by the DHM simulation. Rather than estimate values, the DHM can make use of its time-study capabilities and joint angle data to get dependable values at least for intensity of exertion (amplitude of forceful exertions), duration of exertion, efforts per minute and hand/wrist posture. The remaining factors – speed of work and duration per day – still need to be subjectively ranked or estimated.
- 4D WATBAK (Neumann et al., 1999) allows for shift-long calculation of cumulative load (force-time integrals) on the spine, peak forces in the hands and on the spine. It is already a software application and can easily be transferred to a DHM. It is based on an epidemiological database of risk factors for Lower Back Pain, which may potentially present a data size challenge for the DHM developer. Specification of the full time in a shift is needed (including periods of inactivity). Outputs include peak force instants and levels as well as the cumulative load. The user can then compare generated values with 'threshold limit values' to assess acceptability of ergonomics for the shift. It might be interesting to combine 4D WATBAK's rather straightforward load integration with counteracting data on 'recovery' behaviour (as in Konz, 1998a and 1998b). Another advantage is that it operates from a task-breakdown stance, which makes it compatible with many other analysis tools.
- An 'animated' *EVA* chart (Mathiassen and Winkel, 1991) could be coupled to a moving manikin to provide an evaluation readout in the form of growing distribution bars (each representing 'varied' work types accumulating), as different work actions are executed.
- *OCRA* (Occhipinti, 1998) specifically targets repetitious movement of the upper limbs (where a distinction is made between left and right). It compares the number of actions performed in one day (or shift) with a 'recommended' (maximum) number of actions, and is closely related to the NIOSH Lifting Index (Waters et al., 1993). The presence of certain risk factors that can easily be characterized by the DHM (force, posture, recovery periods etc.) alter the value of the index, which categorizes the work into problematic or non-problematic. It takes into account insufficient recovery time and perceived effort, meaning that there is a subjective component which may require OCRA calculation in a DHM to be based on a motion recording of a real worker, who should also be interviewed to gauge the perceived discomfort.
- *LUBA* (Kee and Karwowski, 2001) is targeted at upper-body loading (hand, arm, neck and back) and is based on discomfort caused by joint motion and maximum holding time. Like OCRA, there is a caveat that the analysis is based on subjectively perceived discomfort, but the joint angle data from the DHM

could prove easily accessible and useful if a similar interview setup as for OCRA is used. Also, LUBA includes a posture classification scheme based on joint angle data.

- *Ergo-Index* (Glimskär et al., 1987; Rose, 2001) is useful as an assessment of lifting, pushing or pulling tasks. It allows for the calculation of recovery time, production time (i.e. work durations + recovery time) and the risk of back injury according to NIOSH criteria levels. Results are adapted to the specified population percentage of the studied worker.
- The algorithm of *Spectral Analysis* described by Yen and Radwin (2000) can be easily transferred to a DHM instead of being used on continuous motion measurements, since the DHM can supply this during the course of the (animated) simulation with high accuracy.
- Ma et al.'s *Dynamic Muscle Fatigue Model* (2009) takes consideration of how external load, workload history and individual differences affect fatigue developments. The caveat with this model is that it requires specification of maximum voluntary contraction, current exertable maximum force and the external load of the muscle (i.e. how much force it need to generate). In other words, the 'current exertable force' needs to be expressed somehow by the DHM. However, Ma et al. (2009) have expressed an ambition to apply their model to a virtual framework including a 'Virtual Human', and thus it can be assumed that a strategy for full implementation exists.

Acknowledgements

This article is written as part of the 4D Ergonomics research project which is carried out within Virtual Ergonomics Centre (www.vec.se) and is financially supported by VINNOVA (the Swedish Agency for Innovation Systems) within the MERA (Manufacturing Engineering Research Area) program under the grant no. 2005-01998 and by the participating organizations (Alviva, Dassault Systèmes, Etteplan, SAAB Automobile, Siemens / UGS and Volvo Car Corporation). This support is gratefully acknowledged.

References

Berlin, C. (2009). Time-Related Factors in Ergonomics Evaluation Part II: a Literature Review and Scientific Basis for the Framework. *Submitted for approval to Applied Ergonomics.*

Bao, S., Spielholz, P., Howard, N., & Silverstein, B. (2009). Application of the strain index in multiple task jobs. *Applied Ergonomics, 40*(1), 56-68.

Buckle, P. W., & Jason Devereux, J. (2002). The nature of work-related neck and upper limb musculoskeletal disorders. *Applied Ergonomics, 33*(3), 207-217.

Colombini, D. (1998). An observational method for classifying exposure to repetitive movements of

Glimskär, B., Höglund, P.-E. & Örtengren, R. (1987). Ergo-Index En beskrivning av ergonomiska effekter. Report in Swedish, TRITA-BEL 0036, LiTH-IERG-R-9, The Royal Institute of Technology, Stockholm, Sweden.

Gilad, I. (1995). A methodology for functional ergonomics in repetitive work. International Journal of Industrial Ergonomics, 15(2), 91-101.

Grant, K. A. (1994). Evaluation of grip force exertions in dynamic manual work. Proceedings of the Human Factors and Ergonomics Society 1, pp. 549-553.

Juul-Kristensen, B., Fallentin, N., & Ekdahl, C. (1997). Criteria for classification of posture in repetitive work by observation methods: A review. International Journal of Industrial Ergonomics, 19(5), 397-411.

Kee, D., & Karwowski, W. (2001). LUBA: An assessment technique for postural loading on the upper body based on joint motion discomfort and maximum holding time. Applied Ergonomics, 32(4), 357-366.

Kilbom, A. (1994). Repetitive work of the upper extremity: Part II - the scientific basis (knowledge base) for the guide. International Journal of Industrial Ergonomics, 14(1-2), 59-86.

Konz, S. (1998a). Work/rest: Part I - guidelines for the practitioner. International Journal of Industrial Ergonomics, 22(1-2), 67-71.

Konz, S. (1998b). Work/rest: Part II - the scientific basis (knowledge base) for the guide. International Journal of Industrial Ergonomics, 22(1-2), 73-99.

Ma, L., Chablat, D., Bennis, F., & Zhang, W. (2009). A new simple dynamic muscle fatigue model and its validation. *International Journal of Industrial Ergonomics, 39*(1), 211-220.

Marras, W.S. (1992) Toward an Understanding of Dynamic Variables in Ergonomics. In: M.R. Cullen, Editor, Occupational Medicine: State of the Art Reviews, Hanley and Belfus, Inc., Philadelphia, pp. 655-677.

Mathiassen, S. E., & Winkel, J. (1991). Quantifying variation in physical load using exposure-vs-time data. Ergonomics, 34(12), 1455-1468.

Moore, J. S., & Garg, A. (1995). The strain index: A proposed method to analyze jobs for risk of distal upper extremity disorders. *American Industrial Hygiene Association Journal, 56*(5), 443-458.

Moore, A. E., & Wells, R. (1992). Towards a definition of repetitiveness in manual tasks. In: Mattila, M., Karwowski, W. (Eds.), Computer Applications in Ergonomics, Occupational Safety and Health, Elsevier, New York,, 401-408.

Neumann et al (1999) 4D WATBAK: Adapting research tools and epidemiological findings to software for easy application by industrial personnel. International Conference on Computer-aided Ergonomics and Safety.

Occhipinti, E. (1998). OCRA: A concise index for the assessment of exposure to repetitive movements of the upper limbs. Ergonomics, 41(9), 1290-1311.

Rose, L. (2001). Models and methods for analysis and improvement of physical work environments. Ph.D. thesis. Chalmers Tekniska Hogskola, (1741), iii+1-50.

Waters, T. R., Putz-Anderson, V., Garg, A., and Fine, L. J. (1993). Revised NIOSH equation for the design and evaluation of manual lift ing tasks. Ergonomics, Vol. 36, No. 7, pp. 749–776.

Yen, T. Y., & Radwin, R. G. (2000). Comparison between using spectral analysis of electrogoniometer data and observational analysis to quantify repetitive motion and ergonomic changes in cyclical industrial work. *Ergonomics, 43*(1), 106-132.