Production Ergonomics

Identifying and Managing Risk in the Design of High Performance Work Systems

W. Patrick Neumann

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Doctoral Thesis
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Department of Design Sciences
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ISSN 1650-9773 Publication 10
ISRN LUTMDN/TMAT-1011-SE

ISBN 91-628-6287-1

Abstract

Poor ergonomics in production systems can compromise performance and cause musculoskeletal disorders (MSDs), which pose a huge cost to society, companies, and afflicted individuals. This thesis presents a research trajectory through the problem space by: 1) Identifying and quantifying workplace risk factors for MSDs, 2) Identifying how these risks relate to production strategies, and 3) Developing an approach to integrating ergonomics into a companies' regular development work.

A video analysis tool for quantifying postures while working was developed. The tools' reliability, accuracy, and ability to identify risks for MSD were evaluated. The tool had generally good accuracy and good to moderate reliability. Low back MSDs were strongly associated with working trunk postures. Operators with high exposure to peak flexion level had 4.2 times higher MSD risk than unexposed operators. Similarly high peak extension velocity increased risk by 2.9 times. (*Paper 1*)

Two pre-post case studies using multiple mixed methods were conducted to examine how production strategies can affect productivity and ergonomics outcomes. The case of electronics assembly, showed how automation can increase output while eliminating repetitive monotonous work. Automation to serial flow, however, resulted in increased repetitiveness at remaining assembly stations. Despite ergonomic workstation design efforts, shoulder loading increased 14%. (*Paper 2*)

The case of engine assembly compared cellular and line production strategies. The line demonstrated system, balance, and disturbance related losses resulting in forced operator waiting. Nevertheless, the line overcame productivity barriers in the operation of the cellular system. The line system showed increased repetitiveness with cycle times that were 6% of previous, uneven distributions of physical tasks such as nut running, and reductions in influence over work scales all implying increased risk. Teamwork in the line system contributed to significantly increased co-worker support – an ergonomic benefit. (*Paper 3*)

An action research project was initiated, with the same engine manufacturer, to integrate ergonomics into regular development work. The change process was slow and marked by setbacks, caused by both individual factors (e.g. disinterest, changing jobs, illness), and organisational factors such as inter-group communication barriers and short project timelines that limited uptake of new approaches. Despite these setbacks the resolute production manager, acting as a "political reflective navigator", was able to establish credibility, overcome resistance, and begin to integrate ergonomics into regular developmental processes. The process remains slow and is vulnerable so long as the manager is navigating alone. (*Paper 4*)

Workplace risk factors can be precisely and accurately quantified. These risks are embedded in strategic choices in the design process. Load amplitudes were determined by workstation layout and the material supply sub-system. Risk related to the pattern and duration of loading are determined more by flow and work organisation elements. Psychosocial risk factors appear to be affected by a combination of system design elements. Managing the emergence of these risks proactively requires attention to ergonomics throughout the design process, especially in strategic choices. Integrating ergonomics into early development stages implies changing roles for groups and individuals in the organisation. This approach appears feasible but is difficult and remains an under-utilised strategy for sustainable competitive advantage.

Keywords:
Production System Design, Strategy, Organisational Development, Human Factors, Musculoskeletal disorders, Manufacturing, Risk Measurement

Sammanfattning

Dålig ergonomi i produktionssystem kan äventyra prestationsförmågan och även orsaka muskuloskeletala besvär (eng. musculoskeletal disorders: MSD). Detta utgör en stor kostnad för samhälle, företag och drabbade individer. Denna avhandling presenterar en forskningsansats att 1) identifiera och kvantifiera arbetsplatsens riskfaktorer för MSDs, 2) identifiera hur dessa risker är relaterade till produktionsstrategier och 3) utveckla ett sätt att integrera ergonomi i ett företags vanliga utvecklingsarbete.

Ett instrument för videoanalys utvecklades för att kvantifiera arbetsställningar. Reliabilitet och indikatorers relation till risk för MSDs testades. Instrumentet hade generellt sett god till måttlig reliabilitet. Besvär (MSDs) i ryggens nedre del var starkt knutna till bålens arbetsställningar. Risken för MSDs hos operatörer med extrem bålflexion var 4.2 gånger högre än för oexponerade operatörer. För operatörer med hög flexionshastighet var risken 2.5 gång högre. (Artikel 1)

Produktivitet och ergonomiskt utfall studerades inom två svenska monteringsindustrier för elektronik respektiv dieselmotorer. Kvantitativa och kvalitativa metoder användes före och efter förändringar av produktionssystemen. Första studien (elektronikmontering) visade hur automation kan öka produktionsvolymen samtidigt som repetitivt och monotont arbete elimineras. Automatisering av transportfunktionen till seriellt flöde resulterade emellertid i ökat repetitivt arbete vid resterande monteringsstationer. Trots försök till ergonomiskt utformade arbetsstationer i designprocessen ökade belastningen på skuldrorna med 14 %. (Artikel 2)

I andra studien (motormontering), jämfördes produktionsstrategierna dock- och linjemontering. Linjen visade på system-, balans- och störningsrelaterade förluster, resulterande i påtvingad väntan hos operatörerna. Emellertid klarade linjesystemet delvis av de produktionsbarriärer som fanns i docksystemet. Vidare linjesystemet visade ökad repetitivitet med cykeltider som bara var 6% av docksystemet. Dessutom varierade rent fysiska arbetsuppgifter på linjesystemet mycket, exempelvis mutterdragning. På psykosocial nivå upplevde operatörna en minskning av inflytande över arbetet. Sammantaget pekar dessa faktorer på ökad MSD-risk jämfort med docksystemet. Dock ökade arbetsgemenskapen i linjesystemet, som hade en team-baserad arbetsorganisation, vilket är en ergonomisk fördel. (Artikel 3)

I syfte att integrera ergonomi i det vardagliga utvecklingsarbetet initierades ett aktionsforskningsprojekt på fabriken för motormontering. Förändringsprocessen var i början långsam och kännetecknades av bakslag, orsakade både av individuella faktorer (ointresse, byte av arbete, sjukdomar, osv) och organisatoriska faktorer såsom kommunikationsbarriärer mellan grupper och korta tidsfrister i projektet. Detta begränsade införlivandet av nya arbetssätt. Trots dessa bakslag lyckades produktionsledaren, agerande som en "politiskt reflektiv navigatör", etablera trovärdighet, övervinna motstånd och påbörja en integrering av ergonomi i vardagliga utvecklingsprocesser. Processen var långsam och känslig även då projektet avslutades, därför att ledaren fortfarande var ensam om att navigera. (Artikel 4)

Avhandlingen konkluderar att arbetsplatsrelaterade riskfaktorer kan kvantifieras precist och tillförlitligt. Dessa risker är inbyggda i de strategiska valen i designprocessen. Belastningens storlek påverkades av utformningen av arbetsstationen och materialförsörjningssystemet. Tidsaspekter av belastning påverkades av systemflödesstrategien och arbetsorganisationen. Psykosociala riskfaktorer visade sig vara kopplade till en kombination av ovan nämnda element i systemutformningen. För att förebygga MSD-risker måste man ta hänsyn till ergonomi i hela designprocessen – tidigast besluten är ofta de viktigast. Integrering av ergonomi i tidiga utvecklingsfaser innebär förändrade roller för grupper och individer i organisationen som normalt inte uppfattar sig som ”ergonomer”. Utveckling av dessa roller är viktig för skapandet av hållbara produktionssystem.

Sökord:
Utformning av Produktionssystem, Organisationsutveckling, Mänskliga faktorer, Muskuloskeletala besvär, Tillverkning, Riskmätningar

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Thesis Papers

Paper 1

Neumann, W. P., Wells, R. P., Norman, R. W., Kerr, M. S., Frank, J., Shannon, H. S., and the OUBPS working group (2001). **"Trunk posture: reliability, accuracy, and risk estimates for low back pain from a video based assessment method."** *International Journal of Industrial Ergonomics*, 28, 355-365.

Paper 2

Neumann, W. P., Kihlberg, S., Medbo, P., Mathiassen, S. E., and Winkel, J. (2002). **"A Case Study evaluating the ergonomic and productivity impacts of partial automation strategies in the electronics industry."** *International Journal of Production Research, 40(16), 4059-4075.*

Paper 3

Neumann, W. P., Winkel, J., Medbo, L., Mathiassen, S. E., and Magneberg, R. **"Productivity and ergonomics in parallel and serial flow production."** *Submitted for peer review.*

Paper 4

Neumann, W. P., Ekman Philips, M., and Winkel, J. **"Integrating ergonomics in manufacturing system development - Moving from reactive to proactive."** *Submitted for peer review*

1 INTRODUCTION

1.1 Topic Under Investigation

The problem under study in this thesis is the occupational source of work-related musculoskeletal disorders (MSDs). The opportunity under study is the ability of an organisation to apply knowledge about humans, 'Human Factors' or 'Ergonomics' (IEA Council, 2000), to create high performance work systems that are effective, profitable, and healthy workplaces. These two aspects – the human health, and the system performance – are central to the research approach of the 'Production Ergonomics' group at the National Institute for Working Life West in Gothenburg Sweden, from which this thesis emerges. It is through the joint optimisation of these two aspects that sustainable development can be achieved.

This thesis presents a 'systems' framework and new data for understanding how MSDs can emerge as an unintended result from the design of a work system. Four research papers are used to study the following problems:

1. How can one identify and quantify risk factors for MSD? (Paper 1)
2. How are risk and other productivity factors related to core 'strategic' elements in the design of the production systems? (Papers 2 & 3)
3. How can an organisation best integrate ergonomic considerations into their daily development processes? (Paper 4)

> **"Ergonomics (or human factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimise human well-being and overall system performance"**
>
> \- International Ergonomics Association, 2000

1.2 System Model

A 'system' model is proposed to help understand how ergonomics is handled in production system development and what consequences this has for MSDs and productivity.

A simplified system model describing the chain of events that can lead to work-related musculoskeletal disorder is illustrated in Figure 1. Skyttner defines a system as 'a set of interacting units or elements that form an integrated whole intended to perform some function' (Skyttner, 2001). This model builds on previous work, which identified relevant factors for ergonomic intervention at the level of the community, the company, and the individual worker (Hagberg et al., 1995; Mathiassen and Winkel, 2000; Westgaard and Winkel, 1997; Winkel, 1992). The model presented here focuses more explicitly on the chain of events that ultimately result in MSDs.

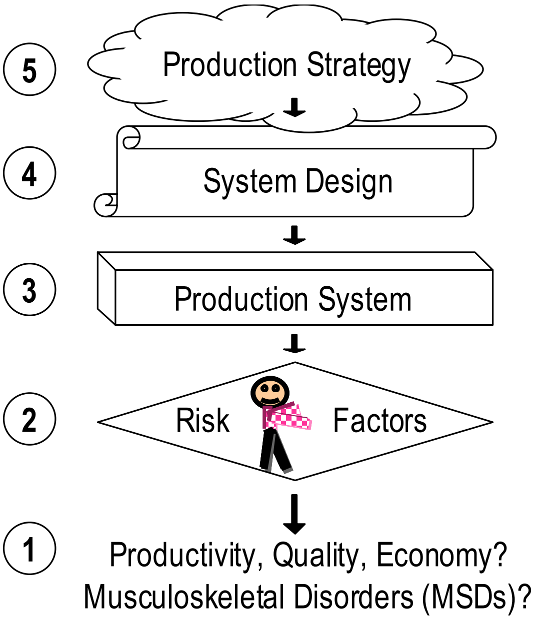


Figure 1: *A simplified systems model for analysing the development of musculoskeletal disorder (MSDs) in a work system. The company's development process can be seen to begin with conceptual choices of production strategy (5), followed by the design stage (4) to the eventual implementation of the production system (3). Production system operators are then exposed to the physical loads and psychosocial working conditions within the system that determine risk for MSD (2). The system outputs (1) include, for example, productivity and quality and also, as a side effect, MSDs.*

I will describe this model from the bottom (outputs, 1) to the top (strategy, 5) and then briefly also discuss the contextual issues related to the individual, company and society levels which can both affect MSD outputs (at 1) but can also affect how the system might react to intervention attempts.

1.2.1 System Outputs

Authors such as Oxenburgh (1991; 2004) have described in detail how health and safety in general can contribute to a firms financial performance. For the purposes of this thesis system outputs are assigned two categories: Musculokeletal disorders, and Productivity.

1.2.1.1 Musculoskeletal Disorders

Musculoskeletal disorders (MSDs) at work are a persistent problem in industrial nations costing a lot of money and causing much suffering. MSDs are an unintended output of many work systems.

In 2003 Sweden's total costs for work related sickness and absence were over 110 billion Swedish crowns (SEK) – an increase of almost 50% in just 4 years**.** The economic costs alone for work related ill health have been estimated by some European nations at between 2.6% and 3.8% of gross national product with about half of this cost being attributed to MSDs (EASHW, 2000b). In the US over 1 million people annually seek medical treatment for Back and upper limb MSDs and *"Conservative estimates of the economic burden imposed, as measured by compensation costs, lost wages, and lost productivity, are between $45 and 54 billion annually"* (NRC and Panel on musculoskeletal disorders and the workplace, 2001). Poor ergonomics in manufacturing not only results in direct costs associated with injury treatment and compensation, but also in indirect costs related to factors such as absenteeism, costs of administration, employee turnover and training, poor employee morale, as well as reduced productivity and quality (Alexander and Albin, 1999; Oxenburgh et al., 2004; WSIB, 2001). Indirect costs may be several times greater than direct costs and are often not measured by companies (Hagberg et al., 1995), which may lead them to underestimate the scope of the problem. For

> **"…in 1997, the overall economic losses resulting from work-related diseases and injuries were approximately 4% of the *world's gross national product.*"**
> **-** World Health Organisation 1999

the afflicted workers the consequences of injury are much more personal and include reduced physical, psychological and economic well being (Pransky et al., 2000; Tarasek and Eakin, 1995). While much research has been done on intervening to reduce MSDs in the workplace (Westgaard and Winkel, 1997) the problem appears to be continuing, arguably, unabated.

Work related musculoskeletal disorders (MSDs) are a heterogeneous group of disorders that, by definition, have a work-related cause and can include a broad range of body parts and tissues (Hagberg et al., 1995). MSDs are also difficult to diagnose with precision (Van Tulder et al., 1997). In the model presented (figure 1) MSDs form the final outcome of a chain of events over the course of the development of the production system. These disorders can be seen as unintended side effects of the production system that have negative consequences both for the operator and for system performance. This thesis focuses specifically on musculoskeletal disorders which form the single most expensive work related ill health category (WHO, 1999). The solution pathway for MSDs deals with many of the same issues that must be handled when trying to solve other work-related health problems. Thus we use MSDs as a kind of 'model' that might be applied more generally to other problems as well.

1.2.1.2 Productivity and Quality

Production systems are designed to maximise profits through productivity or quality outputs. This focus often excludes human factors.

There is increasing awareness of the strategic value of ergonomics for companies (Dul, 2003b). Konningsveld (2003) has described how ergonomics can be integrated with core business performance such as productivity, lead-time, reliability of delivery, quality, and flexibility. Recent research in the quality field suggests that around 30-50% of quality deficits are related to poor ergonomics (Axelsson, 2000; Drury, 2000; Eklund, 1995; Lin et al., 2001). The high rate of failure of manufacturing initiatives (Clegg et al., 2002) has also been associated with failures to accomodate human factors (Nadin et al., 2001). Under these circumstances it should be easy to justify ergonomics since multiple objectives

> **”…the time required for the task and the postural deficiencies were together able to account for 50% of the quality variance on each assembly line”** - Lin et al. (2001)

are achieved simultaneously. The case for productivity can be more difficult since the most obvious way to increase productivity is to simply make the production system operators work faster, thereby increasing MSD risk. Nevertheless economic analysis can demonstrate how profitability can be enhanced through better health and safety (Aaras, 1994; Hendrick, 1996; Oxenburgh et al., 2004).

In this thesis I argue for a joint optimisation approach whereby humans and other key system elements are simultaneously considered so that globally optimal solutions to the production problem can be developed. Achieving this in practice is, proverbially, easier said than done.

1.2.2 Risk Factor Exposures in the Production System

Many risk factors for MSDs, including physical and psychosocial factors, have been identified. Being able to measure risk factors is important as these act as *leading indicators* – allowing potential intervention before MSDs occur.

The exposure of production operators to risk factors (level 2 in the model in Figure 1) is an inescapable part of work. If ergonomic conditions are good risk will be low. That working postures and forces can cause musculoskeletal disorders has been known for over 300 years (Ramazzini, 1700). Nevertheless the last quarter of the 20th century saw a tremendous amount of research on the physical and psychosocial risk factors for MSDs and a number of excellent reviews exist (Ariens et al., 2000; Bernard, 1997; Bongers et al., 1993; Buckle and Deveraux, 1999; Buckle and Deveraux, 2002; de Beek and Hermans, 2000; Hoogendoorn et al., 2000b; Malchaire et al., 2001a; Netherlands, 2000). More recent epidemiological studies continue to corroborate these reports and enhance our understanding of the relationship between workplace demands and MSDs to the back (Hoogendoorn et al., 2000a; Hoogendoorn et al., 2001; Kerr et al., 2001), neck (Ariens et al., 2001a; Ariens et al., 2001b), neck & shoulder (Fredriksson et al., 2000; Östergren et al., 2001); and hand-wrist (Malchaire et al., 2001b). Conceptual models of MSD onset mechanisms have been developed (Armstrong et al., 1993; Kumar, 2001; McGill, 1997; NAC et al., 2001) that generally account for risk from high peak loads (Neumann et al., 1999c) as well as the accumulation of load or prolonged loading (Kumar, 1990; Kumar, 2001; McGill, 1997; Norman et al., 1998). Long exposure to very low amplitude load, or low variation repetitive movements, have also been associated with MSDs (Hagberg et al., 1995; Hägg, 1991; Westgaard, 1999; 2000; Winkel, 1985). These low level risks can be aggravated by poor psychosocial conditions, themselves an independent class of risk factor (Bongers et al., 1993; Karasek and Theorell, 1990; Kerr, 1997).

Utility of Quantifying Risk Factors: Identifying and quantifying risk factors may help understand how to prevent the emergence of these factors when production systems are created. Quantification of the factors associated with MSD is a useful approach to identifying potential problems before injury occurs – they present leading indicators of MSDs (Cole et al., 2003). Precise quantification can be used to provide specific design criteria to designers of the production system (Wulff et al., 1999a) as well as to help find solution pathways for problems identified in existing systems (Norman et al., 1998). Quantification of hazards can also act to build credibility in the negotiation of constraints for new designs (Perrow, 1983) and has potential to support the integration of ergonomics with other performance elements in the production system design process.

> **"It has been difficult to find the best compromise between the precision and cost of direct measurement exposure and the loss of precision and accuracy of less expensive ...methods."** - Armstrong et al. 1993

Research Challenge: Measuring posturally related MSD risk factors poses an important measurement challenge (Burdorf, 1992; Burdorf and Laan, 1991). A number of approaches to risk factor quantification have been proposed including self report questionnaires, observational techniques and direct technical measurements (Mathiassen and Winkel, 2000; Neumann et al., 1999c; Van Der Beek and Frings-Dresen, 1998; Wells et al., 1997). Questionnaire approaches have not proven to be reliable (Burdorf and Laan, 1991). Observational techniques often try to account for the amount of time spent in particular posture categories (Neumann et al., 2001a; Punnet et al., 1991) but rarely capture the time-history of movement. Instrumented measurement approaches have identified movement velocities as a risk factor (e.g. Hansson et al., 2003; Marras et al., 1995), but are relatively expensive and require specialised training to operate. An approach is needed that can be used without special electronic equipment or educational requirements. Recently, video approaches have been developed to help workers identify and communicate specific physical workload related tasks (Kadefors and Forsman, 2000) and psychosocially problematic aspects of work (Johansson Hanse and

Forsman, 2001). While helpful, these approaches do not provide data on specific physical load demands, nor the dynamic or time aspects of working postures. Video analysis has potential for this kind of analysis although reliability, accuracy, and the indicators with best risk-predictive capability would need to be determined.

Paper 1 in this thesis presents a video-based approach to the quantification of posture-related risk factors for low back pain (LBP). In this study we tested the reliability, accuracy, and risk-relationship of indicators resulting from this measurement tool.

1.2.3 The Production System

Risk factors for MSD are related to the design of the production system and the nature of the work performed.

By production system I refer primarily to an operating system that manufactures a product (Wild, 1995) although many aspects of this discussion could also apply to other kinds of operating systems such as service provision. Risk factors emerge from the interactions between the individual operators and other elements (machines, materials) in the production system (Peterson, 1997). The production system has been described as a sociotechnical system with technical and social subsystems (Eijnatten et al., 1993).

> **"…production systems should be designed as tools for the shop-floor employee, that these employees are trained and motivated to use their judgment and abilities, and that such systems are organised for continuous innovation and market exploration. "**
>
> - Badham et al. 1995

It is the nature of the work itself that will primarily determine the operators' mechanical exposure profile (Allread et al., 2000; Kerr, 1997; Wells et al., 1999). The design of the system therefore will provide a number of performance constraints for the worker who must perform within the assigned parameters. From this perspective the design of the work becomes a critical element in determining the loading pattern, and hence injury risk. Many risk factor studies have focussed on operator aspects, such as posture or lifting activities (Bernard, 1997), fewer studies have identified risk associated directly with production system performance features such as cycle time (Silverstein et al., 1987). Mathiassen and Winkel (1996) found that reductions in work pace, controlled using the engineering methods-time-measurement (MTM) system, were associated with similar reductions in muscle activity, heart rate, perceived effort, and muscle tenderness. Bao et al. (1997) have shown that well balanced production lines with fewer production irregularities result in higher movement rates, increased time-density of muscle activation, and hence decreased tissue recovery time than less well balanced systems. These few studies suggest that risk factors in the realised production system are related to the design of the system itself. Where in the design process risk emerges does not appear to be well understood.

Papers 2 & 3 in this thesis both examine production systems that have undergone redesign after changes production strategy.

1.2.4 Ergonomic Impact of Production System Design

The production system itself is the product of a design process. The design process will shape the eventual production system which, in turn will determine MSD risk factor levels for system operators.

The design of the production system is divided into two main areas of concern: 1) the setting of production strategy, primarily the responsibility of corporate management, and 2) the system design process itself (Figure 1). Understanding the design process provides a first step to understanding how designers deal with ergonomic factors in their work.

Production system design decisions are made within the context of the direction established by the corporation's production strategy. Very few studies have examined this process with regards to ergonomics. Skepper et al. (2000) have described a deliberately simplified design process with a linear series of stages with iterative elements. In the case of product design, the process has been shown to be neither rational nor linear but instead represents a complex organisational process involving uncertainty, iteration, and negotiation (e.g. Broberg, 1997). Burns & Vincente (2000), examining control station design, have described the negotiation process involved in resolving the web of design constraints which often conflict. Designers of complex systems can face an overwhelming number of criteria and constraints and conflicts must be resolved based on personal interpretation as well as the influence of other stakeholders (Wulff et al., 2000; Wulff et al., 1999a; b). In this context, knowledge of ergonomic factors in design decisions does not necessarily guarantee their implementation, especially when these are seen as 'soft' or 'vague' criteria which are difficult to verify or demonstrate (Wulff et al., 2000; Wulff et al., 1999b). Even when ergonomic factors are applied to a local design aspect this does not guarantee success because locally optimal ergonomic design do not necessarily result in globally optimal solutions in the resulting system (Burns and Vicente, 2000). There has been little systematic documentation regarding the relationships between decision-making at this level and the emergence of MSD risk factors in the production system. Indeed it seems that there is generally a lack of feedback to designers about problems that emerge in the systems that they design:

> *"Short of a well publicised catastrophe, the design engineer will probably never know the consequences of his or her design, and top management will only hear of it faintly and perhaps not until the next project is already under construction."* (Perrow, 1983)

For this reason the model makes explicit the production strategies chosen in the development of the new system.

1.2.5 Production Strategy as an Ergonomic Determinant

Strategic choices in design may be a root source of MSDs. Production system designers react to strategic priorities set by senior management. Strategic thinking sets the stage for system design and eventual MSD risk factor patterns.

Some 75 years after Ramazzini began writing on the medical consequences of poor ergonomics (although the word "ergonomics" was not coined until 150 years later by Jastrzebowski in 1857 (Koradecka, 2001)), Adam Smith described the productivity benefits he observed in of the division of labour (Smith, 1776). By the twentieth century authors such as Taylor (Taylor, 1911) had extended the idea of division of labour into a strategy of 'Scientific management" whereby the work of assembly was atomised into minute tasks with each worker repeating their task many times. This strategy set the foundation for the modern assembly line as first realised by Henry Ford in his car factories (Ford, 1926). Since the time of Taylor we have seen a vast array of production strategies presented and discussed in both scientific and popular literature. Some of these, such as the famous 'lean manufacturing' (Womack et al., 1990), or 'reflexive production' (Ellegård et al., 1992), may really be thought of as a collection of strategic elements intended to work in concert. In this thesis I emphasise the importance of *'production strategy'* (at level 5 in the model in figure 1) because these reflect fundamental choices early in the development process that set the stage for risk factor patterns in the resulting system. Production strategies, I argue, present the seeds from which operators' MSDs can result. Compared to the volume of research around risk factors very little is known about production strategies from an ergonomics perspective.

> **"The greatest improvement in the productive powers of labour… seem to have been the effects of the division of labour"** *- Adam Smith (1776)*

Strategy is a broad and imprecise term. Mintzberg (1987) characterised strategy as a plan, a pattern, a position, a ploy, or as a perspective. Manufacturing can include a number of the characteristics outlined by Mintzberg (1987). 'Just In Time' (JIT), for example, has been termed a philosophy that incorporates a number of more specific strategies (Gunasekaran and Cecille, 1998) such as reduction in buffer sizes, and fast change-over. The extent to which a strategy is realised in practice may vary (Ghobadian and Gallear, 2001; Womack et al., 1990), with the gap between strategy and practice being apparently a more important indicator of (poor) performance than the strategy itself (Rho et al., 2001). It is difficult therefore to determine the ergonomic consequences of production strategies directly without considering the specific implementation for each case . Winkel & Aronsson (2000) have discussed the strategic objective of 'flexibility' with respect to potential ergonomic impacts in a number of performance areas. Reviewers suggest that some production strategies, such as business process reengineering, may provide better potential for good ergonomics than do other strategies, such as lean manufacturing (Björkman, 1996; Eklund and Berggren, 2001). Like other design decisions, strategies can be difficult to isolate and cannot always be directly measured but must be inferred from observation. Strategic decisions regarding manufacturing approaches occur relatively infrequently and are most obvious during the development of a new production system that may then operate for a number of years.

Health consequences of different production strategies are not well understood although the linkages between these strategies and ergonomics is readily apparent (Björkman, 1996). Vahtera et al. (1997) have found MSD risk to increase by 5.7 times during ‘corporate downsizing’. The individuals’ perception of the downsizing process itself also appears to affect health (Kivivmäki et al., 2001; Pepper et al., 2003). Landbergis et al. (1999), in their review of available literature, noted increased negative health outcomes are often associated with the adoption of Lean Manufacturing approaches. Karltun et al. (1998) found signs of increased physical loading with the implementation of ISO 9000 standards. Looking at more specific system design elements Coury et al. (2000) have demonstrated increased physical risk with partial automation strategies which couple workers more tightly to the production system. An increasing number of studies are finding risk increases with the adoption of line-based production approaches (Fredriksson et al., 2001; Neumann et al., 2002; Ólafsdóttir and Rafnsson, 1998). On the positive side, Kadefors et al. (1996) found that ergonomics improved in the application of long-cycle parallelised assembly flows without sacrificing productivity. This small but growing body of research demonstrates how higher level strategic decisions can result in increased, or decreased, MSD risk for employees. Nevertheless, not enough is known to develop tools by which industrial stakeholders can judge the ergonomic consequences of their decisions.

Research needs

In papers 2 & 3 in this thesis we attempt to isolate ‘strategic’ production *elements* that form a critical role in shaping the production system. By dealing with specific strategic design choices we attempt to move beyond the ‘lean’ ‘not-lean’ dialectic initiated by Womack et al. (1990). It is in the early stages of design that the greatest lattitude for good ergonomics exist while the system concept is still malleable (Burns and Vicente, 2000; Engström et al., 1998; Imbeau et al., 2001; Kilker, 1999). Early design choices allocate the majority of project resources and set critical initial design constraints (Buur and Andreasen, 1989; Wild, 1995). While design choices at subsequent stages in the design process may affect MSD risk these are generally less expensive to retrofit, and are thus possible targets for shop floor level improvement schemes such as participatory ergonomics (Haimes and Carayon, 1998; Haines et al., 2002; Nagamachi, 1995; Noro and Imada, 1991). Strategic design elements, however, tend to be ‘locked in’ and thus pose critical decisions with regards to ergonomics. The relationship

> **“One of the main difficulties faced by ergonomists is that their contribution is generally solicited too late in the design process”** *- Imbeau et al. 2001*

between ergonomics, productivity, and these strategic design choices is not well understood and poses a critical research need.

Papers 2 & 3 explore the relationship between 'strategic' production system elements and their consequences for productivity and ergonomics in the resulting system.

1.3 System Contexts

When considering the system model's structure or behaviour, recall that influential factors can come from societal, organisational, and individual levels.

Figure 2 presents a simple model of the context in which decisions are made by individuals in the system modelled in Figure 1. In this simplified model I present just three contextual levels: Society, Organisation, and Individual. This is consistent with other available models (Hatch, 1997; Mathiassen et al., 2000; Moray, 2000; Rasmussen, 1997).

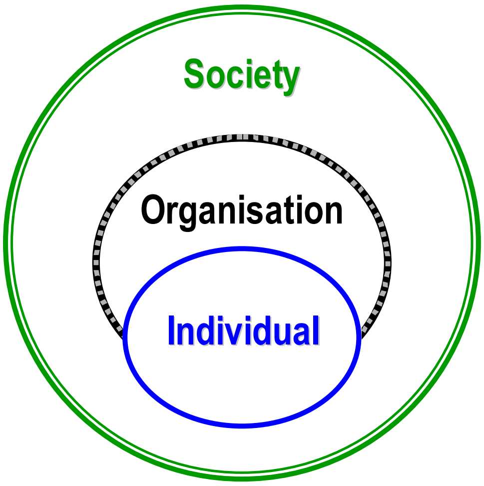


Figure 2: *A contextual model for the theoretical framework (in figure 1) identifying individual, organisational and society levels which will influence the development system's behaviour and response to intervention.*

1.3.1 Societal Context of Ergonomics

Companies are acting in a society with particular market conditions, legislation, and cultural attitudes. These forces create the context in which the organisation operates and can influence ergonomics.

Social contexts influence selection of production models (Boyer and Freyssenet, 2002), and influence change processes (Bamford and Forrester, 2003). Current social trends of relevance for ergonomics may include: rapid pace of change – with technology changing faster than management structures, increasing scale of industrial operations (globalisation), integration of operations (with tight supply chains), aggressive competition, work intensification, and deregulation (D'Aveni, 1994; Docherty et al., 2002; Mergler, 1999; Merllié and Paoli, 2000; Moray, 2000; O'Neill, 2000; Paoli and Merllié, 2001; Rasmussen, 2000; St.John et al., 2001).

This thesis does not specifically study social factors. Nevertheless, companies are social institutions (Hatch, 1997) and design is a social process that plays out in an array of conflicting interests (Gustavsen et al., 1996) and is thus inherently (micro) political (Broberg, 1997; Engström et al., 1998). Organisations and individuals both act on and are acted upon by their social environment.

1.3.2 Organisational Context of Ergonomics

How a company responds to an intervention effort will depend in part on the structure and culture of the organization. These factors can also influence how well human factors are incorporated in production system design.

The developmental model presented (Figure 1) is embedded in an organisation. Organisations have many features including a social structure, organisational culture, physical structure, technology, and strategic profile (Hatch, 1997), each of which can influence developmental and change processes.

From an interventionist perspective, involvement of a broad range of stakeholders in the organisation has shown good promise for effective ergonomics development (Gustavsen et al., 1996; Westgaard and Winkel, 1997). Securing support of these stakeholders may require an attempt to 'solve ergonomics problems in a profitable way' (Winkel and Westgaard, 1996). By emphasising the interconnectedness of ergonomics and productivity it may be possible to 'jointly optimise' these two output domains – an approach advocated by a growing number of researchers (e.g. Burns and Vicente, 2000; Clegg, 2000; de Looze et al., 2003; Gustavsen et al., 1996; Hendrick and Kleiner, 2001; Huzzard, 2003; Ingelgård and Norrgren, 2001). Achieving this is a problem of organisational change – an entire field of study itself (Hatch, 1997). Saka (2001), among others, has pointed out the organisational complexities here:

> *"The heavy emphasis in the literature on a rational-linear approach to understanding organisational change overlooks the significance of the cultural and political dimensions of organisational life."* - (Saka, 2001)

This irrational nature of organisational change might even be exacerbated by an organisation's own psychotic tendencies (De Vries, 2004). Broberg and Hermenud (2004) have also emphasised politicality suggesting that ergonomists need to act as 'political reflective navigators' as they attempt to negotiate priorities in a company's development projects amongst a network of different actors. Organisational actors such as production engineers tend, for example, to have no social mandate (Ekman Philips, 1990), to have little ergonomics training (Neumann et al., 1999a), and can be technology focussed (Kilker, 1999) which can provide a tremendous contrast to the ergonomist's own context.

1.3.3 Individual Contexts of Ergonomics

How individuals respond to the work demands will depend on their role in the company and their physical and mental capacities. We humans are only partially rational.

'Individuals' in this model are everywhere in the organisation – not just the production operator. The operator is important and individual tolerance to some physical load patterns vary with individual characteristics (Kilbom and Persson, 1987; NAC et al., 2001; NRC and Panel on musculoskeletal disorders and the workplace, 2001), and tolerance may be successfully improved (Westgaard, 2000; Westgaard and Winkel, 1997). This model attempts to highlight he role of all the stakeholders in the organisation who might influence the development process – and thus MSD risk factors – in the organisation. When dealing with a specific individual the arch types from general analysis (Ekman Philips, 1990; Neumann et al., 1999a) may not apply fully – the practitioner must be open to the uniqueness of the individual. Furthermore, humans tend to operate within a 'bounded' rationality (Schwartz, 2002); implying a certain amount of irrationality, or non-linearity, in the entire system (Guastello, 2003; Skyttner, 2001).

"When individuals are not involved in establishing their goals, they are much less likely to feel motivated to achieve them than when they are allowed to participate in the process" - *Hatch 1997*

1.4 The Challenge of Intervention in a Complex System

To be most effective ergonomic considerations should be a natural part of the development process focussed on improving total system performance. This is easier said than done.

While the system under study is complex (Backström et al., 2002; Guastello, 2003), research tends to be conducted along traditional academic lines. The problem, as Rasmussen (1997) points out, is that there is very little research that spans the problem domain. Since there are non-linear and dynamic connections between system elements, the models generated by different academic disciplines cannot be simply stuck together. Greenwood, from the social sciences, rails against this problem:

> *"The world does not deliver social problems in neat disciplinary packages, despite the pathetic insistence of most academic social scientists in defending their academic turfs against all other forms of knowledge"* (Greenwood, 2002).

What is needed, according to Rasmussen (1997), are 'vertical' studies of the system behaviour that engage a broad range of skills and perspectives. This is proving difficult as there is almost no attention to ergonomics, for example, in the management literature (Dul, 2003a) and the incorporation of management science perspectives in ergonomics may be similarly absent.

"…effective risk management strategies cannot be developed by the integration of the results of horizontally oriented research within the various disciplines… Instead vertical studies of the control structure are required." *- Rasmussen (1997)*

Despite many successful ergonomics case studies (Aaras, 1994; Abrahamsson, 2000; EASHW, 2000a; GAO, 1997; Hendrick, 1996; Kemmelert, 1996; US Federal Register, 2000) researchers have generally had difficulty demonstrating consistent effects when trying to intervene in businesses for better ergonomics (Westgaard and Winkel, 1997). Karsh et al. (2001) have expressed the problem thus:

> *"A pressing problem that has plagued ergonomic intervention research is the lack of understanding as to why seemingly identical interventions work in some instances but not in others... We propose that research pay special attention to various implementation approaches to ergonomic interventions."* (Karsh et al., 2001)

From an organizational change perspective this is a classic problem, and from a systems perspective this is hardly surprising. Growing evidence (Burnes, 2004; Clegg et al., 2002) indicates that 50-75% of organisational change efforts and attempts to implement advanced manufacturing processes are not successful. Researchers are suggesting that these failures relate less to technical failures than to failures to accommodate people (Badham et al., 1995; Das, 1999; Nadin et al., 2001) – an example of how poor ergonomics can undermine system effectiveness.

Researchers in both organisational development and ergonomics communities point out that "ergonomic" interventions engaging a broad range of organisational actors who own the process show most promise for success (Gustavsen et al., 1996; Westgaard and Winkel, 1997). Similarly Bamford and Foster (2003) point out that:

> *"In today's business environment, one dimensional change interventions are likely to generate only short term results and heighten instability rather than reduce it."* (Bamford and Forrester, 2003)

Considering the time dimensions of change Bateman and Rich (2003) claim that:

> *" 'Point Changes' without sufficient infrastructure to support improvements, at the business level, are unlikely to yield real and sustainable change."* (Bateman and Rich, 2003)

Considering this evidence we see a need to integrate ergonomics into the development process to avoid the expense and delay of retrofitting processes. In order to avoid 'one dimensional change' it may be helpful to emphasise the performance benefits along with the health benefits of good ergonomics (Dul, 2003b; 2004). Figure 1.4 provides an illustration of how design may lead to a doube-win, or synergy effect, if productivity and ergonomics goals are optimised jointly for increased total system performance (Gustavsen et al., 1996; Huzzard, 2003). If increasing the engagement of personnel in human factors is not to be a 'point change' then an evolutionary seems appropriate to accommodate the time needed to change organisational practice. In order to support better management of human factors throughout the development process, particularly in the early stages of development, we see a need to improve utilisation of leading indicators of MSDs, such as risk factors, in the design process. Achieving this will require 1) tools by which risk can be identified and quantified, 2) an understanding of how and where risk emerges in the design process, and 3) development of the design process itself so that ergonomic issues are actively managed and integrated with technology concerns throughout the process.

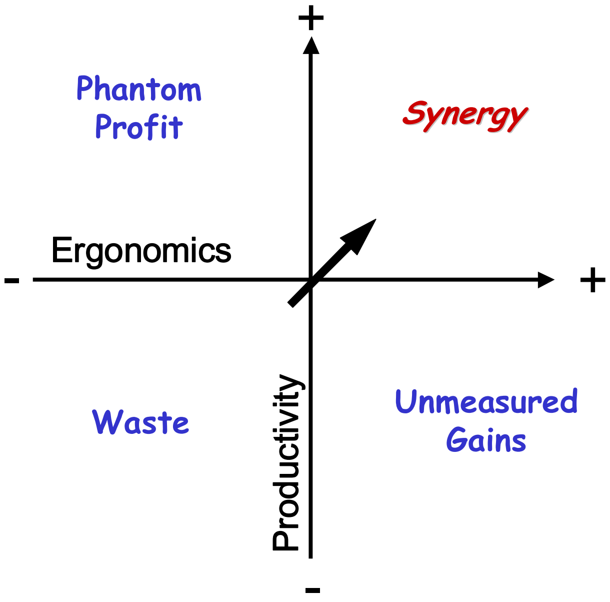


Figure 1.4: *A simple 2 dimensional model illustrates how a 'navigator' can attempt to steer development. A synergy effect may be achieved if ergonomics and other productivity aspects are optimised jointly (top right). Although good ergonomics may have 'hidden' gains not immediately visible in productivity data (bottom right), poor ergonomics may compromise anticipated productivity - phantom profit (top left).*

1.5 Thesis Papers & Research Aims

This thesis incorporates four (4) journal articles that study vertical linkages in the model (figure 1). First the ability to identify risk before MSDs occur is addressed. Then the sources of risk in production system development are explored. Finally an attempt to integrate human factors into regular development work is studied.

1. The aim of paper #1 was to develop and evaluate a video based tool for quantifying postural factors at work in terms of inter-observer reliability, accuracy, and association with risk of reporting low back pain at work. This paper illustrates the relationship between risk factors and MSDs illustrated at the bottom of the theoretical model (figure 1: level 2 to level 1 linkage).

2. The aim of paper #2 was to examine the productivity and ergonomics consequences of a strategic redesign of a production system. In this case automation of assembly and automatic serial-flow strategies were implemented in electronics assembly. In this study we attempt to link high-level system elements (strategy) to lower levels (risk & output levels) in the system model (Figure 1: level 5 to level 2 & 1 linkages).

3. The aim of paper #3, similar to paper 2, was to examine productivity and ergonomics consequences of a change in production strategy from a long-cycle parallel flow workshop to a serial flow line assembly. Here, as in paper 2, we make a 'vertical' analysis through the development system (Figure 1: level 5 to level 2 & 1 linkages).

4. The aim of paper #4 was to investigate how ergonomics might be integrated into a company's regular development process, with special focus on barriers and assists to achieving such integration. This study focuses on the organisational level (Figure 2) and includes the entire development process (Figure 1).

2 METHODS

2.1 Paper 1: A Tool for Quantifying MSD Risk Factors

Paper 1 describes the development and evaluation of a video-based tool to track working postures. The relationship of postural indicators to risk was then quantified by comparing workers with and without low back pain.

The Measurement tool (Figure 2.1) uses videotapes that can be recorded in the field without interfering with the operator. The section of video to be analysed is first digitised and stored on the computer. The analyst then controls playback speed while recording trunk flexion-extension and lateral bending position on continuous scales using a joystick. Twisting postures were recorded using a binary on-off scale and was considered present whenever the line between the shoulders was angled more than 20 degrees from the line between the hips. During analysis the computer would sample the joystick (or keyboard) input device once for every frame of video while providing feedback to the analyst with a mannequin image. The system provides a continuous time-history of posture, visually synchronised to video, from which exposure parameters relating to flexion amplitude, duration of flexed postures, and flexion velocity can be extracted.

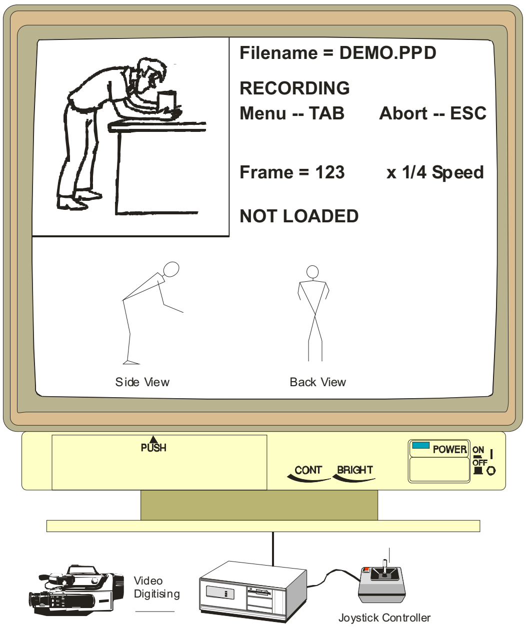


Figure 2.1: *Video analysis system in which field recorded video is digitised and then analysed using a joystick to track posture.*

The inter-observer reliability of the system was assessed by having seven (7) trained observers analyse video from the same ten (10) production jobs. The jobs were selected from the epidemiological study database to include the variety of work observed in the field. The inter-observer reliability data were analysed using intra-class correlation coefficients (ICC) to provide indexes of similarity between observers relative to the range of job exposures observed (Shrout & Fleiss, 1979).

System accuracy was determined by comparison to a laboratory based optoelectric reference system that was considered a 'gold-standard'. Eight (8) trained analysts each analysed the same 1 minute video which had been recorded synchronously with the referent system. Comparisons between the video and referent systems were made for both the time series data and for the amplitude probability distribution function (APDF) data. The accuracy assessment included the calculation of RMS differences between the APDF data from reference and new systems, and average differences for selected variables of interest, and Pearson correlations between observer results and those of the reference system for both time-series and APDF data.

Methodological Background – The Ontario Universities Back Pain Study (OUBPS)

The OUBPS examined physical and psychosocial risk factors related to low back pain in workers at General Motors in Canada. It remains one of the world's largest most comprehensive databases of workplace exposure measures.

In the 1980s and early 90's researchers were debating weather risk for low back pain (LBP) was entirely psychosocial or entirely biomechanical – a polemic Frank et al. dubbed 'unhelpful' (1995). In response to this controversy the Institute for Work & Health in Toronto, Canada initiated the Ontario Universities Back Pain Study (OUBPS), a large incident case-control study at General Motors in Ontario, Canada where 10,000 hourly employed workers formed the study base. The study, which engaged a multidisciplinary team from a number of universities in Ontario, included state of the art in epidemiological design as well as the best psychosocial and biomechanical data collection techniques available (Andrews et al., 1996; Andrews et al., 1997; 1998; Kerr, 1997; Kerr et al., 2001; Neumann, 1999; Neumann et al., 1995; Neumann et al., 1999c; Neumann et al., 2001a; Neumann et al., 2001b; Norman et al., 1998; Wells et al., 1997; Wells et al., 1993). Biomechanical exposure data was collected over 2 ½ years from a remote research centre established at the site where cars were produced 24 hours/day in two car plants and 16 hours / day in a truck plant. Biomechanical measure development, field operations, data collection, and data analysis were the author's primary responsibility from 1992 to 1996.

(see results section for further details on the OUBPS)

The risk association of exposure variables quantified by the system to the reporting of low back pain was determined within a case-control study of low back pain in the automotive industry. Incident low back pain cases (105), defined as workers who reported low back pain to the company nursing stations, were recruited. Controls (129) were selected randomly from the company rosters synchronously with incident cases. No subjects had reported pain in the previous 90 days. The relationships between kinematic indicators and case-status were explored in a series of bi-variable comparisons as well as through multivariable logistic regression modelling.

2.2 Paper 2: Automation Strategies in the Electronics Sector

In paper 2 we used multiple methods to examine ergonomics and productivity consequences in a case of automation technology implementation in electronics assembly.

The Case: An electronics company decided to increase automation of assembly and to adopt an automated line-conveyor system in its manufacturing of AC/DC power converters for the telecommunications industry. This automation was intended to improve the technical performance of the system. The company was concerned about ergonomic conditions in the new system and engaged the research team, through the COPE (Co-operative for Optimisation of Industrial Production Systems Regarding Productivity and Ergonomics) program (Winkel et al., 1999). The COPE team assisted the company in making its own ergonomics assessments for its work-organisation team from the design group.

Evaluation Approach: The research team evaluated the ergonomic and technical consequences of the production system re-design using detailed video analysis of working activities (Engström and Medbo, 1997; Medbo, 1998), production information available from company records and interviews with company personnel, and biomechanical modelling procedures (Neumann et al., 1999b; Norman et al., 1998). Comparisons were made at the level of the production system including data calculated to the ‘per product’ level and also expressed as a function of operator working hours. While information on psychosocial working conditions was gathered, this analysis focussed on the mechanical loading consequences of the re-design. A detailed analysis of ergonomic and technical performance at matching manual assembly was conducted. This allowed the assessment of some of the specific ergonomic consequences of the strategies applied in the new system.

In paper 2 the limited sample sizes available for comparisons of mechanical load variables precluded the use of statistical comparisons. Instead, multiple methods, supported with qualitative data (Cozby, 1989) from company personnel and researcher observations, were used in order to 'triangulate' and support key-findings (e.g. Mergler, 1999).

2.3 Paper 3: Cellular vs. Line Production Strategies

In Paper 3 we study productivity and ergonomics in a case of production strategy change from long-cycle cellular manufacturing to short-cycle serial line assembly.

The Case: This study was conducted in a Swedish company assembling large diesel engines. After decades of using a cellular manufacturing approach with parallel flow and long cycle times (1¼ hours), the company decided to implement a serial flow 'line' based assembly system with a cycle time under 5 minutes. This case appears consistent with a trend we have observed in Scandinavia to return to line-based production (Jürgens, 1997) after decades of using more sociotechnically based approaches (Engström et al., 2004; Forslin, 1990). This trend appears despite theoretical and empirical evidence that parallel flow assembly can be more effective (Ellegård et al., 1992; Engström et al., 1996; Medbo, 1999; Nagamachi, 1996; Rosengren, 1981) and have better physical and psychosocial ergonomics than conventional lines (Engström et al., 1995; Kadefors et al., 1996). This case allowed further exploration of the relationship between core system design elements, such as flow strategy or work organisation, and system outputs such as productivity and ergonomics. The product itself was largely unchanged between systems.

Evaluation Approach: We integrated qualitative and quantitative methods in the evaluation. Informal interviews and document analysis were conducted to understand both process and outcomes in the system redesign project. Production and economic data were obtained from company records and interviews. Questionnaires (n=54 pairs) were used to assess operators' perceptions of pain status (Kuorinka et al., 1987), workload (Borg, 1990), and psychosocial conditions (Karasek et al., 1998; Karasek and Theorell, 1990; Karasek, 1979; Rubenowitz, 1997). Video recordings were made and analysed (Engström and Medbo, 1997; Medbo, 1998) with respect to the time used for work activities including direct (e.g. value adding assembly) and indirect (e.g. getting components or checking instructions) work. Biomechanical models (Neumann et al., 1999b; Norman et al., 1998) were used to assess individual loading and flow simulation models were used to understand system behaviour and working patterns (AUTOMOD; AutoSimulations Inc, USA).

This was a pre-post case study and comparisons were made with 1year interval for 2 matching months to control for seasonal production variability. The data from these methods were used to support an analysis of the advantages and disadvantages, in terms of both productivity and ergonomics, for each of the major elements in the production system design: The adoption of serial flow with its associated reduction in cycle time, workstation layouts, material supply sub-system, change away from product kits, the adoption of automated guided vehicles (AGVs) for transport and IT systems, and the work organisation approach used. We focus our comparison on that portion of the production system which was changed from work cells ('OLD') to line assembly ('NEW').

2.4 Paper 4: Integrating Ergonomics into Development Work

Paper 4 reports on an 'action' research project in which we collaborate in a company's efforts to improve the way ergonomics issues are handled in the development and operation of their production systems.

In this longitudinal case study, a carry-on from the study in Paper 3, we adopted an 'action research' stance (Badham et al., 1995; Reason and Bradbury, 2001) as we participated cooperatively with the company in their efforts to integrate ergonomics into their business processes. This provides a close insider perspective on the organisational change process as it evolves over time (Toulmin and Gustavsen, 1996) allowing greater insight into the complexity of company processes (Ottosson, 2003). Throughout the process we participated in meetings and discussions providing advice and information to the best of our abilities. We also strove to avoid an overbearing "relationship of dependance" (Westlander, 1995) where the process became too dependent on the researchers which might lead it to collapse once we left the company (Siemieniuch and Sinclair, 2002). Our role therefore was more like a coach or advisor than a consultant or contractor. Field notes were made during and after site visits and meetings were tape recorded for review or sharing amongst the research team.

> **”Standardised questionnaires, structured interviews, and statistical analyses cannot begin to grasp the complex fabric of organizational change.”** *– Badham et al. 1995*

Organisational change is incredibly complex (Ottosson, 2003). It is not possible to represent the ‘whole’ reality of this change in a linear narrative of limited length (such as this thesis)(Sørensen et al., 1996). It is important therefore, to acknowledge the ‘filtering’ process which necessarily occurs in presenting such a project (Pålshaugen, 1996). In this case we attempt to reflect on the case in terms of the theoretical base described in our introduction opening a kind of dialectic between theory and observation (Greenwood, 2002; Pettigrew et al., 2001; Vicente, 2000; Yin, 1994). Some researchers have argued that, since theory is created to reflect an evolved practice, action research is ‘beyond’ theory as it focuses on advancing current practice (Toulmin and Gustavsen, 1996). Here we also take the opportunity to advance current theory. In reporting this study we attempt to identify those aspects of the case which might, in a coherent fashion, be useful to other practitioners and researchers who are faced with their own organisational change ‘mess’ (Saka, 2001).

A paradigm shift in methodology?

> **“The underlying assumptions of positivism are indefensible: objectivity, controls, rational choice, etc. – all of these pillars have been taken down”** *- Greenwood, 2002*

The methodology adopted in paper 4 marks a departure from classical positivistic research. I will refrain from an extended discourse on research paradigms but agree generally that the use of numbers and statistics, must always come back to the world of language to become meaningful and, through this transition, enter the social domain of language mediated reality (Collins, 1984). With this in mind, I don’t really understand the positivist hostility to social constructivism or what Ottosson refers to as the quantum (as opposed to the classical ‘Newtonian’) paradigm (Ottosson, 2003). With tongue in cheek I would say that positivists are simply social constructivists who tend to operate in a state of denial. More fruitfully I can say that we are moving into what Gibbons and colleagues have dubbed “Mode 2” knowledge generation in which knowledge regarding solutions to complex problems are studied *in situ*, transdisciplinarily, with a focus on solution efficacy, and embedded knowledge exchange mechanisms that go beyond the usual peer review oversight (Gibbons, 1994). ‘Mode 2’ is seen as a response to societal needs for solutions to complex problems and diffusion of research occurring as a natural part of the process rather than the narrow communications channels institutionalised in the traditional disciplinary research (Mode 1) model. The ‘action research’ approach applied in paper 4 is one method for achieving this.

2.5 Methodological Overview

Table 1: *Key methodological features of the two papers presented in this thesis.*

Study Feature	*Paper 1*	*Paper 2*	*Paper 3*	*Paper 4*
Study Type	Epidemiological & method evaluation	Exploratory & Demonstration of causal theory	Exploratory & demonstration of causal theory	Action research & feedback intervention
Point of Focus	Individuals	Production systems	Production systems	Organisation
Study Design	Case-Control	Pre-Post Case	Pre-Post Case	Longitudinal intervention case
Industry	Automotive assembly	Electronics assembly	Motor assembly	Motor assembly
Study Location	Canada	Sweden	Sweden	Sweden
Subjects/ participants	Industrial workers, analysts	Industrial workers	Industrial workers	Managers, engineers, operators
Study Sample Size	Method evaluation (n=7-10) Epi. study (n=234)	Varies with level of analysis: video (n=1-5), Questionnaire (n=100+)	Varies with level of analysis: Video (n=1-12), Questionnaire (n=100+)	1 Society, 1 Organisation, 1-200 individuals
Focal Body Part	Low back	Shoulder & neck	Back, shoulder, neck, wrist & psychosocial	Whole body & psychosocial
Production focus	Not included	Production volume & changes in labour usage	Production volume, quality, changes in labour usage, costs	Companies own indicator set
Assessment Approach	Quantitative (video analysis)	Mixed qualitative and quantitative methods	Mixed qualitative and quantitative methods	Qualitative
Key Analysis	Inter-obs. reliability, criterion accuracy, case-control differences	Pre-Post productivity and ergonomic conditions of production system	Pre-Post productivity and ergonomic conditions of production system	Change process, change initiation

3. RESULTS

3.1 Paper 1: Tool Performance and Postural Risks for LBP

The tool appeared to have generally good performance characteristics for flexion/extension postures. Operators reporting low back pain bent their trunks more, further, and faster than operators not reporting low back pain.

Tool Evaluation. The results of the reliability study showed that the ICC for peak flexion and time-in-posture categories exceeded 0.8. Dynamic indicators such as peak velocity, average velocity, and flexion movement variables tended to have somewhat lower reliability coefficients. Inter-observer reliability was not good for variables relating to twisting and lateral bending. The accuracy assessment showed that flexion-extension time series data was highly correlated (r = 0.92) to data from the criterion optoelectric imaging system. The amplitude probability distribution function (APDF) data had, on average, an RMS difference of 5.8^{o} from the criterion system's APDF.

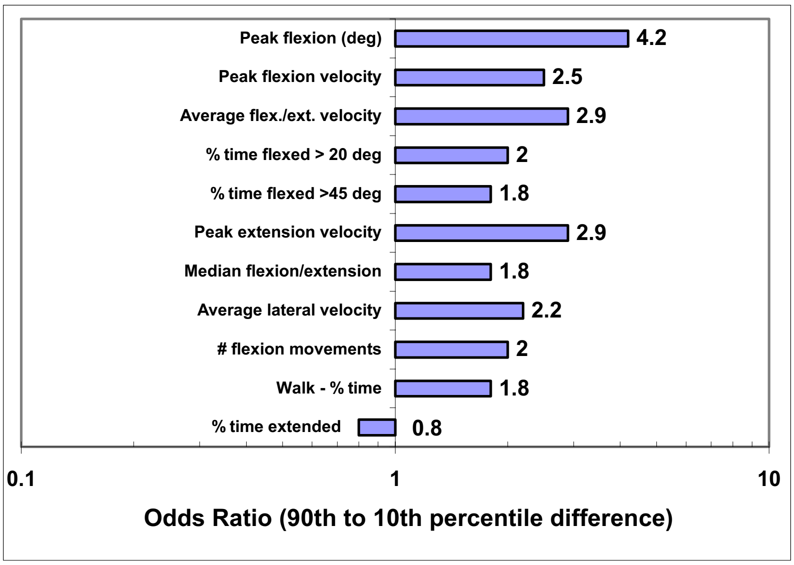


Figure 3.1: *Odds Ratios, plotted on a log scale, for trunk posture and movement variables with statistically significant case-control differences.*

Background Results – Main Findings of the OUBPS

The Ontario Universities back Pain Study (OUBPS) study showed clearly that biomechanical factors, psychosocial factors, as well as psychophysical factors were all independently associated with risk of low back pain reporting (Kerr, 1997; Kerr et al., 2001). Analysis of the biomechanical databases revealed that peak load and shift-cumulative load were both simultaneously and independently associated with LBP reporting risk, a result for which we received the International Biomechanics Society's *'Elsevier Clinical Biomechanics Award'* in 1997 (Norman et al., 1998). In my masters thesis (Neumann, 1999), I demonstrated how a pencil and paper based load and posture sampling technique can quantify peak and cumulative spinal load, both LBP risk factors (Neumann et al., 2001a) and how checklist, questionnaire, load and posture sampling, and video digitisation compared in quantifying peak spinal load: all methods identified risk at the group level but they could not always be used interchangeably at the individual level (Neumann et al., 1999c). Taken together these results demonstrate a number of different approaches to identifying and quantifying risk to both physical and psychosocial workplace factors associated with MSDs and that these factors all provide independent contribution to an individual's 'total' MSD risk. Noteworthy is that these independent risks **multiply** when present in combination.

The risk relationship study confirmed the importance of trunk kinematics as risk factors for low back pain reporting. Odds ratios for variables with significant case-control differences are plotted in Figure 3.1. In bi-variable logistic regression comparisons peak flexion accounted for the most variability in case status and had the highest odds ratio. Other significant predictors included peak and average velocities as well as the 'percent of time spent in flexion' category indicators. Multivariable modelling resulted in a final model with peak flexion level and average lateral velocity as risk factors. This model also included percent time in laterally bent postures, which was not significant in bi-variable comparisons, as a protective factor in the multivariable model.

3.2 Paper 2: Partial Automation in Electronics Assembly

The introduction of automation appeared to increase output efficiency. The assembly work remaining however showed increases in load amplitude and monotonous movement frequency.

The implemented re-design included strategies of automation of assembly, adoption of an automatic line transport strategy, construction of adjustable sit-stand workstations, and adoption of a new work organisation strategy. The technical and ergonomic consequences of the automation strategies implemented are qualitatively summarised in Table 3.2.1. The resulting system increased output volume 51% and reduced per-product labour inputs 21%. Management personnel reported the amount of quality work (required to reach 100% quality for delivered products) to be unchanged between the old and the new system. The automation strategies used resulted in a 34% reduction in manual assembly work and some increases in other work such as loading cases onto the new conveyor system and monitoring automatic machines. The line system had less buffering between stations and thus a reduced amount of work-in-process (WIP). Utilisation of manual assembly operators decreased due to forced waiting caused by occasional stoppages in the line-system related to the linear flow strategy.

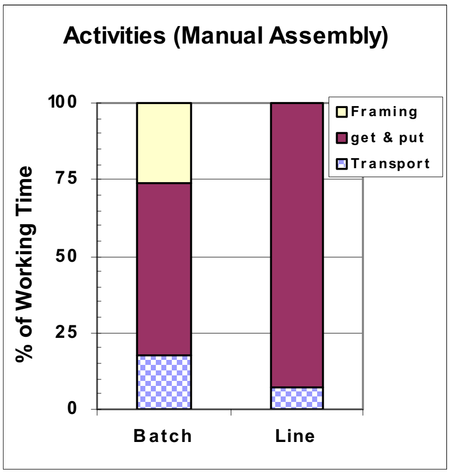


Figure 3.2.1: *Activity analysis for comparable manual assembly stations in the two production systems (from video analysis data used in biomechanical model)*

The examination of manual assembly work showed that, although both the old and new stations were responsible for approximately the same amount of assembly work, the new line-based workstation had less task variety and consisted almost exclusively of repeated reaching for and inserting ("get & put") components (Figure 3.2.1). The old system also included the activities of transporting product and mounting the product into a frame for the soldering operation. Task time analysis used with the biomechanical modelling procedure indicated a reduced task variety with over 90 percent of the new manual assembly operators time during uninterrupted production spent in "get & put" activities compared to 56% in the old parallel system. Increases in the percent of time with arms elevated, and increased average shoulder load were also observed (Figure 3.2.2). Head postures, however, tended to be less inclined as operators looked up when reaching to components elevated above table height. The workstation design provided sit-stand capability but postural changes by the operators were not frequently observed during field visits.

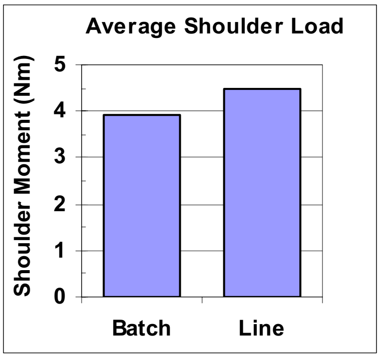


Figure 3.2.2: *Average shoulder load for operators at comparable manual assembly stations (from biomechanical model).*

The workforce on the new system consisted of fewer company employees and a larger number of individuals hired from a temporary agency compared to the old system. The work organisation strategy, developed by the work organisation team, was not implemented. Management personnel, who had not been involved in designing the work organisation strategy, felt the plan was unworkable. Instead particular operators staffed the jobs with complex loading patterns, such as robot supervision, without job rotation. Operators who rotated every shift in an informal pattern filled the remaining positions. The jobs in which rotation occurred tended to be low in task variability, such as manual assembly and visual inspection work, with frequent montonous upper arm movements.

Table 3.2.1: *A qualitative summary of the production and ergonomic consequences of the two partial automation strategies implemented in the re-designed production system. The table also identifies 'side-effects' that were observed in this case but appeared to be either sub-ordinate to or unintended effects from the implementation of the chosen strategy.*

	Production		**Ergonomic**	
Strategy	**Benefit**	**Deficit**	**Benefit**	**Deficit**
Assembly Automation	Reduced manual assembly work		Overall decrease in monotonous work (system)	
		Increased machine support work	Increased variable work	Some awkward bending and reaching
Side Effect (Some parts could not be automated)		Shift of components back to manual assembly workers		Increased shoulder loading (parts on elevated rack)
Automatic Line Transport System	Reduced manual transportation work	High capital costs		Reduced variability of work
	Reduced handling of product in preparation for assembly		Some reduction in handling activities	Increased arm elevation & average shoulder moment
Side Effect: (Disturbances in un-buffered system)	Reduced work in process (WIP)	Decreased operator utilisation (due to forced waiting)	Forced waiting may provide recovery time for some, but not all, operators.	

3.3 Paper 3: Results

The new line system had slightly higher output with higher costs, poorer physical ergonomics and worker autonomy, but better co-worker support compared to the old cell assembly.

OLD system (left side Fig 3.3.1): The OLD production system, designed with 18 'dock' stations, was studied having 12 Docks and a small 'learning line' in parallel for newer Operators. Operators worked alone at each dock to assemble each motor. Operators were required to finish 5 engines per day, which increased to 5.5 shortly before measurement. Operators could stop working once this quota was reached. The system was designed, based on standard times, to allow 6.2 motors to be completed per shift per dock but this target was not enforced and not all operators were believed to be capable of this pace. Hand steered motorized carts allowed transport and lift-tilt position adjustment of motors. Parts were supplied to the dock using a 5-shelf 'kit' stocked with variant specific components by 'order pickers'.

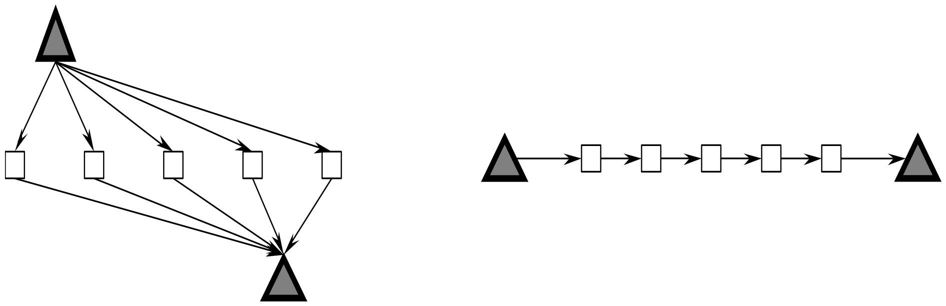


Figure 3.3.1: *Schematic diagrams, abridged to illustrate flow principle with 5 stations (squares) between 2 buffers (triangles), for the OLD parallel flow system (left) and the NEW serial line system(right)..*

NEW system (right side Fig. 3.3.1): The NEW line system used a serial flow of 18 stations. Automated Guided Vehicles (AGVs) provided motor transport and eliminated short walks between assembly cycles. Parts were supplied directly to the line in large crates. Operators retrieved parts directly from the crates occasionally adopting awkward postures. The AGV contained a computer monitor providing part numbers for the particular variant to the operator. The product itself was largely unchanged between OLD and NEW systems requiring about the same component assembly work. There were however many product variants requiring different components that, for lower volume variants, were positioned further away from the operators' workstation resulting in load carrying.

Production volumes, a primary change driver, were 12% higher in the NEW system where cycle times had been reduced to 6% of those in the OLD system. Time to learn a single station in the new system was about 1 day although time to learn the entire system, an organisational objective, was about the same in both systems at 1 month. Total staffing levels were about the same with 46 people in the OLD and 47 in the NEW system – 6 persons were no longer needed to pick OLD kits, but 7 more people were needed along the NEW line. Unit labour costs were 3% higher in the NEW system when adjusted for scheduled wage rate increase. Costs per motor were 32% higher in the NEW system in the period of comparison driven mostly by capital and support costs for the new high-tech AGV system.

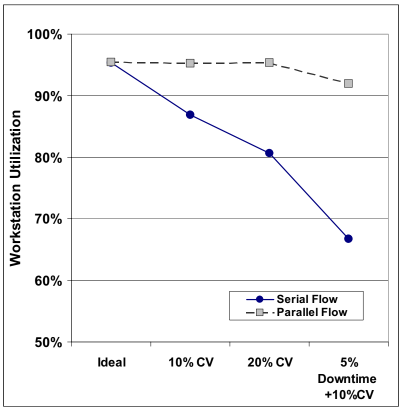


Figure 3.3.2: *Flow simulation illustrating effects of operator variability (modeled here using a coefficient of variation (CV) of 10%, 20% of mean cycle time, and 10% CV with 5% machine downtime) on workstation utilisation – an indicator of operator/station efficiency.*

As predicted by the companies own corporate standard *"serial flows with short cycle times generate waiting times that are not experienced as pauses but as disturbances in the work rhythm. This also generates accelerated work with poor ergonomics as a consequence."* (Backman, 2003). We observed this in the video analysis where waiting was 0.1% of assembly time in the OLD system and 18% of assembly time in the NEW system. This waiting was largely caused by starving and blocking disturbances that are inherent in serial flows with normal human variability in performance. Flow simulation illustrated (Figure 3.3.2) the effects of human variability and the additional vulnerability lines have to other disturbances such as machine downtime.

Psychosocial indicators revealed significant ($p<0.05$) reductions in Decision latitude and control over work scales and significant improvements in co-worker support and team climate scales. Figure 3.3.3 depicts the spread of operators' opinions when asked to make direct comparisons of the two systems themselves.

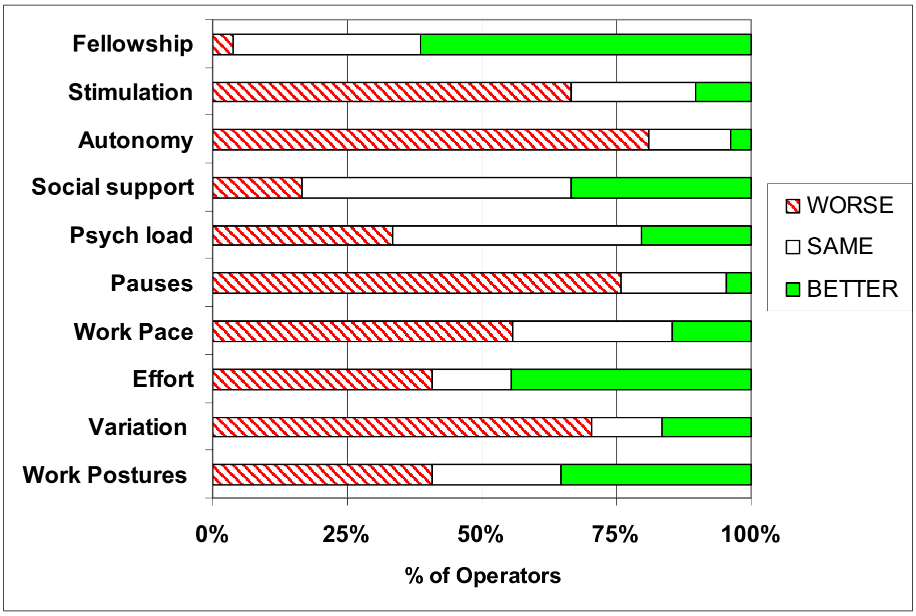


Figure 3.3.3: *Spread of opinion of operators with regards to how the OLD and NEW systems compared. 'Better' for each index is the response associated with better ergonomics e.g. reduced load, increased fellowship or increased variation at work.*

Pain levels were highest for the low back with 72% in the NEW system reporting pain in the previous 3 months, down 9% over OLD. Hand-wrist pain was also high and similar in both systems with 62% reporting pain in both systems. Shoulder pain increased 28% in the NEW system with 60% of operators reporting pain in the past 3 months. Perceived physical exertion rates showed a pattern similar to the pain reporting, ranged from 5.3-6.5 ("hard" to "very hard") on the Borg scale, and tended to be lower in the NEW system but were only significantly ($p<0.05$) reduced for the Back. We examined nut running activity on video recordings as an indicator of upper limb loading and found a range from under 500 nuts/day to just under 3000 nuts/day depending on the workstation. In comparison the old system, with its production quota, had a consistent load of about 1200 nuts/shift based on designed work pace. This unevenness of load was also observed for peak spinal loading which, when considered system wide, was similar in both systems with 470 N L4/L5 Shear load and 2600 N compression. In the NEW system however not all operators were exposed to the 'worst case' lifting situation every day.

Table 3.3.1 summarises the strategies' consequences observed in this case.

Table 3.3.1: *Summary of advantages and disadvantages, in terms of both ergonomics and productivity, observed with key design elements in this case. The dotted line between some elements indicates the tighter coupling of these particular elements.*

Strategy	**Advantages**	**Disadvantages**
Parallel to Serial Flow	• Facilitated change in work organisation • Production disturbances may provide physiological rest	• Fragile with system and balance losses • Production disturbances not perceived as pauses • Reduced job control
Cycle Time Reduction	• Easier to learn 1 cycle • Easier to tell if work pace matches system	• Reduced physical variety (increased repetitiveness)
Changed System and Workstation layouts	• Increased opportunity for interaction (improved co-worker support) • Not all stations handle heavy parts (e.g. reduced spinal load)	• Difficult to add new parts (space limitations) • Lift assists can't reach all part variants • Space shortage results in awkward reach to small parts
Kitting to Line Picking	• Order picking eliminated (positions eliminated) • Lift assists available for heaviest parts	• Operators must walk more to get parts • Lifting parts from large crates causes high loading
Manual to Automated Guided Vehicles (AGVs)	• On screen checklists & logging • Adjustments (if used) can reduce physical load – counts for both carrier systems • No manual cart steering work	• High capital and maintenance costs • Contributes to reduced job control • Reduced physical variation • AGVs interacted with layout to raise height of tools
Work Organisation (solo to team-work + eliminate quota)	• Operators remain 'on-line' for full shift • Team work fosters co-worker support • Eliminate incentive to rush	• 'Runners' need to assist with line flow (positions added) • Work pace steered by system – reduced job control • Reduced work content

3.4 Paper 4: Integrating Ergonomics into Development Work

The change process was slow with inhibitors coming from both individual and organisational factors. The production manager, using internal knowledge to act as a 'political reflective navigator', was able to steer the process forward.

3.4.1 The Case Story

Initiation: When the results from paper 3 were presented to the project steering group the production manager (PM) emphasised his vision statement that "*operators should be able to continue to work in these systems up to retirement".* Having seen the systems comparison (in paper 3) he wished to see action to capitalise on the new knowledge. Realising that the steering group was too large to analyse the problem effectively he created an 'Analysis group' charged with identifying opportunities for improvement as part of a 'Production Ergonomics' (ProErg) initiative. The analysis group included union, health & safety service, line supervision, engineering and research representatives. After a series of discussions the group returned suggesting the creation of three working groups: 1) 'Return to Work' for rehabilitation issues, 2) 'Future' group for line development, and 3) 'Measurement' group to improve information gathering and utilisation. These groups began to form and, as needed, created sub-groups to deal with specific tasks or activities such as making improvements based on an ergonomics audit. Initiation of activity was fastest when it involved persons already engaged in the process and took some time when persons new to the process needed to be recruited. This period was marked by considerable activity surrounding 'ergonomics' in the company and many small improvements were implemented. The group could not deal with improvements related to more central system features such as the material supply system as they were too expensive.

Reflection – The group structure chosen initially made sense to the company. The researchers had entered the company through the production department via the PM who provided strong support and a clear vision. The structure created appeared to reinforce the position of ergonomics as a 'production' issue with little engagement of system developers from engineering. For those not previously involved in the ProErg initiative the new tasks appeared to pose *additional work – not integrated with regular duties. Ergonomic problems relating to core system features appear to be "locked in" once built.*

Problems Emerge: A dramatic slowdown in activities was observed immediately after summer holidays with many meetings cancelled or postponed. It emerged that each of the three group leaders was being transferred to new positions in the company. Problems also emerged as some of the sub-group's activities began to intersect with other activities. Individuals with heavy workload were not sure how the 'new' ergonomics tasks should be prioritised, particularly when their supervisor from another department was not fully supportive of the initiative. Toward the end of this stage the company's safety engineer, who had been coordinating and driving the process, left work on sick leave and, sadly, died in January 2004 marking a low point in the project.

Reflection – Individual factors, including normal life events such as promotion, retirement, marriage, and cancer, all appeared to influence individuals ability and/or willingness, to engage in the change effort. Organisationally engineering groups responsible for system development remained distanced from the process, which thus remained a 'production' issue. The process was insufficiently anchored in daily work routines to survive the turbulences of ordinary life.

New opportunities: The production manager (PM) and researchers reflected upon the situation in the fall of 2003. The PM decided to lift the issue up to the site management group to inform and engage senior managers from other departments. At this meeting it became clear that developing the new system, not retrofitting the old system, was the primary focus of the engineering groups. The site manager called for a workshop so that knowledge gained from the system evaluation (paper 3) could be spread to the new system's design team. Having reviewed the system comparison data in the workshop, engineering management decided that developing ergonomics capabilities needed to be done outside the current development project which had tight budget and time constraints. Following the workshop a number of discussions were initiated engaging both engineering and the health and safety service. For example, the consideration of ergonomics through computer simulation technologies (Medbo and Neumann, 2004; Neumann et al., 1999b) was demonstrated and discussed in connection with development being made by the engineering groups.

Upon further reflection of how to better anchor ergonomics into the development process, the PM arranged for the company Ergonomist and Safety engineer to join the ‘Assembly steering group’, which was responsible for managing all assembly development via the company’s product development gate system, the ‘Global Development Process’ (GDP). The PM saw the integration of ergonomics into the GDP as a strategy for locking in ergonomics considerations throughout the development process. Another tactic pursued by the PM was to establish an ergonomics training program for leadership, design teams, and assembly personnel to help improve knowledge and communications surrounding the management of MSD risk.

Reflection – Here we see the PM acting politically to gain support for his vision. Having researchers present ‘hard’ data on both technical and human factors appeared to establish credibility for ergonomics concepts and created a forum for further development of ergonomics capability in design. By integrating health and safety personnel into the steering group the PM signalled the importance of this issue in development. Targeting the GDP as an area for ergonomic improvement sets the stage for the PM to ‘lock-in’ ergonomics and provides a practical opening to engage the H&S personnel in early stages of process development.

3.4.2 Stakeholder Analysis

The company had divided responsibility for development between a number of organisational units. ‘Product development’, for example, was based in different city from the manufacturing facility. ‘Pre-Production Engineering’ was responsible for the basic form and flow strategy of the system, while ‘Production Engineering’, closest to the production system, was responsible for more detailed workstation layouts and assembly task distribution. ‘Purchasing’ and ‘Logistics’ were responsible for supply of components to the system including the choice of parts containers – frequently large crates from which parts were manually extracted on the line.

Reflection – By mapping these stakeholders onto the development model (Figure 3.4.2) we were able to see how influence on the design task was distributed through the organisation. ‘Engaging engineering’ as an objective for ergonomics therefore is not a simple task but affects a number of groups, some of whom had not yet been engaged by the ProErg initiative. Similarly, *the responsibility for system ergonomics is distributed across a number of groups each trying to make their zone of responsibility as efficient as possible – leaving the possibility for poor ergonomics to emerge as these disparate elements are combined with crucial risk determining consequences.*

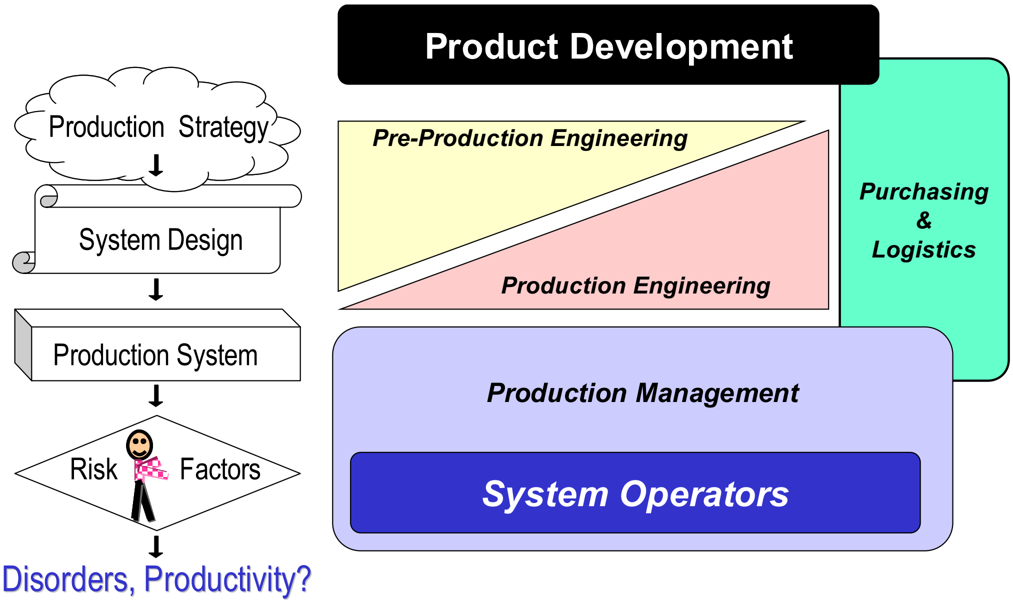


Figure 3.4.2 *Stakeholder map illustrating key organisational groups positioned according to their role at different stages in the development and operation of production system as modelled in Figure 1.*

4 DISCUSSION

This discussion reflects upon the model presented in the introduction in terms of what has been observed in these studies and attempts to further develop the theoretical model.

The re-examination of theory in light of empirical evidence allows both ‘testing’ of the model – is it useful? – and also further development of the model in areas where it is found lacking (Gustavsen et al., 1996; Yin, 1994). The intent here is to see how the papers, as a whole, interact and contribute to the understanding of the system and to the development of theory.

4.1 System Outputs: MSDs & Productivity

Clear relationships have been demonstrated between MSDs and workplace risk factors, in this case postural factors. Companies seem to have much more detailed data on productivity & quality than they do on MSDs.

Results - Paper 1 demonstrated the close coupling between risk factors at work, in this case working postures, and musculoskeletal disorder (MSD), in this case risk of reporting low back pain. This result is consistent with other methods applied in the same study (Neumann, 1999; Neumann et al., 2001a), and is also consistent with the broader literature (Bernard, 1997; de Beek and Hermans, 2000).

Papers 2 & 3 demonstrated the interconnections between strategic elements in the production system design and the ergonomic and productivity outputs of the system. The difficulty in using MSDs as an outcome in such a system design evaluation led to our using risk factors and pain reporting, proven to be leading indicators of risk in studies such as Paper 1, for MSD related disability as suggested by Cole et al. (2003). The complex interactions between productivity and risk associated with different strategies and the interactions observed amongst the strategies themselves (described in section 4.5) emphasises the need for designers to consider human factors and productivity outputs simultaneously throughout the design process.

The case of engine assembly (Papers 3 & 4) , highlighted the challenge for a company that had general sickness absence as a pooled outcome. Swedish regulations on privacy inhibit the gathering of more detailed information allowing a better understanding of the pattern of MSD related absenteeism inside the organisation. This in turn inhibited the company's efforts to manage this problem. In this case we saw that the company's gathering of quality and productivity data was much more detailed, and frequent, than for sickness and absence data. This provided a much richer source of feedback into the organisation and may be inhibiting uptake of ergonomics. Interestingly in both Papers 2 & 3 we observed changes in the way the company gathered their production data at the same time as the production system changed. Implementing an indicator improvement at such a time makes it difficult to compare the performance of the new and old system and reduces the risk that the new system might be seen as inferior to the old system – it eliminates the chance of failure.

Model Issues – Despite the possible variability of the risk-performance relationship, the model (Figure 1) points out that production systems with humans will always have some measure of risk. Systems theory points out that, in dynamic systems, the relationship between elements (in this case say risk factors and productivity) can be unstable over time and unexpected linkages can emerge (Skyttner, 2001). While the model (and this thesis) focuses on MSDs, other work related health outputs could be considered as appropriate to the situation being examined.

Methodological issues – Measurement of health outputs is currently much more difficult and imprecise than productivity outputs. More precise and reliable diagnostic tools might help. The health outputs and performance outputs occur in different time frames – making it difficult to correlate these two different types of outputs. While high spinal loads may cause low back pain very quickly, exposure to prolonged and repetitive loading combined perhaps with psychosocial strain, may take months or even years to develop an MSD (Cole et al., 2003). This delayed response is a particular problem for providing feedback comparable to that available for other outputs to production system designers. Under these circumstances we have relied more heavily on 'symptom' or pain surveys (e.g. Kuorinka et al., 1987) and especially physical and psychosocial risk factors that provide a more leading indicator of potential problems (Cole et al., 2003).

4.2 Risk Factors

This thesis demonstrated a 'risk calibration' of a tool to measure trunk posture at work from video. These tools may be useful as 'leading' indicators of MSD outputs that are more closely connected to current system design.

Paper 1 demonstrated how an exposure measurement tool that can be evaluated and risk-calibrated. This tool showed the importance of trunk movement factors, particularly peak flexion level, in the reporting of LBP at work consistent with the literature (Marras et al., 1995; Neumann et al., 1999c). It also showed that analysts without special technical skills could measure these dynamic parameters precisely and easily. In principle these parameters could be predicted from simulation during design (e.g. Sundin, 2001). Peak flexion exposure can be related to a number of mechanisms, including increased lumbar loading from the mass of the torso, worsened mechanical advantage due to changes in musculoskeletal configuration, as well as possible localised tissue loading due to deformation effects in extreme postures (Hagberg et al., 1995). The results from this study also confirm velocity as a risk factor, previously identified by Marras et al. (1995). High velocities, in a fixed range of motion, imply high acceleration and, according to Newton's second law (Force = Mass * Acceleration) (Newton, 1687), high force with related potential for tissue overload (McGill, 1997).

Musculoskeletal disorders are multifactorial in nature (Frank et al., 1995). While paper 1 focuses on a single method for posture quantification, the larger OUBPS study identified a number of physical and psychosocial risk factors (Kerr et al., 2001; Norman et al., 1998). This broader range of risk factors is studied subsequently in papers 2 & 3. Meaningful interventions will need to consider as broad a range of risk factors as possible any one variable rarely carries more than 10% of the injury variance. If an interventionist manages to cause a 10% decrease in such a single risk factor, then the challenge will be to isolate the anticipated 1% drop in MSD in a workplace with 20% variability in sickness absence data.

Model Issues – The model seems consistent with observations that there is always some measure of risk in any work system. The correlation between risk factors and MSD is well demonstrated (eg Paper 1). While examples exist demonstrating correlations between MSD risk factors and quality (Axelsson, 2000; Drury, 2000; Eklund, 1995; Lin et al., 2001) and also profitability (Hendrick, 1996; Oxenburgh et al., 2004), the data here is not as extensive as for MSD. It is possible that other human 'risk' factors for poorer productivity, beyond those for MSDs, exist and could be identified. These 'poor productivity' risk factors may vary depending on the nature of the production system.

Measurement of MSD risk factors is a tricky business. Variables of interest have a wide range in frequency characteristics, which affects sampling strategy effectiveness. Infrequent events, of concern for peak loading, might only occur once or less each day and pose a sampling challenge (Kihlberg et al., 2000). Wrist movement, in contrast, contain relevant signal frequency components content up to approximately 5Hz (Balogh, 2001). Muscle activity levels, recorded using electromyographic techniques, contain relevant signal up to 400Hz (Merletti et al., 1999) and are often sampled at over 1000Hz. Measures sensitive to the nuances of human performance, like electromyography, may be swept away by larger variability in the production system – for example during an unusual downtime cause by supplier-side delays or machine breakdowns. In papers 2 & 3 it was particularly important that methodological and sampling strategies account for the behaviour of the production system and system boundaries if the measures are to represent operators' exposure in a meaningful comparison.

4.3 Production System

The difficulty we observed in making ergonomic improvements to existing systems highlighted the need to integrate ergonomics into system design. Once built key performance and risk aspects of the system are 'locked in'.

While paper 1 focussed on the individual at work in a production system, papers 2 & 3 focus more on the production systems directly. Here we attempt to understand the *strategic design elements* (production strategies) that contribute to a particular risk profile for the system. These will be discussed subsequently.

In trying to integrate ergonomics into the engine-manufacturing organisation (Paper 4) we observed problems trying to make changes in the existing system. By the time the system comes into operations most (if not more than all!) of the project budget is spent – few resources remain for further development. While relatively simple changes can be implemented given sufficient time, risks associated with more central design features are 'locked in'. This highlights the importance of trying to integrate human factors into the early stages of production system design (Burns and Vicente, 2000; Engström et al., 1998; Imbeau et al., 2001; Jensen, 2002).

"Paying insufficient attention to human resource issues until after the technology has been selected and implemented creates a risk of problems that are so severe that the capital investment in new technology may be completely negated" - Johansson et al., 1993

Model Issues: The distinction between the existing system, the system design, and the production strategy as formulated in the system model can become confusing. The production system is an 'artefact' of the design process which in turn is guided, or bounded, by demands and constraints established by decision makers. The separation of these aspects in the systems model supports consideration of time sequence and separate stakeholder groups: the senior managers who chose strategies, the engineers who figure out how to implement them (and perhaps lobby for specific strategies), and the production staff who operate the resulting system. These distinctions proved helpful in understanding the complex situation in the engine assembly organisation.

Methodological Issues: Production systems are dynamic in their daily operations, and continuously changing with ongoing interventions constituting 'design' changes. This can make measuring 'normal' system outputs like trying to hit a moving target. Our analyses reflect a particular window in time at a particular stage in system development. To help control for system variability calculations have used production averages over a month or more. Biomechanical models, which allow the application of 'standard' data to particular work situations, can be particularly useful as it bypasses or systematizes some the system's variability to allow unambiguous comparison of different situations. In other instances, for example when using flow simulation (paper 3), this variability is of critical importance as it can influence the extent to which system parts influence or interfere with one another. The choice of when to include or bypass system variability must be made carefully depending on what aspect of system function one wishes to explore. It can be helpful to get operators', engineers', and supervisors' opinions and experiences with the system so as to understand system behaviour before making critical measurement decisions ("oh yeah, on Fridays we run just half a shift – that won't affect your measurements will it?").

Some performance indicators might, under a strict interpretation, be considered ‘internal’ to the system. ‘Work in Process’ (WIP), for example, provides an indicator of how much material is in the system and represents an operating cost (Wild, 1995). These indicators are not always well tracked and can be difficult to quantify. Gaining access to raw data to obtain indicators not usually used by the company can, on occasion, test a researcher’s skills of persuasion.

4.4 Production System Design

Even if ergonomics is considered during design, such as through workstation layout, this is not always enough to deal with problems related to production strategies.

In our close collaboration with the engine production facility in Papers 3 & 4 we became aware of the complex dynamic between the stakeholders at the production system’s operational level and those responsible for design of the system. In this case we saw that the selection of the work organisation was heavily influenced by production personnel, while the technical system was largely chosen and designed by the engineering group. This can be seen as a separation of the social and technical subsystems as problematised in classical sociotechnical systems theory (Eijnatten et al., 1993). In this case we, similar to Wulff et al. (Wulff et al., 2000; Wulff et al., 1999a; b), saw that corporate standards for human factors were not fully embedded and used in the design process. We also observed that a number of different organisational groups are responsible for different aspects of the design a common practice and problem in engineering design (Johansson and Medbo, 2004; O'Brien and Smith, 1995). This implies that ‘engaging engineers’ may be a more complex task than originally conceived. The specific structure or distribution of the design process is likely to be specific to the case of study – the problem of managing emergent human factors in distributed design environments however is quite general and warrants further investigation (Burns and Vicente, 2000).

> **“…engineers and designers had poor knowledge of both the formal design processes in use in their company and how to apply ergonomics principles.”**
>
> - Skepper et al 2000

Workstation Design – The design of workstation layouts appeared to occur after other choices of production system design and is here discussed as a ‘design’ issue rather than a ‘strategic’ one. In the case of electronics assembly (paper 2) considerable investment was made in the design of ‘ergonomic’ adjustable sit-stand assembly stations. This sit-stand capability, however, did not really address the dominant arm-shoulder loading risk factors related to repetitive, monotonous ‘get & put’ activities. While the intention to produce ergonomically adjustable sit-stand workstations was good, the effort failed to account for the pattern of work created by the choices surrounding the serial flow system set at the very earliest stages of the design project. The ergonomic importance of early design decisions has been previously discussed (Burns and Vicente, 2000; Helander, 1999; Imbeau et al., 2001; Jensen, 2002).

Model Issues: A critical aspect of the design process not accounted for in this model lies in the design of the product itself. Design of a product that can be quickly and easily assembled could, in principle, contribute greatly to reducing physically awkward postures or forceful actions. In the case of engine assembly product designers were based in a different city from production system designers creating a barrier in communications. Neither product strategies nor product design issues are explicitly included in the current model. As mentioned previously, there is a certain ‘fuzziness’ between ‘design’ and ‘strategy’ elements and these two activities are closely linked in the model (Figure 1). It is perhaps best left up to the analyst/investigator to make this distinction according to the particular development process under study.

Methodological Issues: Our approach to understanding the design process was essentially qualitative. The action research approach allowed us to develop an intimate understanding of how this process was running and the subtle individual and organizational forces that were shaping this particular design project. Unfortunately the bulk of strategic decisions were already made as we began to come into regular contact with the design team – gaining early access is an important issue. Isolating a decision in a design process can be quite difficult (Langley et al., 1995).

4.5 Production Strategy

Production strategies pose core choices that affect both ergonomics and productivity of the resulting system. These strategies interact. Understanding the relations between specific strategies and their ergonomic and productivity consequences appears critical to improving total system performance.

In both electronics and engine cases (Papers 2 & 3) the companies were concerned with increasing production volume. Changes in production strategy were observed to flow patterns, to the use of automation, to material supply sub-systems, and to the work organisation. In general we found benefits and drawbacks in both ergonomics and performance consequences of these strategic elements. Understanding how these individual strategies can contribute to both good performance and good ergonomics seems essential to facilitate the joint optimisation (of human and technical factors) necessary to find system solutions that are globally optimal and thus maximally productive (Axtell et al., 2001; Burns and Vicente, 2000; Clegg, 2000; Hendrick and Kleiner, 2001; Ingelgård and Norrgren, 2001; Neumann et al., 2002). Like others (Kuipers et al., 2004) we attempt to move beyond debates about archetypes like 'lean' tayloristic or 'reflexive' sociotechnical systems (labels Engström and colleagues suggest are "pretentious" (Engström et al., 1998)) that has populated the literature (Adler and Cole, 1993; Adler and Goldoftas, 1997; Babson, 1993; Berggren, 1994; Björkman, 1996; Cooney, 2002; Ingelgård and Norrgren, 2001; Landsbergis et al., 1999; Sakai, 1990; Womack et al., 1990). Thus, instead of engaging in a 'line' vs. 'cell' debate, we seek instead a more nuanced understanding of the interplay of strategic elements in determining system outputs – including both productivity and ergonomics factors.

> **"…top management personnel are indifferent to good human factors design… the social structure favours the choice of technologies that centralise authority and de-skill operators and … encourages unwarranted attributions of operator error."**
> - Perrow 1983

In paper 4 we observed that the early choice of production strategy, made by highest managers, inhibited the consideration of alternatives by the design team who were already overloaded with the task of realising the design assigned to them. This illustrates how ergonomics can be 'locked in' by early design choices. These strategic choices were made by senior managers who are perhaps most distanced from the daily risk exposure of the system operators. Since the vast majority of resources are allocated (Mortensen, 1997), early choices become a critical domain for maintaining approaches that include potential for good ergonomics:

> *"The true leverage points of design occur in the negotiation of contextual constraints, the making of wise decisions early in a project, and in negotiating ergonomic priorities with designers from other domains"* (Burns and Vicente, 2000)

Applying 'ergonomics' principles after key decisions have already been made, or after the system is fully functional, may not be sufficient to substantially reduce MSD risk.

Model Issues: The interconnectedness of production system elements can make it difficult to isolate a '*strategic'* design element. In general the 'production strategy' choices tend to be decisions implying core features, with a large portion of the system cost, chosen in the early stages of the project. The analyst's final determination will depend on the site context and research intent. Larger issues of corporate strategy are not included in the model – although these must surely influence the selection of production strategies.

Methodological Issues: When faced with a given case, isolating a chosen 'strategic' element is essentially a qualitative exercise. This is complicated by the distance between strategic decision (level 5) and the observed resulting system (level 3). As Langley et al. (1995) point out:

> *"It is a perplexing fact that most executive decisions produce no direct evidence of themselves and that knowledge of them can only be derived from the cumulation of indirect evidence."* (Langley et al., 1995)

Compared to muscle EMG for example which one might sample at 1000 Hz, strategic production elements are chosen once for the life of the production system – and may in fact span a number of system life-cycles until new strategies are chosen. There is a fundamental difference in time frame. Following along the design process longitudinally as done in Paper 4, can allow the decision chain to be better understood (Langley et al., 1995).

4.5.1 Flow Strategies: Serial and Parallel Flows

In both Paper 2 and Paper 3 we saw cases in which parallel flow strategies were replaced with automated serial flow. This change was most pronounced in the engine assembly case (Paper 3). The move to serial flow reduced cycle times and thereby also decreases the physical variability of work at the workstation level. The observed physical and psychosocial drawbacks of this strategy are consistent with previous literature (Bildt et al., 1999; Fredriksson et al., 2001; Melin et al., 1999; Ólafsdóttir and Rafnsson, 1998). We observed that the flow strategy controls the pattern of physical loading throughout the shift, although this is modified by the work organization features such as job rotation.

Serial flows have inherent inefficiency due to system losses (Engström et al., 1996; Medbo, 1999; Wild, 1975; 1995), which we observed in both cases. Interestingly, in paper 3, operators did not perceive these disturbances as a ‘pause’, although it *does* seem to reduce physical workload levels (Palmerud et al., 2004). While this knowledge existed inside the company’s corporate standards it did not appear to be used by the design team. Buffering can mitigate these negative effects of serial flow although this increases WIP levels and is particularly expensive with AGV conveyance systems. This represents a kind of ‘interaction effect’ between the different system design elements. Having the workforce shift flexibly up or down the line to overcome flow irregularities as part of a ‘team working’ approach, as observed in paper 3, is another strategy for reducing system losses. Unexplored here is the extent to which reducing these system losses will affect ergonomics with possible increases in mechanical loading, decreases of recovery time, and psychosocial effects in response to reductions in forced ‘waiting’.

4.5.2 Automation Strategies

We observed automation of assembly as a production strategy in the case of electronics assembly (Paper 2), and automation of transportation functions as an expensive part of both cases’ production strategies (papers 2 & 3). Automation has been associated with improved firm performance (Fawcett and Myers, 2001) and appeared to have improved labour efficiency in Paper 2. At the system level the strategy to automate assembly reduced the total exposure of operators to repetitive monotonous assembly work – an ergonomic benefit. For the individuals at manual assembly stations, however, the loading pattern tended to increase in time-density and monotony with operators performing repeated and rapid ‘get & put’ movements almost continuously with increased MSD risk (Veiersted, 1994; Veiersted et al., 1993; Westgaard, 1999). In the engine assembly case the AGV transport system (combined with serial flow) eliminated the short walks operators took delivering the motor to quality control after assembly – also a reduction in physical variation. Partial automation strategies have been linked with increased exposure to MSD risk factors (Coury et al., 2000). Thus the remaining work can be as important as the automated work when considering the ergonomic effects of automation. In the case of automation of transport ,Arndt (1987) has described how operators struggling to match a machines pace can result in elevate muscle activity levels and hence increased MSD risk.

In both cases the implementation of new technology did not go as smoothly as planned and required extra resources to bring to full functioning. Interactions with other system strategies were observed. In the electronics case for example, problems buying components suitable to robotic assembly (a problem in the material supply sub-system) resulted a shift of these components to manual assembly stations where space constraints resulted in elevated parts and thus elevated shoulder loading. Implementation of the AGV’s in the engine assembly case also interacted with the physical workstation design, as power tools were elevated 10-20 centimetres to avoid collision with the AGV’s monitor. This problem, now corrected with some effort, also lead to increased shoulder loading for operators. These examples illustrate how a division of design tasks can lead to ergonomics problems when the different elements finally come together.

4.5.3 Material Supply Strategies

The material supply sub-system (MS) is an important aspect of operating systems with potential to contribute to both performance and health and safety (Wild, 1995). The relation between ergonomics and the MS can be obvious, as in the peak spinal loading observed in engine assembly when operators reach to retrieve heavy parts from the bottom of a large crate. This illustrates how the MS can influence risk due to load amplitudes. The type of container can affect loading experienced during picking activities (Christmansson et al., 2002), as can the positioning of the container at the workstation.

In paper 4, we observed that attempts to change the parts container interacted with business agreements with parts suppliers. Change here would require both engagement of the purchasing department and the supplier company - a daunting task for a busy production engineer. One solution to space constraints is to create a product kit as observed on the cell system in paper 3, a strategy particularly useful in cases with many product variants (Bozer and McGinnis, 1992). The design of the component kit is critical to performance in long cycle dock assembly as it provides all necessary components and implicit guidance in assembly sequence to complete the assembly task without leaving the workstation (Bozer and McGinnis, 1992; Medbo, 1999; 2003; Nagamachi, 1996). A well designed kit can facilitate both fast learning times and fast assembly times (Medbo, 1999; 2003; Nagamachi, 1996) although, in the case in paper 3, assembly speed and learning were both seen by the company as weaknesses in the existing cellular assembly system in paper 3. The picking of the kit itself remains a weak spot in this MS strategy and was seen in the engine assembly case as one reason for abandoning the cellular manufacturing strategy. Parallel flow cellular assembly strategies will likely remain unpopular unless more efficient kitting approaches can be developed.

4.5.4 Work Organisation Strategies

The absence of a rotation scheme in the automotive site used in Paper 1 made it feasible to quantify physical workload on many operators since each operator needed only to be assessed working on their particular workstation. In the electronics case (Paper 2) the issue of work rotation was more complex. Managers rejected a team-based rotation plan. Part of the reason for this rejection appears to be the use of workers from a ‘temporary’ employment agency. This made the multi-skilling of workers appear less cost effective because future automation efforts would lead to the elimination of these temporary operators. The tendency to favour an un-skilled workforce, a trend noted by Perrow (1983), may also have been part of a larger corporate strategy to shift production to China – where this system is now based.

In the engine assembly case, the new line system had a team-based work organisation, originally a central element of sociotechnical design approaches (Eijnatten et al., 1993; Engström et al., 1995). In this case we observed improved co-worker support, an ergonomic benefit (Karasek and Theorell, 1990), over the OLD dock system where operators worked alone in their own ‘dock’ workstation until they reached their quota, itself a barrier to productivity. The team structure, along with ‘runners’ who moved along the line, was seen as necessary to overcome the systems losses inherent in serial flows. Job rotation within the teams provided some task enlargement (but not enrichment) and can distribute time-intensive loading across the workforce (Kuijer et al., 1999). Rotation may also expose more workers to hazardous peak load situations thus increasing a system’s total risk level (Frazer et al., 2003).

4.5.5 Social and Technical Sub-System Interplay?

Taken together there appears to be a tendency for companies to use technical solutions to circumvent problems arising from the work organisation, and work organisational solutions to solve problems inherent in the technical sub-system. The extent to which the design of the technical system is influenced by the design of the social-subsystem is difficult to isolate, we observed simultaneous consideration of these issues in the design team. In practice this discussion can be inhibited by the lack of clear, unambiguous objectives for the work organisation (Wulff et al., 1999a; b). Medbo & Neumann (Medbo and Neumann, 2004) have demonstrated how the interaction of specific social and technical sub-system features can be examined using flow simulation - an application approach that appears to be novel. Further work is needed here to understand the complex interactions in these two domains.

4.6 Individual Factors

Individuals and normal life events had a great impact on the uptake of ergonomics into the organisation.

In paper 1 we demonstrated how individuals’ workplace exposure to postural risk factors is associated with LBP risk. The larger OUBPS study suggests that workplace factors are generally more important than individual factors in determining risk (Kerr, 1997; Kerr et al., 2001). In Paper 4 we changed our focus from individual operators to individuals throughout the organisation. Here we observed how individual’s situations can influence organisational change efforts. Of the many life events that were experienced by company personnel during the time of the project, it is primarily staff turnover that has been discussed in the change literature (e.g. Smith, 2003). For the practitioner trying to navigate ergonomics issues through the organisation it may be helpful to understand what is going on in peoples lives and careers. If the navigator (c.f. Broberg and Hermenud, 2004; Jensen, 2002) is experiencing resistance, understanding the contributing personal factors may help the navigator choose alternative approaches to moving the ergonomics agenda forwards. The human factors of organisational change appear to be important.

Model Issues: The studies here seem to support the need to consider 'individuals' beyond just the system operator, especially if one is trying to affect organisational change. The extent to which individuals' acceptance of ergonomics objectives is affected by group membership, for example connection to the sub-culture of engineering, remains an interesting research issue. This is similar to the concept of 'Clan' control mechanisms in organisational theory (Hatch, 1997). The model presented does not explicitly include the presence of multiple overlapping group memberships although these could be mapped to better understand an individuals' particular organisational circumstance.

Methodological Issues: While we have used primarily qualitative methods there exist many possibilities to use, for example, questionnaires to measures specific aspects of individual psychology. Reporting of individual factors can be quite sensitive, particularly in a case study scenario where individuals might be readily identified. If we believe there are certain 'types' of individuals with different knowledge sets, for example the "worked my way up engineer" as opposed to the "University trained engineer", exploring the differences of these types would be better done with a broader survey, similar to Broberg 's (1997) approach to studying product and process engineers' approach to ergonomics.

4.7 Organisational Factors

Organisational features can influence ergonomics due to the trend to separate human and technical aspects in the design process. Organisational boundaries can also inhibit the uptake of ergonomics into existing routines.

The action research study (paper 4) revealed organisational barriers to integrating ergonomcis into development processes. This analysis illustrated how the communication and responsibility barriers created by an organisational structure, such as the sub-division of the system design task, can lead to problems as the various pieces come together. Senge (1990), from an organisationl learning perspective, has discussed the kind of dysfunctional side effects that can emerge from the organisational design and the importance of alignment amongst stakeholders. In this case we observed the utility of Broberg & Hermenud's (2004) 'political reflective navigator' stance, in this case taken by the production manager (PM) acting as an internal agent with 'insider' knowledge to overcome setbacks and identify new approaches to integrating ergonomics into development. The program however remains vulnerable so long as the PM stands alone in the organisation supporting the initiative. Fortunately in this case the engineering department and company health and safety service both appear poised to take up this ongoing challenge.

> **"What faces those charged with bringing about changes in organisations is much more of a mess than a difficulty."** – *Saka 2003*

In paper 4 we were able to map how different organisational units participated in the development process (Figure 3.4.2). While other companies might have other developmental structures, the need to divide large design tasks amongst groups to ensure timely completion is quite common. Recent development in concurrent engineering, for example, appear to have potential for improved attention to human factors (Badham et al., 2000).

Model Issues: The model used does not explicitly include the many organisations that make up a companies "interorganisational network" in a particular supply chain (Hatch, 1997). This network structure could be incorporated in a particular formulation of this model when analysing a specific situation. The distribution of the design task amongst different groups, as was elaborated in Paper 4, may require elaboration in model applications.

Methodological Issues: The methods applied here were exploratory and qualitative. The extent to which the trends observed here apply to other cases may depend on their similarity and tools are needed in this area. Methodological issues here include sampling or recruitment strategies, and choices regarding breadth vs. depth implicit in for example quantified surveys vs. qualitative interview approaches. The slow rate of change of organisations creates a further time-frame problem when trying to evaluate the effects of an organisational change effort. The research and developmental challenges here are immense.

4.8 Societal Factors

While this dissertation is not focussed on social factors – understanding the role of society and cultural differences in the application of ergonomics is critical both to ensure that local action is appropriate and to ensure global trade is socially equitable.

In both cases of production redevelopment (Paper 2 & 3) the company was reacting to increased demand for their products from customers, and also wished to decrease product cost to improve their competitiveness in the global market. Neumann and Winkel (2004) have discussed how investor and customer demands place the organisation under competitive pressures. Rasmussen (1997) has described, and Woo and Vicente (2003) have illustrated, how the individuals in a complex system, reacting to pressures of competition by making changes (or cutting corners) in their own domain of authority, can drive the whole system into unsafe operational states. Paper 4 illustrated how risks can emerge when disparate development sub-systems, are combined. In the face of senior manage disinterest in human factors (Perrow, 1983), and the general absence of long term focus (Huzzard, 2003), it is easy to see how Rasmussen's (1997; 2000) osmosis into risk zones hypothesis might occur.

> **"In a culturally diverse and globally competitive world, scholars can only sit in discomfort in their own corners of the world pretending their patterns of change are the world's patterns of change"**
>
> - Pettegrew, 2001

Pettegrew (Pettigrew et al., 2001) has pointed out that international comparative research on organisational change is an important priority. In paper 4 (engine assembly) we studied a situation in which a senior production manager, with a clear vision for human factors, demonstrated an unwavering resolution to achieve his goal. Perhaps this is a special individual who is the product of a special (Swedish) culture and is thus a social aberrant? Further research is needed here to understand the sociological determinants by which management will accept human factors agendas.

Model Issues: The model presents society as a single entity. While some might say technology has led to us to living in a 'Global Village' (McLuhan, 1968), this is not sufficient to understand how global societal forces can affect ergonomics. Better model resolution in social structures would be needed to study, for example, how consumer demand for cheap goods can lead to working conditions in foreign factories that the consumers themselves would consider unacceptable.

Methodological Issues: There is a very large range of approaches to studying social factors including qualitative and quantitative approaches applied on both micro and macro scales. Discussing these possible approaches is beyond the scope of this thesis. Paper 4 was not really able to isolate the external social forces that are said to influence change process (Bamford and Forrester, 2003).

4.9 Model Redevelopment

The studies conducted suggest an extension of the model would be helpful. Emphasising 'overall' corporate strategies and product development processes underlines the influence of these two aspects that are not considered in this thesis.

In light of the research presented and reflections discussed in this thesis, I propose a modification, or an extension of the original model (Figure 1) with increased emphasis on the strategic choices at the corporation and an explicit inclusion of the product development process (Figure 4.9).

The inclusion of product design has, similarly to process design, both strategic and design elements (levels 7 and 6 respectively). The importance of product development in defining the assembly task was discussed previously. As Broberg (1997) has pointed out: *"Design and production engineers have a great influence on ergonomics in manufacturing.*" since it is the product designer that defines the assembly task.

The inclusion of 'overall' corporate strategy (level 8) is an attempt to make explicit some of the larger forces in the organisation that are shaping behaviour. A decision to shift production to China (paper 2), for example, would be perhaps more of an 'overall corporate strategy', than a 'production strategy' per se. Corporate culture for example may be deliberately manifested in the form of value statements and visionary objectives (Hatch, 1997) as a strategy for anchoring employees to a desired behaviour pattern (Docherty, 2002). This model feature highlights the potential mechanisms by which corporate strategy can set the stage for developmental processes that can ultimately result in production operators suffering from MSDs. There is little research on how corporate strategy at this level affects ergonomics or on how ergonomics can contribute to the realisation of a particular company's strategic objectives.

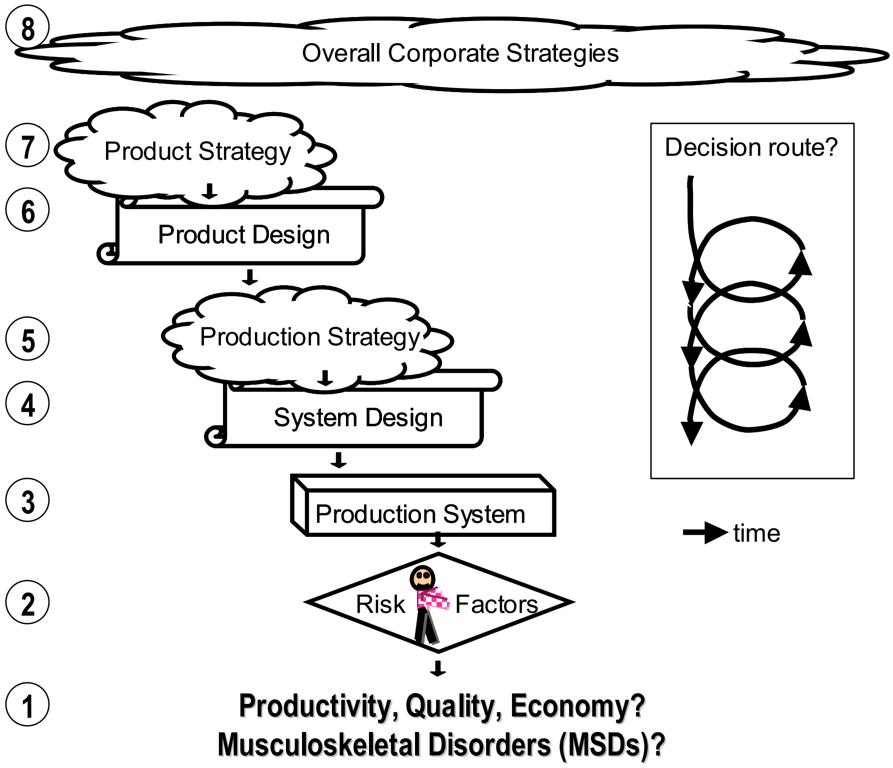


Figure 4.9: *Redeveloped process model in which 'overall' corporate strategies (8) set the stage for product development which has strategic and design decision elements (7&6) and defines the assembly task for production system development (5&4) this development will result in a production system (3) whose operators will be exposed to risk factors (2) as they run the system to generate outputs (1). If the risk factor profile (2) is disadvantageous then MSDs will result (1). Influence flow is generally downwards although decision pathways may be iterative and looping. Time flow is generally left to right with the extent of parallel development indicating the practice of concurrent engineering.*

The fuzzy border between “strategic” and “design” decisions, noted in the discussion (section 5.6), is further emphasised in the model (Figure 4.10) by the overlapping of these two concept bubbles in both the product (levels 7 & 6) and production system (levels 5 & 4) development processes. The principle that larger conceptual (strategic) choices set the stage for more specific design tasks remains useful to understand how certain aspects of production get “locked in” and are very difficult to change if they have negative consequences for ergonomics in the system. Design is a complex process with non-linear and iterative elements that can appear irrational (Broberg, 1997; Engström et al., 1998) despite the proliferation of apparently linear design models (Hammond et al., 2001; Jensen, 2002). This is emphasised by the circular ‘decision route’ spiral beside the model in Figure 4.9.

The lateral shifting of elements (flow from left to right) has been used to emphasize time aspects in the developmental process. In many organisations product and production process design are linked in parallel processes called concurrent engineering (Badham et al., 2000; Boujut and Laureillard, 2002; Luczak, 2000). In this model the extent of vertical overlap between design processes in a particular case will indicate concurrency in the engineering process. Concurrent engineering creates the potential to adjust the product design so as to improve ergonomics in production (Helander and Nagamachi, 1992).

”…the product development process is not a rational problem solving process and does not proceed in a sequential manner as described in engineering models. Instead it is a complex organisational process involving uncertainties, iterative elements and negotiation between key actors. ” - Broberg (1997)

This model should not be considered rigidly. Instead it can provide a flexible framework that can be adapted to local situation. Dynamics of a particular company with a particular developmental trajectory may require a changing adaptable approach over time. Every model is, by necessity, a simplification of reality. The point is not to build a model that reflects some absolute reality or represent a mythical ‘general’ firm (Toulmin and Gustavsen, 1996). Instead it should provide a *useful framework* to assist with the development of approaches to integrate ergonomics into a specific development situation.

4.10 Some Limitations of This Thesis

There are many limitations to this thesis. Application of any research findings should be done with the practitioners' eyes and mind wide open.

All texts, including this one, are 'coloured' by the readers and writers social contexts (Toulmin and Gustavsen, 1996). Hermeneutics suggests that misunderstanding, errors, or even new truths can emerge from the reading of a text (Wallén, 1996).

The Hazards of trandisciplinarity. Even the humble author of this thesis cannot be expert in all domains of relevance to the problem studied here. The role of researchers from other disciplines becomes critical. Similar to 'triangulation' approaches (Mergler, 1999; Nutt, 1998), this thesis strives for an interweaving of perspectives to provide a resilience which overcomes flaws in a single thread.

The case studies presented here can only illustrate the relationships in the model (Yin, 1994). Rather than 'prove' relationships in the classical positivistic sense, we attempt to understand of how system elements can interact to affect outputs. Further cases could help identify how common the findings in these cases are.

Attribution error poses a potential weakness in this thesis. Identifying which 'strategic' elements were associated with particular risks was an act of analysis in which quantified data, worker reports, supervisor comments and existing research evidence were all considered. Misattribution and overlapping effects remain a possibility. Presentations to and discussions with company stakeholders strengthen our confidence in the results.

4.11 Future Research & Development Priorities

Further work is needed if we are to benefit from the integration of human considerations into developmental processes. Attention is needed at the societal, organisational, and individual levels. Ideally this work would be coordinated across levels.

At the Society Level

- Can a society-wide trend to apply ergonomics in work system design be established? By what mechanisms?
- Are there social factors (e.g. attitudes, values, knowledge base) inhibiting uptake and application of ergonomics? Do these differ between countries?
- What groups are critical to success? Can customer and investor power be harnessed to foster good ergonomics? Can other groups be engaged?

At the Company Level

- How can companies be motivated to integrate ergonomics into development? Can the strategic and performance benefits of ergonomics be better demonstrated?
- If ergonomics *is* to be integrated into development work – how can this integration be best achieved?
- How do the organisational dynamics and patterns of risk emergence observed here play out in other companies? In smaller enterprises? In other sectors?

At the Individual Level

- How can individuals be helped to handle ergonomics in their development work? What knowledge, tools, or support is needed?
- Can knowledge about risk factor dose-response relationships be made more useful to system designers? How stable/linear are these relationships?
- How does integrating ergonomics into daily development work affect the individuals involved? Is there extra work? How does the individual's role change? Do we create new problems?

5 Conclusions

With regards to risk identification:

- It is possible to obtain reliable and accurate quantification of work related risk factors for MSD from video recordings: in this case posture and movements related to low back pain. MSD risk factors can be measured in existing systems and, by implication, could be predicted in planned systems to provide leading indicators of MSDs.

With regards to sources of risk in production system design:

- The early selection of technological solutions tended to lock in risk factors and could not be overcome by adjustments to the workstation layout. This highlights the ergonomic impact of early strategic decisions made by senior managers.

- While workstation layout (in conjunction with the material supply sub-system) determines operators' physical load amplitudes, the flow strategy and work organisation influence the pattern of physical loading. Psychosocial factors appear to be influenced by a combination of flow strategy, work organisation and, to a lesser extent, layout.

With regards to production strategies effects on ergonomics:

- The automation of repetitive assembly work (robots) increased productivity reduced system-wide operator exposure to manual assembly work, and thus system-wide MSD risk. The automation of transportation functions (to serial flow conveyors), however, contributed to starving and blocking losses, increased repetitive monotonous work, and hence increased MSD risk for remaining manual assembly workers. The ergonomics impact of automation appears to depend on the tasks automated and the tasks remaining to the operators.

- The performance of parallel flow systems can be compromised by the work organisation, such as the use of quotas, as well as inefficiencies in the kitting system.

- The serial line systems studied here showed increased risk of musculoskeletal disorders due to increased repetitiveness and physical monotony, as well as reduced job control with elements of machine pacing, and uneven load distribution across stations.

- Serial flow systems exhibit system and balance losses. While these reduce physical workload and movements, operators do not experience this forced waiting as a 'pause'.

- The use of team structures in the serial line system improved co-worker support, which implies a risk reduction. Teamwork also seemed to support productivity by reducing the impact of system disturbances.

With regards to integrating ergonomics into an organisations' development work:

- Integrating ergonomics into the organisation, even with strong support from production management, is a slow process marked by setbacks. Developmental barriers may be at organisational (e.g. inter-group barriers, communication gaps), or at individual levels (e.g. work overload, pending retirement, life events).

- 'Ergonomics' groups that are outside of regular development processes are vulnerable to disruption from, for example, reorganisation. Lack of engineering engagement in the initial process development can lead to barriers when engineering personnel became involved in the change effort.

- A deliberate process of 'political reflective navigation', taken on here by an internal stakeholder, supports the identification of new avenues for the integration of ergonomics into regular development practice.

- Workshops appear to be a good method to provide information, solicit support, and initiate dialogue with the engineering design team. Tools such as computer simulation appear to have good potential in providing designers with quantified or unambiguous indicators they can use to consider ergonomics simultaneously with other production concerns.

- The stakeholder map was a useful 'navigational aid' and helped us understand that not all design groups with relevant control over ergonomics have yet been reached by the process.

- Engineering teams work to the mandate given by senior managers – if innovative designs are to be developed senior managers must sanction them. Introducing innovations after key strategic choices may be too late to be taken up into the design process.

Taken together the results of this thesis suggest there are clear linkages between strategic choices made early in system design and musculoskeletal disorders. Each stage of the development process appears to have potential to contribute to or mitigate risk in the resulting system. Managing this risk implies changing roles for individuals and groups in the organisation. The change process to achieve this appears slow. Integrating human factors into work system design has potential to improve total system performance, but remains an under-utilised strategy for sustainable development.

6 Message to Practitioners

Based on the results of this thesis and on available information in the reviewed literature the following few suggestions, oriented to practitioners, seems appropriate:

1. Regarding risk factor quantification:
   a) Quantification of workplace risk factors, such as physical workload, can provide precise information related to MSD risk, and can support communication and build credibility for ergonomics.
   b) Risk factors can be used as leading indicators of MSDs and can help evaluate the ergonomic quality of existing or planned systems.
   c) Watch out that reducing risk factors in one area does not result in a shifting of risk to another risk factor. For example, reducing load amplitude may open the door to increased repetitiveness, while improving back postures may lead to increased shoulder loading. Would your measurement strategy catch this shift in risk?

2. Regarding automation:
   d) Consider not just what tasks are being automated but also what tasks remain for humans – removing repetitive work may decrease total risk but if variety-giving tasks are automated, risk at particular workstations may increase.
   e) Design managers should ensure that technological design is properly integrated with human factors in terms of physical load amplitude, loading pattern, and psychosocial conditions.
   f) Managers should encourage healthy scepticism as to the ease of reaping the benefits of technology systems.

3. Production system designers should establish ergonomic objectives and set the stage for work-related musculoskeletal disorders in their systems. Therefore ergonomics should be considered in all aspects of system design:
   g) Focus on the design <u>process</u> not just on the design problem.
   h) Tools estimating risk factor exposure, leading indicators of risk, should be applied at the earliest design stages possible.

i) Human factors requirements, specified as specifically as possible (ideally in reference to the tools!), should be set as design requirements. Consider here both psychosocial and physical working conditions.

j) Avoid design processes that isolate consideration of ergonomics issues from other productivity elements – ergonomic issues should be integrated into all design stages.

k) 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.

4. Parallel flow, long-cycle assembly has both ergonomic and productivity advantages over short-cycle line assembly, particularly in multi-variant production environments. Nevertheless careful implementation, particularly of the material supply system, is needed to realise these benefits. A good kit can make even complex assembly fast and simple.

5. Making change to an organisation's development process takes years and can suffer setbacks. Don't get discouraged – adopt a reflexive stance. Consider what the current situation is and try to identify new courses of action with potential to further the ergonomics agenda. Think (micro) politically about how the organisation is structured, seek allies and build coalitions to support integrating human factors into regular development – it is, after all, the way to better performance.

7 Acknowledgements

This thesis has been financially supported by the National Institute for Working Life West in Gothenburg, Sweden. The first study in this thesis was funded by the Institute for Work & Health in Toronto, Ontario. Support was also received from the Ergonomics Initiative, a collaboration between the University of Waterloo and General Motors of Canada, A.G. Simpson Corp., and The Woodbridge Group. This work is also associated with the COPE (Co-operative for Optimisation of industrial production systems regarding Productivity and Ergonomics) network. The financial assistance of VINNOVA - the Swedish Agency for Innovation Systems, Project d.nr. 2002-01679, is gratefully acknowledged.

I would like to thank my supervisory team for the incredible richness of thought and stimulation they provided throughout this work: Jørgen Winkel, Richard Wells, Svend Erik Mathiassen, Marianne Ekman Philips, and Roland Akselsson. It has been a pleasure working with you.

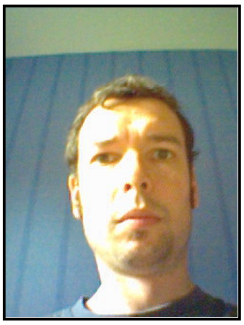
More people than I can name have influenced this thesis and supported me in my work. Thanks to those in Canada: Bob Norman, Mardy Frazer, John Frank, Harry Shannon, Donald Cole, Mickey Kerr and all of the OUBPS project gang (Do you remember who you all are?), Ergonomics Initiative types, the CAW, as well as technical support everywhere.

Thanks to my Swedish research cohorts: Per Medbo, Lars Medbo, Steve Kihlberg, Rutger Magneberg, Karolina Kazmierczak, Mikael Forsman & Gunnar Palmerud amongst many. Thanks also to all the *Duktiga Doktorander* as well as all of you at ALI-väst for the high quality of working life!

Tusen Tack to the staff at Volvo Powertrain in Skövde, the kind Företaghälsovård folk, Leif Olsson, Johnny Bjur, Erik Larsson and all the D12 team. Thanks also to Sigvard Lantz, I miss you but remain grateful for the learning we shared – it was too brief!

Finally I send a great 'HEJ!' to all family and friends for support and good times. An extra super duper thanks goes to Sara for your support, good humour, and unfailing willingness to leave the beaten path in search of adventure.

October, 2004.
-P.



Laptop's view of the author thanking you for reading this thesis!

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PAPER 1

Trunk Posture: reliability, accuracy, and risk estimates for low back pain from a video based assessment method

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International Journal of Industrial Ergonomics, 2001, 28: 355-365.

ELSEVIER

International Journal of Industrial Ergonomics 28 (2001) 355–365

International Journal of
Industrial Ergonomics

www.elsevier.com/locate/ergon

Trunk posture: reliability, accuracy, and risk estimates for low back pain from a video based assessment method

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Received 29 June 2000; received in revised form 15 February 2001; accepted 30 April 2001

Abstract

It has been recently reported that both dynamic movement characteristics, as well as the duration of postures adopted during work, are important in the development of low back pain (LBP). This paper presents a video-based posture assessment method capable of measuring trunk angles and angular velocities in industrial workplaces. The inter-observer reliability, system accuracy, and the relationship of the measured exposures to the reporting of low back pain are reported. The video analysis workstation consisted of a desktop computer equipped with digital video capture and playback technology, a VCR, and a computer game type joystick. The operator could then use a joystick to track trunk flexion and lateral bending during computer-controlled video playback. The joystick buttons were used for binary input of twisting. The inter-observer reliability for peak flexion and percentage of time spent in posture category variables were excellent (ICC$>$0.8). Lower reliability levels were observed for peak and average velocity and movement related variables. The video analysis system time series data showed very high correlation to the criterion optoelectronic imaging system ($r = 0.92$). Root mean square errors averaged 5.8° for the amplitude probability distribution function data. Trunk flexion variables including peak level, peak velocity, average velocity indicators, and percent time in flexion category indicators all showed significant differences between cases and controls in the epidemiological study. A model consisting of the measures peak trunk flexion, percent time in lateral bend and average lateral bending velocity emerged after multivariable analysis for relationship to low back pain.

Relevance to industry

Risk of injury for the low back is multifactorial. The trunk position and movement velocity are emerging as important parameters. This analysis confirms the importance of these factors and demonstrates the utility of a video-based method to measure them in industrial settings.

Keywords: Low back pain; Posture; Kinematics; Epidemiology; Reliability; Accuracy

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PII: S0169-8141(01)00042-7

1. Introduction

Effective prevention strategies for work related low back pain (LBP) demand a detailed understanding of the risk factors associated with low back pain. Awkward postures adopted during work are risk factors that have been identified as having consistently significant and epidemiologically powerful associations with LBP (Bernard, 1997; Garg, 1989). LBP, however, is known to be a multifactorial problem with both physical, psychophysical, and psychosocial components operating in the injury process (Kerr et al., 2001). To understand the relative importance of these factors, and to engage in active risk factor identification and quantification processes in the work place, reliable and accurate measurement tools are needed.

Many studies have used self-report methods to assess postures at work (Bernard, 1997). These approaches suffer from disadvantages of unreliability (Wiktorin et al., 1993; Burdorf and Laan, 1991). Additionally, the precise definition of what constitutes "awkward" in working postures is unclear for many body joints. Recent studies using detailed quantification of kinematic parameters have found strong risk-relationships (Punnett et al., 1991; Marras et al., 1995; Norman et al., 1998). These methods have helped to identify trunk kinematic variables in specific terms such as "percent of time flexed beyond 20°", "maximum trunk velocity", and "peak flexion level". If practitioners are to quantify these risk factors in the field they must have access to techniques which can be readily used in a variety of work situations. Data collection based on commercial video-recorder technology is portable, familiar to many people, does not encumber the worker in anyway, and is relatively inexpensive. Once a workplace recording is made, it must then be processed to extract the desired indicators. This paper describes and evaluates a method that allows quantification of trunk posture and velocity, in continuous scales, from field recorded video.

The purpose of this paper was to assess the reliability and accuracy of a computer-assisted video analysis technique for measuring trunk kinematics in the workplace. Additionally, this paper reports on the risk relationships of the kinematic parameters, determined using this system, in an epidemiological study of low back pain in the automotive industry.

2. Methods

2.1. Measurement system

The video analysis workstations consist of a desktop computer equipped with digital video capture and playback technology, a VCR, and a computer game type joystick, Fig. 1. Video was recorded in the field. Since flexion-extension was of primary interest, a side view was obtained whenever possible. The video section of interest, usually 3–10 min of work, was digitized and stored on a computer hard disk. During analysis, the digital video was played back in the top left quadrant of the screen while rear and side views of a stick figure, representing the figure in the video, were displayed on the bottom half of the screen. As the operator entered postural information corresponding to the displayed video frame the stick figure, at the bottom of the screen, adopted the entered posture. The system, therefore, provided continuous feedback to the operator with two orthogonal views of the stick figure mannequin to help the operator judge the correctness of complex body positions or postures outside of the plane of the camera. Constraints in the workplace often resulted in a variety of viewing angles on the video. In all the cases, the operator was required to use their best judgement in determining the correct posture or angle inputs to the system. Categorical postures such as sit, stand, walk, or squat were recorded using keyboard input. Continuous measures of trunk flexion/extension and lateral bending, operationally defined as the angle formed by the line between L4 and T9 with respect to the vertical, were recorded by the operator using a joystick to track the posture seen on the video. Trunk twisting was defined as being present, whenever the angle of a line between the hips relative to the line between the shoulders, was greater than 20°. Twisting was recorded using the

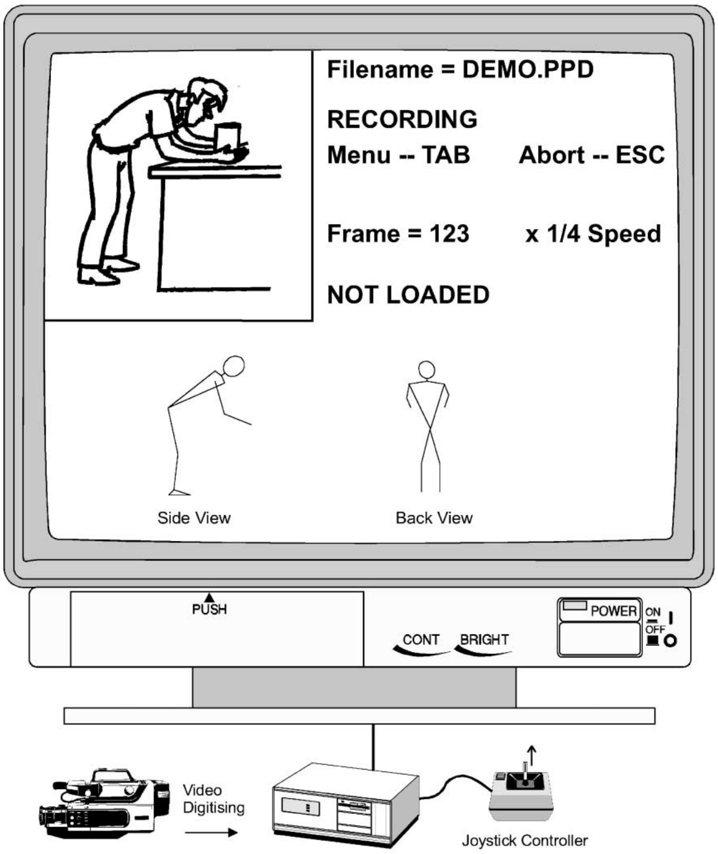

Fig. 1. Schematic diagram of the video-based posture analysis system in which the operator uses a computer game type joystick for continuous tracking of posture over a selected section of digitised video. Captured video is played back in the top left corner of the screen while stick figures (bottom of screen) provide continual visual feedback for the operator.

joystick ‘fire’ buttons, which allowed for binary recording of this variable.

The operator’s task was to ensure that the joystick and keyboard controlled stick figures matched the posture adopted by a worker on the video throughout the video clip being analyzed. The computer sampled the mannequin posture once for each frame of digital video presented, resulting in a nominal 30 Hz signal recording regardless of the analysis speed chosen by the operator (usually about 1/5 speed). The computer handled all time-synchronizing functions allowing the operator to adjust playback speed and make changes or corrections at any point in the analysis. Data were then low pass filtered at 3 Hz using a dual pass Butterworth filter to remove high frequency artifact caused by the operator and input device characteristics. The time series data were then differentiated to generate a velocity profile. These traces were then converted into amplitude probability distribution functions (APDF) from which exposure variables were extracted in both time and amplitude domains (Jonsson, 1982). These included the percent time in neutral postures (−5° to 15° flexion), the percent time spent in forward flexion greater than 20°, and the percent time spent flexed greater than 45° (cf. Punnett et al., 1991). The peak flexion, lateral bend, and velocity levels were taken as represented by the top (1st) percentile level from the APDF.

2.2. *Inter-observer reliability study*

Seven (7) trained observers were used for the reliability portion of the study. All observers used in this study were the staff from the Ontario University's Back Pain Study physical loading assessment team and had been trained using a standard 10–15 h training protocol.

Ten (10) production jobs were selected from a larger pool of worksite video collected as part of the epidemiological study used in the risk-validity portion of this paper. All the jobs selected provided an unobstructed view of the worker throughout the work cycle, had a regular cycle time of approximately 1 min, and provided a realistic range of work activities seen in production workers in a large automobile assembly facility. A single cycle, deemed to be representative of the job, was chosen from the video and was digitised for further analysis. Each operator analysed the minute-long video samples, or clips, of each job, which were presented once, in random order. Intra-class correlation coefficients were used as an index of similarity of results between the observers (Shrout and Fleiss, 1979).

2.3. *Accuracy study*

Eight (8) trained observers were used for the accuracy assessment. The accuracy of determining trunk kinematics using the computer-assisted video method was assessed by comparing the operator's video analysis results to a criterion, or gold standard, measurement system. The video and the criterion 3D co-ordinate data, derived from an optoelectric imaging system (Optotrak, Northern Digital Inc., Waterloo), were collected simultaneously during the performance of a 1 min long simulated manual material handling task in a lab setting.

Infrared emitting diodes (IREDs) were attached to the skin at the C7 and L4 levels. A trial of quiet standing was collected to establish a baseline bias level that was removed from the data collected during the simulated task. The co-ordinate data from the optoelectric imaging system were processed, windowed and converted into degrees of trunk inclination and velocity, which were directly comparable to the video system data. This system had a stated accuracy of 0.3 mm in the x–y plane at the distance used for this study and was assumed as the criterion measure for comparison purposes (Northern Digital Inc., Waterloo, Canada). Accuracy was assessed by calculating the average difference and percent difference for selected variables of interest. Root mean square errors were calculated for the APDF values. Additionally, Pearson correlations between the observers' results and those from the reference system were calculated for both the time series and APDF data.

2.4. *Risk relationship study*

The study was performed in a large automobile assembly facility with a study base of over 10,000 hourly-paid workers. Incident cases were identified as they reported to the plant nursing station with low back pain. Cases were not required to have lost any work time due to their LBP. Controls were selected randomly from the employee roster at the same rate as cases. Both cases and controls were screened to have had no LBP reports in the previous 90 days. When a case was not available to be assessed, a worker doing the same job as the unavailable case was recruited and their data were used as a "proxy" to the missing case (cf. Punnett et al., 1991). In total, 129 controls and 105 cases (including 20 "proxies") were studied while they performed their regular work using a detailed battery of physical loading measurement instruments simultaneously. These methods included the computer-assisted posture assessment system described in this paper. Further details of the epidemiological investigation are available elsewhere (Kerr et al., 2001).

Participants included 'on-line' production workers, whose jobs had regular cycle times, as well as non-cyclic support and maintenance workers. Participants were monitored for 2–8 h, depending upon the complexity of observing the tasks of their job. The observer performed a breakdown of the job into tasks. This record was subsequently used to select representative sections of each task for each participant. This paper will report only on the results from the computer-assisted posture assessment method. Details of the other measurement strategies applied in the larger epidemiological study, different from the video-based method described here, are published elsewhere (Wells et al., 1997; Norman et al., 1998; Neumann et al., 1999, 2001).

Cases and controls were compared initially using a student's *t*-test. Variables showing significant differences were further examined in bivariable logistic regression analysis to generate odd ratios. Multivariable logistic regression analysis, using a backward selection procedure starting with all variables, was conducted to identify a set of postural variables, which have independent contributions to injury risk. Multicollinearity among the whole body posture categories (sit, stand, walk), which collectively summed to 100% of time, was identified as a problem in initial analysis. To avoid this problem only the "percent of time standing" category was retained for submission to the model as the most common risk factor present in this group (Magora, 1972; Xu et al., 1997).

3. Results

3.1. Inter-observer reliability study

Inter-observer reliabilities for key variables are presented in Table 1. The reliabilities of peak flexion and percentage of time spent in posture category variables were excellent (ICC > 0.8). Somewhat lower reliability levels (ICC of 0.4–0.8) were found for peak and average velocity and movement related flexion variables. Slight or fair reliabilities (ICC < 0.4) were found for the peak extension and lateral bending variables.

3.2. Accuracy study

The video analysis system data showed very high correlation to data from the optoelectric system ($r = 0.92$) when examined as time-series data. A representative example of a time-series trace is given graphically in Fig. 2. Root mean square errors were 12.85° when calculated from the time-series data and 5.79° when calculated from the APDF, which was used for the extraction of variables in the risk relationship study. Comparison of the operator mean scores to the optoelectric data is presented in Table 2. The lag of the video signal contributed to the moderate RMS errors but did not affect the APDF parameters that were used in the epidemiological study. Differences between the two systems were lowest for posture variables and highest for velocity variables. Digital video analysis tended to overestimate peak trunk velocity while average velocity showed less than 4% difference over the reference system.

3.3. Risk relationship study

The results of bivariable comparisons of all variables against case-control status are presented in Table 1. Trunk flexion variables including peak level, peak velocity, average velocity indicators, and percent of time in flexion category indicators all showed significant differences. Compound postures of flexion, twisting, and or lateral bending, which were infrequent in this population (less than 2% of time), showed no significant differences, and were not included in Table 1. Odds ratios indicating the strength of associations, for variables with significant case-control differences, are presented in Table 3. Odd ratios were calculated using an exposure difference equal to the inter-quartile spread observed in the randomly selected control subjects. Less conservative risk estimates were also calculated using an exposure difference equal to the spread between the 10th and 90th percentiles observed in the random controls. A multivariable model indicating a minimum variable set with statistical independence is presented in Table 4.

Table 1
Results of both the inter-observer reliability test and LBP risk relationship study[a]

Variable	Reliability	Case			Controls			*t*-test
	(ICC)	*N*	Mean	s.d.	*N*	Mean	s.d.	*p*-value
Peak extension 1%ile (deg)	0.04	80	−2.2	2.3	114	−3.0	3.6	0.05
Median flexion/extension (deg)	0.79	105	3.8	4.0	129	2.6	3.4	0.01*
Peak flexion 1%ile (deg)	0.80	105	51.2	22.3	129	39.2	23.4	0.00*
Peak lateral bend amplitude	0.24	105	28.9	12.6	129	29.1	12.4	0.90
% time extended (past −5°)	—	105	0.3	1.4	129	2.1	8.6	0.03*
% time in neutral (−5° to 15°)	0.90	105	84.5	12.7	129	87.6	13.5	0.08
% time flexed over 20°	0.87	105	11.6	11.2	129	7.5	10.6	0.00*
% time in severe flexion (>45°)	0.88	105	4.3	6.5	129	2.2	3.9	0.00*
Peak extension velocity 1%ile (deg s^{-1})	0.48	105	−42.5	16.8	129	−35.9	18.5	0.01*
Median trunk velocity (deg s^{-1})	0.09	105	0.7	0.4	129	0.7	0.4	0.71
Peak flexion velocity 1%ile (deg s^{-1})	0.43	105	41.3	15.2	129	34.2	17.3	0.00*
Peak lateral speed (deg s^{-1})	0.11	105	108.2	47.5	129	103.7	44.4	0.45
# back flexion movements (# min^{-1})	0.61	105	2.9	2.1	129	2.3	2.3	0.04*
# back lateral bend movements (# min^{-1}) amplitude	0.16	105	1.1	1.6	129	1.2	1.6	0.64
# back twists (# min^{-1})	0.27	105	1.4	2.3	129	1.0	1.6	0.11
% time in twist (>20°)	0.23	105	2.0	4.0	129	1.7	4.2	0.52
% time in lateral bend (>20°)	0.02	105	1.5	2.5	129	2.4	5.3	0.10
Average lateral velocity (deg min^{-1})	0.17	105	269.9	109.2	129	238.1	118.9	0.04*
Average flex./ext. velocity (deg min^{-1})	0.62	105	306.6	136.7	129	252.7	133.7	0.00*
Stand—% time	0.82	105	64.1	27.5	129	63.6	30.2	0.88
Sit down—% time	—	105	28.1	27.1	129	31.5	30.3	0.37
Walk—% time	0.82	105	6.9	8.4	129	4.5	6.5	0.02*
Squat—% time	—	105	0.3	1.2	129	0.2	0.6	0.42
Kneel—% time	—	105	0.5	3.1	129	0.2	1.4	0.42
Lie—% time	—	105	0.1	0.4	129	0.0	0.0	0.15

[a] Reliability is indicated by the intra-class correlation coefficient (ICC) or, if not available, with a '–'. The sample size, means, and standard deviations (s.d.) of cases and controls as well as *t*-test results from case-control comparisons are indicated for all variables. Significant differences ($p<0.05$) are indicated with a*. %ile = percentile.

4. Discussion

In selecting the video clips to be used for the inter-observer reliability evaluation, every effort was made to ensure that the trials used would be as similar as possible to the data collected in the epidemiological study. Comparison of the test data used here to the data from the Ontario Universities Back Pain Study, revealed that the test data set generally contained higher exposures in terms of increased flexion amplitudes, longer times spent flexed, and more flexion/extension movements than those seen in the main database. This use of more difficult tracking trials suggests that the reliability results are not inflated by the selection of unrealistically simple trial tasks.

The accuracy trial used a single test file for this study (see Fig. 2 and Table 2) which contained many movements with large amplitudes and fast movement speeds. In the accuracy test, the peak velocity was over twice as fast as those observed in the industrial site from the epidemiological data. Similarly, the average velocity in the accuracy test was over eight times higher than in the field observations. This suggests that the accuracy results presented in this paper are a conservative estimate of the results that might be expected in industrial worksites. The system presented here was put through a rigorous test of its performance characteristics with robust results. While caution may be required when assessing extension postures, or movement out of the plane of the video such as lateral bending or twisting, reliable and

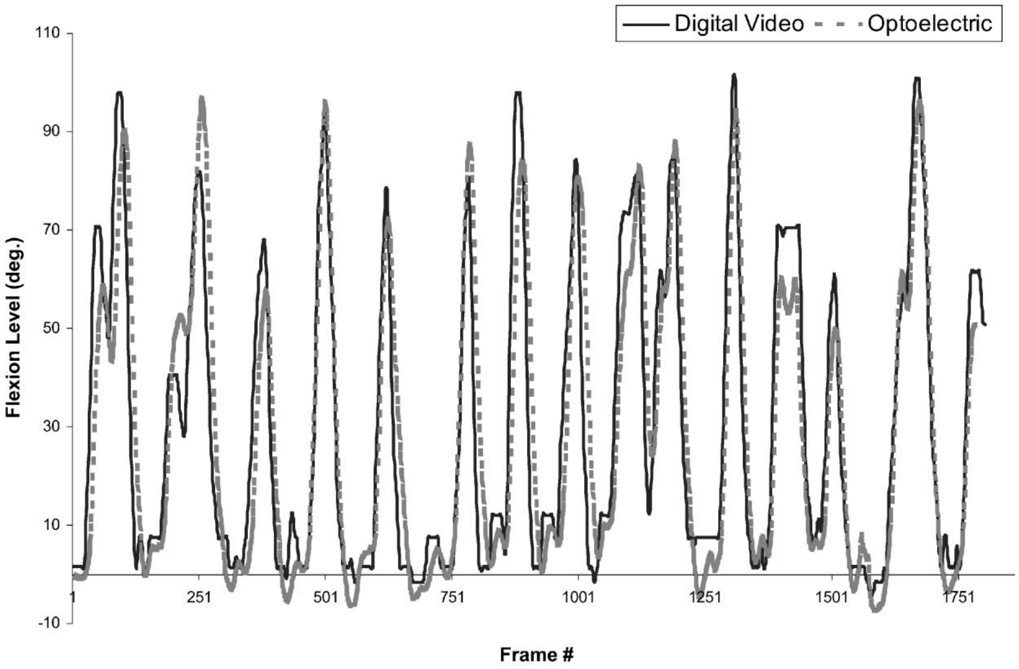

Fig. 2. A sample accuracy test result comparing digital video analysis system data over the simultaneously recorded data from the optoelectric imaging system in a trial lasting about 1 min and including many large flexion/extension movements.

Table 2
Results of the accuracy test for specific variables[a]

	Optoelectric system	Operators			Difference	% dif.
		Mean	s.d.	C of V		
Peak extension—1%ile (deg)	−6.6	−1.9	1.3	−0.70	4.7	71.4
Peak flexion—1%ile (deg)	94.6	97.8	5.7	0.06	7.1	9.4
% time in neutral (−5° to 15°)	45.1	49.7	2.2	0.04	4.6	10.3
% time flexed over 20°	48.9	47.3	2.4	0.05	−1.6	−3.3
% time in severe flexion ($>45°$)	33.3	33.7	4.6	0.14	0.4	1.3
Peak extension velocity 1%ile (deg s^{-1})	−112.1	−145.1	13.4	−0.09	−33.0	−29.4
Extension velocity—10%ile (deg s^{-1})	−76.5	−87.6	9.6	−0.11	−11.1	−14.4
Flexion velocity—10%ile (deg s^{-1})	77.0	83.8	5.6	0.07	6.8	8.8
Peak flexion velocity—1%ile (deg s^{-1})	110.7	150.2	21.7	0.14	39.5	35.6
# back flexion movements (min^{-1})	34.3	32.2	0.9	0.03	−2.1	−6.2
Average flex./ext. velocity (deg min^{-1})	2487.4	2581.2	242.2	0.09	93.8	3.8

[a] Optotrak system results are compared to the operator means, while operator variability is indicated by the standard deviation (s.d.) and coefficient of variation (C of V). Mean operator differences and percent difference (% dif.) from the referent system are also represented. %ile = percentile.

Table 3
Univariable odds ratios (OR), 95% Confidence Intervals (95% CI), and variance accounted for (*R*-square) for selected significant variables as calculated using an exposure difference (Unit) equivalent to the inter-quartile spread and to the difference between 10th and 90th percentiles of the random control subjects. %ile = percentile

Variable	*R*-square	10th–90th spread			Inter-quantile range		
		Unit	OR	95% CI	Unit	OR	95% CI
Median flexion/extension (deg)	0.04	5.6	1.8	1.1–2.9	0.3	1.0	1.0–1.1
Peak flexion—1%ile (deg)	0.08	63.6	4.2	2.0–8.9	39.0	2.4	1.5–3.8
% time extended (past −5°)	0.03	1.9	0.8	0.55–0.97	0.3	1.0	0.9–0.1
% time flexed > 20°	0.05	18.3	2.0	1.2–3.3	9.8	1.4	1.1–1.9
% time in severe flexion (> 45°)	0.05	6.7	1.8	1.2–2.8	2.7	1.3	1.1–1.5
Peak extension velocity—1%ile (deg s^{-1})	0.04	51.2	2.9	1.4–6.4	25.5	1.7	1.2–2.5
Peak flexion velocity—1%ile (deg s^{-1})	0.06	35.2	2.5	1.4–4.6	22.6	1.8	1.3–2.7
# back flexion movements (min^{-1})	0.03	5.5	2.0	1.0–3.9	2.9	1.4	1.0–2.1
Average flex./ext. velocity (deg min^{-1})	0.05	355.9	2.9	1.4–5.9	176.6	1.7	1.2–2.4
Average lateral velocity (deg min^{-1})	0.03	315.7	2.2	1.1–4.5	160.4	1.5	1.0–2.1
Walk—% time	0.03	13.3	1.8	1.1–3.1	5.4	1.3	1.0–1.6

Table 4
Results of the multivariable logistic regression of the trunk kinematic variables against case/control status using backwards elimination selection[a]

Variable name	10th–90th spread			Inter-quartile range		
	Unit	OR	95% CI	Unit	OR	95% CI
Peak flexion—1%ile (deg)	63.6	4.03	1.9–8.9	39.0	2.35	1.5–3.8
% time in lateral bend > 20°	5.8	0.50	0.2–0.9	2.2	0.77	0.6–0.96
Average lateral velocity (deg min^{-1})	315.7	2.54	1.1–5.9	160.4	1.61	1.1–2.5

[a] Odds ratios (OR) are calculated for exposure differences equivalent to the inter-quartile spread (IQS) and at the 10th–90th percentiles from the random control subjects. Model performance characteristics were as follows: Max. *R*-square adjusted = 0.127, Concordance = 66.9%, −2 Log Chi-Square = 292.7. %ile = percentile.

accurate assessments of trunk flexion parameters were possible from our field recorded video.

The postural risk factors identified in this analysis are consistent with other research identifying awkward postures as LBP risk factors (Garg, 1989; Bernard, 1997; Punnett et al., 1991). The results and data presented in this paper are comparable to, and consistent with, the previous work of Marras et al. (1995). Workers in the present study had higher average peak flexion levels, lower flexion movement speeds, and higher lateral bending speeds when compared to those reported by Marras et al. (1995). This is likely to be related to the different types of work studied; Marras studied manual material handling work while this study looked at hourly-paid workers in automobile assembly plants including maintenance workers and skilled trades.

While the average lateral bending velocity was an independent risk factor for LBP reporting, the percent of time spent in lateral bending postures showed an unexpected protective effect in multivariable analysis. Sensitivity analysis indicated that this variable added about 2% to the estimated injury variance accounted for in the multivariable model. This relationship has been observed with other instruments applied in this same epidemiological study (Neumann et al., 2001). Similarly, the percent of time spent in extension postures, defined as extension beyond 5°, showed some protective effect in bivariable comparisons. Mean exposure to extension postures in controls of 2.1% of time compared to the cases who averaged 0.3 % of time in these postures. Marras et al. (1995), reporting exposure differences between low, medium and high risk jobs, found that low risk jobs had slightly higher maximum left bending and maximum extension positions than did medium or high risk jobs. In the study by Marras et al., the exposure in all groups was also very low but statistically significant for the extension variable while lateral bending was marginally significant for low–medium risk job comparisons. In this study, the average percent of time spent laterally bent beyond 20° was small, under 2.5% of time, for both groups. It is biomechanically improbable that extreme amounts of lateral bending or trunk extension postures will prevent low back injury.

Neither sitting nor standing emerged as risk factors in this study. This result would be expected in situations where a risk factor such as standing is distributed evenly throughout the population, as was the case in the assembly workers. Walking, defined as taking more than two consecutive steps, emerged as a risk factor in bivariable comparisons even though the average time spent for walking is quite low, below 7% of time for both groups. This variable did not contribute to the multivariable model. There is not a large body of evidence in the literature supporting walking as a LBP risk factor so these results should be interpreted with caution. Anannontsak and Puapan (1996) have reported decreased LBP prevalence with standing and walking and Biering-Sorensen (1983) also reported walking as providing some LBP relief. It is possible that, in this study, the walking variable is acting as a marker for an exposure, such as carrying loads that was not recorded by this kinematic measurement method, although it was part of other methods used in this study.

In their recent review of epidemiological evidence surveying the association between postural factors and low back pain, the National Institute for Occupational Safety and Health (Bernard, 1997) concluded there was some, but not strong, evidence for posture being a LBP risk factor. Of 12 studies cited only one study failed to show an association in bivariable comparisons between posture and low back pain. Of six studies that examined it, five identified a dose-response relationship between posture and LBP. In three studies, postural risk factors, which were identified in bivariable comparisons, were not retained in multivariable modeling procedures. The exclusion of terms from a multivariable statistical model does not necessarily indicate a lack of relationship with outcome status, but rather that the variable retained in the final model accounted for slightly more of the injury variance than did the excluded, correlated terms. Other factors, such as practicality and clarity, need to be considered before dismissing potentially useful variables based on statistical grounds alone.

We found the risk relationship to be most obvious in postural indicators associated with higher biomechanical loading such as extreme flexion or fast movement. Norman et al. (1998) showed that, of the variables selected from all measurement methods, including the video method presented here, four groups of variables contributed independently to risk of reporting low back pain: peak spinal load, cumulative spinal load, hand load, and trunk kinematics. In particular, they showed that, in multivariable modeling with variables from all four factors, trunk velocity accounted for more additional injury variance than did peak trunk angle. When trunk kinematic variables were modeled multivariably here without peak spinal load, trunk angle remains in the logistic model instead of trunk flexion velocity. This is likely because peak trunk flexion captures injury variance from two factors: trunk kinematics (correlation $r \sim 0.68$ with trunk angular velocity), and peak spinal load (correlation $r \sim 0.33-0.48$ with peak spinal load; Norman et al., 1998).

The video analysis system described here has the advantage of allowing quantification of trunk kinematic parameters without encumbering the worker in any way. While there may be resistance to using video in some work places, and line of sight limitations in other locations, we were able to use the system successfully to assess a large number of workers in a broad range of types of work in an automotive manufacturing facility. Video analysis, if conducted at 1/4 speed, would take 20 min for a single pass through a 5 min section of video plus the time required to select and capture a representative video sample.

The case-control study design used in this project has a number of advantages over cohort designs including greatly reduced costs and less vulnerability to changes in physical exposure which occur regularly in this environment due to job or engineering changes. In the present study, substantial design efforts were made to assess post-injury reporting, and job performance bias that might have systematically altered cases' psychosocial and biomechanical exposure measurements via changes in either attitudes or body use after injury. No such serious biases were found to affect the final full multivariable model (Kerr et al., 2001). The 'proxies' used in this study were part of a larger group of 'Job Matched Controls' (JMCs) who performed the same work tasks as their case matches but had not reported LBP. When cases' physical loading data were compared to JMCs' agreement was generally good and no statistical differences were found (Kerr et al., 2001). This is consistent with Allread et al. (2000) who found that job design accounted for far more variability in trunk kinematics than did within or between worker differences. In our case, the JMCs had slightly lower exposures than the cases suggesting that the use of proxies would, by narrowing the difference between cases and controls, tend to attenuate the odd ratios found in this study (Norman et al., 1998). We agree with Punnett et al. (1991) who found that using proxies increased statistical power without unduly affecting their conclusions.

While steps were taken to limit the awareness of the field study teams to the worker's case-control status, formal blinding was not feasible. Although a physical exam was conducted, this study used the behaviour of reporting pain to the plant nursing staff, only some of whom subsequently filed a compensation claim. While genetic factors related to low back pain were not examined in this study, no major differences on personal characteristics were found which might counter the job-related risk factors identified in this paper (Kerr et al., 2001). Variability resulting from the selection of representative video clips and their analysis remain a potential source for error. These factors would likely to be a random error and affect both groups equally, thereby tending to reduce rather than exaggerate the likelihood of observing differences between the cases and controls. In spite of these limitations, significant differences and substantial odd ratios emerged on a number of trunk kinematic parameters. Trunk kinematics are one of a number of known risk factors for low back pain. These results indicate the utility of video-based methods for measuring these exposures both for etiologic research and for ergonomic practice in efforts to reduce musculoskeletal disorders in the workplace.

5. Conclusions

It is possible to obtain reliable and accurate quantification of trunk flexion/extension kinematic parameters from field recorded video. This type of low cost, adaptable system has the advantage of not encumbering the worker while providing a permanent record, which can be examined for other visible risk factors. Trunk flexion parameters, such as extreme flexion or velocity show strong and consistent associations with increased LBP risk. Trunk posture and other trunk kinematic parameters, especially those associated with high tissue loading, are risk factors for low back pain reporting in industrial workplaces.

Acknowledgements

This work was funded by the Institute for Work and Health, whose core funding is provided by the Workplace Safety and Insurance Board of Ontario, Canada. The University of Waterloo employed the first author while this study was conducted. The authors would like to acknowledge all of the members of the Ontario Universities Back Pain Study (OUBPS) working group: D.E. Beaton, C. Bombardier, S. Ferrier, S. Hogg–Johnson, M. Mondloch, P. Peloso, J. Smith, S.A. Stansfeld, V. Tarasuk, Dr. David Andrews, M. Dobbyn, M.A.Edmondstone, J.P. Ingelman, B. Jeans, H. McRobbie,A. Moore, J. Mylett, G. Outerbridge , and H. Woo. The OUBPS working group would like to thank General Motors of Canada Ltd., Mr. Elmer Beddome, the Canadian Auto Workers'

Union, Mr. John Graham, the Occupational Health Nurses and all of the GM medical staff, as well as the study participants themselves.

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PAPER 2

A Case Study evaluating the ergonomic and productivity impacts of partial automation strategies in the electronics industry.

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International Journal of Production Research,
2001, 40(16), 4059-4075.

INT. J. PROD. RES., 2002, VOL. 40, NO. 16, 4059–4075

A case study evaluating the ergonomic and productivity impacts of partial automation strategies in the electronics industry

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A case study is presented that evaluates the impact of partial automation strategies on productivity and ergonomics. A company partly automated its assembly and transportation functions while moving from a parallel-batch to a serial line-based production system. Data obtained from company records and key informants were combined with detailed video analysis, biomechanical modelling data and field observations of the system. The new line system was observed to have 51% higher production volumes with 21% less per product labour input and lower work-in-process levels than the old batch-cart system. Partial automation of assembly operations was seen to reduce the total repetitive assembly work at the system level by 34%. Automation of transportation reduced transport labour by 63%. The strategic decision to implement line-transportation was found to increase movement repetitiveness for operators at manual assembly stations, even though workstations were constructed with consideration to ergonomics. Average shoulder elevation at these stations increased 30% and average shoulder moment increased 14%. It is concluded that strategic decisions made by designers and managers early in the production system design phase have considerable impact on ergonomic conditions in the resulting system. Automation of transport and assembly both lead to increased productivity, but only elements related to the automatic line system also increased mechanical loads on operators and hence increased the risk for work-related disorders. Suggestions for integrating the consideration of ergonomics into production system design are made.

1. Introduction

Global market competition has placed manufacturing companies under pressure to improve their production systems. These improvements may target a number of performance parameters including production capacity, work in process (WIP), and cost efficiency. The ergonomic consequences of these improvement processes, in terms of exposure to risk factors for work-related musculoskeletal injuries, are rarely investigated. Nevertheless work related illness and injury have emerged as major social problems that can also compromise industrial competitiveness (Aaras 1994, Hendrick 1996) due to costs related to labour turnover, absenteeism, spoiled and defective goods, and reduced productivity (Andersson 1992). The European

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Revision received April 2002.

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International Journal of Production Research ISSN 0020–7543 print/ISSN 1366–588X online © 2002 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/00207540210148862

Agency for Safety and Health at Work (EASHW) reports that over 600 million working days are lost each year in Europe due to work-related ill-health (EASHW 2000). The EASHW also reports that estimates of the economic costs of work-related ill-health are up to 3.8% of the gross national product with 40–50% of this cost being attributable to work-related musculoskeletal disorders (WMSDs).

1.1. *Causal pathway of WMSDs*

Biomechanical and psychosocial factors at work have both been shown to influence the occurrence of work-related musculoskeletal disorders. Extensive reviews have particularly identified force demands on the body, repetition and working postures as being associated with WMSD type injuries for a number of body parts (Hagberg *et al.* 1995, Bernard 1997, Buckle and Deveraux 1999). The amplitude pattern of loading on body tissue over time is suggested to be a key element of injury risk (Westgaard and Winkel 1996, Winkel and Mathiassen 1994). Muscular efforts, even when as low as 2% of maximum capability on average, have been associated with injury when the total duration of exposure is long (Westgaard 1999).

Production operators' exposures to biomechanical risk factors are the consequence of the design of the production system (figure 1). The model presented in figure 1, extended from Westgaard and Winkel (1997), illustrates how strategic decisions made by senior managers can provide constraints to the design process that will ultimately determine working conditions, and hence risk factor exposures, for the operators of the production system. Westgaard and Winkel (1997) have explicitly identified cultural, social and corporate level forces as influencing these

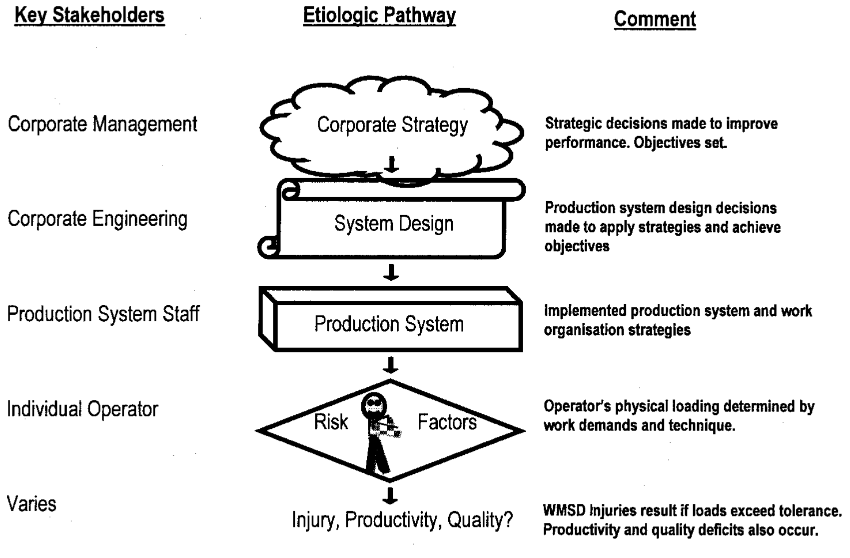

Figure 1. Theoretical model describing sources of injury (and related quality and productivity deficits) in production systems. WMSD Injuries (work related musculoskeletal disorders) are the consequence of a chain of events which start with corporate strategic decisions. This framework is embedded in social and economic contexts that will affect individual decisions at all levels of the organization.

processes. Production systems have been described as 'sociotechnical' systems with both equipment (technical) and human (social) subsystems. It has been suggested that the optimal design in both these domains requires simultaneous consideration, or 'joint optimization', in which different constraint domains are negotiated during design (e.g. Clegg 2000, Hendrick and Kleiner 2001, Ingelgård and Norrgren 2001).

If this were to be achieved in practice, it would be helpful to understand the relation between the technical sub-system and risk-related loads on human operators of the system. Each stage of the production system development process (figure 1) involves decisions that may affect system operators' biomechanical loading, and hence determine their WMSD risk. If a company is to control risk to system operators it must be able to recognize the injury potential in strategic and engineering decisions. Some connections have been identified between worker health and work production strategies such as 'Lean Manufacturing' (Landsbergis *et al.* 1999), or 'downsizing' (Vahtera *et al.* 1997). Engström *et al.* (1996) presented a number of cases of production using a parallel organization rather than conventional line, and showed that parallel production improved both productivity and working conditions. However, empirical data on linkages between specific strategies applied in production systems and their ergonomic consequences are sparse. Other negative consequences, such as quality deficits noted in figure 1, have also been linked to the presence of WMSD risk factors in the production system (e.g. Eklund 1995).

1.2. *Objectives of the investigation*

The aim of this paper was to conduct a field evaluation of the consequences of a production system re-design in terms of ergonomic and production performance characteristics. The increase in automation and the implementation of a line-based product flow observed as part of the re-design are consistent with common trends in the current industrial production strategy. The evaluation was addressed in the following series of enquiries:

(1) How did the change happen and what strategic, technical and work organizational design decisions were made during the change process?
(2) What changed in the production system and the organization of work as it was actually implemented?
(3) What were the consequences of these changes in terms of technical and ergonomic performance?

This paper focuses on the observed changes in the system, identifies the key strategic decisions implied by these changes, and examines their impact on productivity and operators' WMSD risk due to biomechanical loading of bodily tissues. Psychosocial aspects and WMSD symptom surveys were included in the larger study (Kihlberg *et al.*) but are not the focus of the analysis presented here. This investigation presents data linking ergonomics and production system design features, and thus contributes to the practical understanding required for the joint optimization of human and equipment elements in production systems.

2. Materials and methods

2.1. *The investigated case and project cooperation*

The site was a Swedish electronics assembly system producing AC/DC converters for mobile telephone transmission stations. The existing system used parallel assembly workstations with a 'batch-cart' production strategy in which operators would complete their assembly operation for one batch of product (between 4–160 items) and then manually transport the batch placed on a cartload to the next station and obtain a fresh cart of 'incoming' product. The company initiated this intervention to improve production performance. New strategies included automating assembly functions and adopting a line-based automated transportation system. The re-design was conducted with the stated goals to:

(1) increase annual production volume from approximately 115 000 to 140 000 units with capacity to expand further;
(2) decrease time to build each unit by 20%;
(3) decrease lead-time from 3.4 days to 24 hours;
(4) reduce the value of 'work in process' (WIP) by 30%;
(4) improve assembly quality so that visual inspection could be decreased by 80%.

The companies' design team was also charged with responsibility to suggest work organizational solutions, which would get and keep motivated personnel, increase the competence levels of the workforce, and organize job rotation to best distribute tasks with varying biomechanical demands between operators. Two project groups were established: The first was the technical design group focusing on production automation. The second was the work organization group charged with optimizing ergonomics and task distribution among operators in the new system.

In August 1998, the company contacted the research program COPE (Cooperative for Optimization of industrial production system regarding Productivity and Ergonomics; Winkel *et al.* 1999) to discuss a cooperation. The drive to redesign the production system came from the company. COPE was involved with the redesign project as participant-observers (Burns and Vicente 2000). Researchers attended meetings, provided advice and training to company groups, and observed the change process. A timeline for the project is presented in table 1. Initially, a three-day training course was provided for the work organization group in a number of technical and ergonomic assessment methods, including the

Start Date		Event
August	1998	Company contacts research group
October	1998	Contract signed for research project
November	1998	Training of company representatives in methods for assessment of exposure to mechanical and psycho-social risk factors
December	1998	Data collection: Video recording and questionnaires
Jan–March	1999	Analysis of activities and postures from video records
Jan–March	1999	Analysis of questionnaires and the interactive video method
May	1999	Presentation of the proposed work organization strategy to management
April/May	1999	Recruiting of personnel to the new line started
July	1999	Presentation of the implemented work organization by management
October	1999	The re-designed line begins operation
March	2000	The new plant owner of the production system takes over officially
September	2000	Data collection: video recordings of the new line, gathering of production data
September	2000	Data analysis started

Table 1. Important times for the evaluation of the production system redesign.

VIDAR (Kadefors and Forsman 2000) and PSIDAR (Johansson Hanse and Forsman 2001) participative video assessment methods. The goal of the researchers was that the work organization group should use information gathered by themselves to answer to their responsibilities towards the company. The work organization group used VIDAR and PSIDAR as well as a questionnaire and their in-house ergonomic checklist approach to assess working conditions in the system. Once the redesigned system had been implemented the research team proceeded to compare the new and old systems.

2.2. *Data collection strategy*

2.2.1. *General considerations*

Problems existed in quantifying specific indicators of company objectives. Changes, for example, in the companies' engineering time study methods, made quantified comparisons based on company data impossible. In such cases, qualitative assessments were made.

Different production operators staffed the new system, preventing individually paired comparisons, a problem that has been observed in similar studies and is part of the challenge of research in real production systems (Johansson *et al.* 1993). Large within and between individual variability, demand large subject pools for statistical power (Mathiassen *et al.* 2002) which is not feasible in most research contexts. In this study, only 1 operator-workstation pair was available for detailed analysis from the old system, although 4–6 subjects were available in the new system and over 100 subjects were available for general questionnaires (Kihlberg *et al.*). The small sample used here allows us to suggest trends but not to make statistical comparisons. While measurement error remains a concern in this study, the same measurement system assumptions, and matched manual assembly workstations, were used for both system assessments so as to limit possible bias. In order to escape the effects of inter-individual variability we have attempted to use production level indicators and biomechanical modelling procedures based on standardized anthropometrics in order to gain insights into the consequences of strategic design elements. We have applied qualitative and quantitative methods to ensure that the indicators reported here are consistent with observations made both in the field and during slow motion video observation.

2.2.2. *Production system level assessment*

Operators' work activities were examined in detail using a video-based activity analysis system with a time precision equal to one frame or 0.04 seconds (Engström and Medbo 1997). Up to 2 hours of videotape of key stations in each system were analysed depending on the frequency of relevant transportation activities. This information was then combined with production records and interview information to assess the technical performance of each system. Key indicators included: *production volume* over nine-week periods, *labour input* (in working hours per product), the amount of *'Work in Process'* (WIP), the extent of *quality work* required including checking and repairing activities, total time spent on *transportation activities* and *machine supervision* activities, *delivery dependability* or the extent to which shipments to the customer were made on time, and *lead time* as the time between receiving an order and delivering product. System features, such as *number of operators, number of workstations*, and the *number of manual component assembly workstations,* number of *manually assembled components* and labour inputs for *manual assembly time*, were determined for each system. Qualitative descriptors were used when quantified comparisons were not possible.

2.2.3. *Detailed workstation assessment*

Matched manual assembly workstations, which had essentially the same work functions, were chosen to explore the technical and ergonomic consequences of the implemented changes at the workstation level. Ten product cycles were video analysed to generate averages for the variables of interest. One subject was available from the batch-cart system and five subjects were available for the line-based system where median values were determined across operators. The limited sample size precluded the use of statistical comparisons. Video recordings were analysed to identify the duration of exposure to risk-related work postures. These included *back flexion* greater then 30°, *neck flexion* greater then 30°, and *arm elevation* of more than 30° from the vertical. Production performance indicators included: amount of time spent in *component get* (acquisition), *component put* (insertion to the circuit board), and *product transportation* activities, as well as forced *waiting time* caused by blockages or shortages in the running system, and *utilization time* when the operator is engaged in work tasks.

Biomechanical modelling. A two-dimensional static link segment model (Norman *et al.* 1998) was used to estimate shoulder moment (torque) for each essential action in the manual assembly workstations examined. Non-assembly activities, such as waiting and talking, and other system-related stoppages were not included. Thus, the comparison focused on the two workstations as designed, and resulted in 'full speed' estimates that represent realistic maximal loading patterns for these two stations. The duration of activities was determined from the video analysis and used to determine a time weighted average shoulder moment and the *cumulative load per product*. The *average shoulder load as a percentage of female capability* was determined using benchmark population data in the model software. The largest single instant of loading was taken as the *peak shoulder moment*. Other model-generated indicators included the *average arm elevation*, percentage time with the *arm elevated beyond 30°,* in *product transportation activities* or in *component get and put activities.*

3. Results

3.1. *Implemented physical changes to system*

The redesign of the production system included the addition of robotic assembly stations, a line-based conveyor system that replaced the product carts, a dedicated wave soldering machine, and both in-circuit testing and automatic circuit board cutting machines. Schematic flow diagrams of the two systems are presented in figure 2. The new system had fewer buffers and thus reduced WIP. There was no apparent change in space utilization between the batch and the line systems. The 'post-assembly' testing and packing operations remained unchanged in the new design. The most substantial changes affecting addition or removal of manual work in the system are summarized in table 2. The final product itself did not change.

3.2. *Work organization strategy changes*

At the macro level, the ownership of the production system changed five months after production was commenced at the new line. The system redesign process,

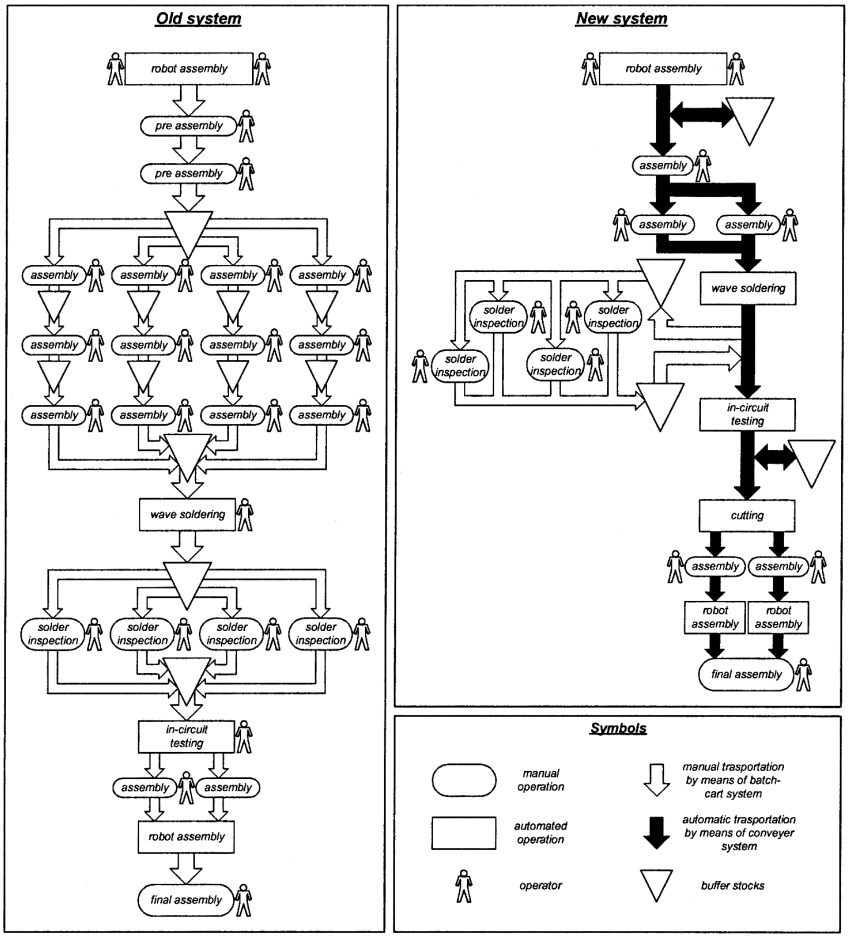

Figure 2. Flow diagram depicting the material flows, workstation arrangement and buffer locations in the old (batch-cart) and new (line-conveyor) systems.

Manual work eliminated	Manual work added
• Component placement (moved to robots)	• Cleaning after board cutting
• Manual soldering (process change)	• Loading cases onto conveyor
• End trimming of component pins (to robot)	• Machine monitoring and maintenance
• Framing of boards (process change)	
• Transport of product (to conveyor system)	
• Product load-unload operations (automated)	

Table 2. Summary of the changes in manual work observed as a result of the adoption of the new Line-based production system.

however, continued without major interruption. The old system had a day shift with 33 operators who worked together with two swing shifts (morning and afternoon) with 13 workers each. *The planned work organization strategy* was developed from exposure predictions based on the results from the work organization group's own ergonomic assessments. This resulted in the categorization of all workstations into three levels similar to those used in Swedish ordinances (Swedish National Board of Occupational Safety and Health 1998). The team used this information to set the intended work organization plan based on a two-shift system. The operators were to be divided into four groups of 4–5 operators each. Each group would be responsible for a set of tasks including each of the three ergonomic 'levels'. The intent of the rotation schedule was to move operators between these tasks, partly so as to increase variability of mechanical workload and thereby lessen the risk-related exposures on any one body part, and partly in order to distribute risks equally among operators. After 2–3 days the groups would shift to be responsible for another set of work tasks.

The manager of the new line, who had not been engaged in developing the work organization plan, rejected the proposed organizational strategy. Instead he established a core group of workers, supplemented by temporary workers from an employment agency to accommodate fluctuations in production. An increase in production volume forced the company to introduce a three-shift 24-hour system. Operators worked one shift at a workstation and changed to another station during the next shift. There was no formal rotation strategy. Several workers though, such as Material Handler/Stockperson and Robot attendants, did not rotate with the other workers and instead specialized at their roles. According to management, the use of temporary workers provided production flexibility and allowed for staff reductions as subsequent automation was expected to reduce the need for operators. The new line manager indicated that the cost of cross-training temporary operators, required for the proposed work organization system, was not warranted given the nature of their employment.

3.3. *System level consequences*

The results of the system comparisons are presented in table 3. Production volume increased, as did the variability of production. System lead-time was observed to decrease substantially. This appeared to be related to changes in the reporting system more than in the production system itself. Decreases in labour input per product were seen to result from automation of both assembly and transportation. The new system also created some increased labour costs due to increases in robot and machine supervision work and decreased operator utilization. Compared to the batch-cart system, the new line system was considerably more expensive to build and was reported to require roughly the same amount of quality work such as checking and re-work.

Peak loading to spinal or shoulder tissues was low for most work in the new line system with the exception of some material handling activities. The storage of some parts close to ground level resulted in about 90° of forward flexion and spinal compression levels as high as 4500 N for a large male. In these actions, spinal joint shear could exceed 1200 N.

3.4. *Work station level consequences*

Table 4 summarizes the results of the manual assembly station comparison. Components located on the table surface in the batch system were elevated to two

Performance indicator	Source	Batch system	Line system	Percentage difference
System perspective				
Production Volume (9 week period)	Docs[1]	19600	29551	51
Production variability (%CV[2] of month average)	Docs[1]	6%	16%	167
Labour input (operator hours 9 week period)	Docs[1]	11 366	13 725	21
Work in Process	Interview		Decreased	—
Quality Work	Interview		Unchanged	—
Delivery Dependability (% shipped on time)	Interview	100%	100%	0
Lead Time (hours to deliver batch order)	Docs[1]	76.8	22	−71
# operators employed	Docs[1]	59	60	2
Total # workstations available	Docs[1]	28	16	−43
# Manual assembly workstations	Docs[1]	16	6	−63
Product perspective				
Labour input (operator min./product)	Docs[1]	34.8	27.8	−20
Total # components (#/product)	Docs[1]	60	60	0
Manual Assembly (# components/product)	Docs[1]	48	26	−46
Robot Assembly (#components/product)	Docs[1]	12	34	183
Manual Component Assembly time (min./prod.)[3]	Video	5.5	2.9	−47
Machine Supervision time	Interview		Increased	
Operator Transport activities (min/product)	Video	3.9	1.1	−72
Workforce perspective				
Manual Component Assembly time (% of total work hours)[3]	Video	15.8	10.4	−34
Robot supervision time (% of total work hours)	Interview		Increased	—
Transportation time (% of total work hours)	Video	11.2	4.1	−63
Quality Work (amount of total work)	Interview		Unchanged	—

[1] 'Docs' indicates internal company records as the information source

[2] %CV is the percent coefficient of variation based on monthly data

[3] Manual component assembly time includes the sum of all workstation times up to the wave soldering operation at which point all components have been added to the product.

Table 3. Comparison of performance indicators between the old 'Batch' system and the new 'Line' system from the perspectives of the entire system, of the product, and from the workforce.

Indicator	Data source	Batch system (stn 3)	Line system (stn 2)	Percentage difference
Workstation perspective				
Observed cycle time (s/product)	Video	141.1	121.5	−14
# component inserted	Docs[1]	17	16	−6
Component get time (s/cycle)	Video	51.8	47.1	−9
Component put time (s/cycle)	Video	24.4	30.2	24
Product transport time (s/cycle)	Video	23.1	7.8	−66
Operator perspective				
Forced waiting (% time)	Video	0	19.2	***
Utilisation (% time at work tasks)	Video	98.5	76.1	−23
Component get & put time (% time)	Video	53.9	63.6	18
Neck Flexion > 30° time (% time)	Video	83.9	42.5	−49
Shoulder elevation > 30° (% time)	Video	23.3	24.2	4

[1] 'Docs' indicates internal company records

Table 4. Summary results comparison for batch and line-based assembly systems at matched workstations performing approximately the same amount of component insertion. Indicators are presented from the product perspective in seconds per product cycle, and from the operator perspective in percentage of working time.

Biomechanical model of assembly work

Indicator	Data Source	Batch System (stn 3)	Line System (stn 2)	Percentage difference
Cycle time used in model	Video	135.1	83.2	−38
Cumulative Shoulder moment (Nms/product)	Model	533	372	−30
Average shoulder moment (Nm)	Model	3.94	4.48	14
Average shoulder load as % female capability (%)	Model	11.4	14.6	28
Peak shoulder moment (Nm)	Model	5.5	6.3	15
Average shoulder elevation (degrees)	Model	31.0	40.4	30
Shoulder elevation > 30° (% time)	Model	44.3	55.6	26
Product Transport Activities (% time)	Model	17.5	7.1	−59
Component get and put activities	Model	56.4	92.9	65

Table 5. Summary of biomechanical model results comparing matched manual component assembly workstations from the old batch system to the new line system.

racks immediately above the new conveyor system. Although the new station had adjustable table heights that allowed both standing and sitting, this feature was not used frequently during the four days of field observation. The conveyor system itself eliminated the periodic standing and walking associated with replacing the cartload of products when each batch was complete. This manual transport was replaced with a button pushing action similar to the component-place action. Operator utilization decreased 23% due to the increased forced waiting in the new line system.

The biomechanical model results, which are based on assembly-related tasks only, are summarized in table 5. These calculations indicated decreased cycle time, increased time in shoulder elevation, increased average shoulder loading, and a substantial increase in stereotyped 'get' and 'put' activities.

4. Discussion

The implemented line system had a higher production volume and lower per product labour inputs than the old batch-cart system. The major strategic production decisions made by the technical design group included the automation of assembly and the automation of transport into a line system. The design of workstations, which was part of the work organization groups' focus, appeared to be constrained by binding decisions made by the technical group. The key ergonomic risks identified in this workplace include arm work with low biomechanical variability, short cycle times, and prolonged duration at some stations. In this case, the time-density of work, and thus work-related biomechanical loads, is probably of greater concern than the actual size of the relatively small loads (e.g. Westgaard 1999). The time-density of work is analogous to the concept of duty cycle (percentage active time within work-cycles), which is emerging as a potentially useful ergonomic indicator (Veiersted *et al.* 1993, Moore 1999). While one should always be cautious when generalizing from case studies, the case presented here appears consistent with Johansson *et al.* (1993) who suggest that isolating or delaying human factors considerations can compromise the success of capital investment in new technology. These results are also consistent with the interview investigations of the change process in which operators reported stress due to the work-pace of the new system and expressed concern about their long-term health (Kihlberg *et al.*). This use of mixed, qualitative and quantitative, methods increases our confidence in the numerical results presented here.

4.1. *The work organization strategy*

The proposed task rotation plan of the work organization group would have shifted operators strategically through positions with varying load patterns. Such a strategy may be useful in reducing risk if there is sufficient latitude, or variety, in the biomechanical loading patterns of available tasks. The group had carefully chosen task patterns to provide a variation in workload for all operators and could have alleviated problems for operators engaged in particularly load-intensive workstations. The decision not to implement this strategy was related to changes in the company's hiring strategy. It was believed that not all of the temporary workers would be able to perform all work tasks. The use of temporary workers, perhaps combined with the increase in technical complexity at some workstations, appears to have inhibited the willingness, or the capability, to invest in educating operators to be multi-skilled. This limited the effectiveness of the work rotation strategy by concentrating the physical exposures of sub-sets of workstations, in particular manual assembly stations with low-variation shoulder exposure, on particular operators. Thus, decisions made by the line-management determined the individual operator's exposure pattern to WMSD risk factors.

Peak loading, observed in only a few tasks here, poses a problem for rotation schemes that can expose all workers to a problematic task (Frazer *et al.* 1999). Risk related to peak spinal loading experienced by the stocking specialist, for example, is not necessarily shared by workers who do not rotate into this role. While these high peaks pose potential risk to the back (e.g. Norman *et al.* 1998), they are not an integral element of the production strategies used here and could be corrected using, for example, a continuous improvement approach. Peak loads aside, having assemblers take turns supplying parts would increase task variability in the relatively time-intensive assembly work and would serve to reduce their repetitive motion exposures.

As the 'temporary' workers become more familiar with the system or as political will in the company shifts, a new work organization system could be implemented to systematically increase variability in operators' daily work exposure patterns.

4.2. *The strategy of the automatic line system*

Automation of transportation and adoption of a serial line system removed transportation-related activities, including the transfer of product to and from carts and machinery, and the elimination of operators' periodic standing and pushing of carts to the next operation. Framing activities were also eliminated by positioning soldering machinery in line with the conveyor, resulting in further reductions in task variability for manual assembly operations (table 4). Reduced work-cycle time, due in this case to the elimination of non-assembly work, is associated with increased injury risk (Bernard 1997). In addition to faster repetitions and more similar work actions ('get and put') we observed small increases in amplitude due to elevated components (table 5), and decreased opportunity for muscular recovery formerly present during transportation activities (table 3). The intensification of manual assembly work seen here is consistent with other studies of partial automation (Coury *et al.* 2000) and poses a potential ergonomic hazard when exposure duration is long (Bernard 1997, Buckle and Deveraux 1999). This strategy provides an example of a production-ergonomics trade-off in which productivity is improved at the cost of increased WMSD risk. The adoption of a serialized line system also reduced opportunities for interaction amongst operators. Increases in WMSD symptoms have been previously associated with the adoption of line-based production systems (Fredriksson *et al.* 2001, Ólafsdóttir and Rafnsson 1998).

The reduction in buffers in the new system would help reduce work in process (WIP) but introduces an element of machine pacing to the work—a potential ergonomic hazard (Rodgers 1996). Reductions in WIP will reduce the company's investment in on-hand stock. Low WIP would reduce throughput time, which in this case was massively affected by the simultaneously implemented information system change. On the other hand, the absence of buffers will tend to increase losses due to starving, the unavailability of upstream products or parts, or blocking, which is an inability to clear the workstation because there is no space in the next station (Wild 1995). This forced waiting, linked to decreased operator utilization, was observed in the line system. Blocking and starving related stoppages are less common in parallel production systems (Medbo 1999) and were not seen here in the batch-cart system. Veiersted (1994) demonstrated that the potential opportunity to recover muscles during a forced waiting caused by machine stoppages might not be utilized by all operators. When interviewed, operators in this system commented on the increased stress associated with technical problems and stoppages in the system (Kihlberg *et al.*). Thus, the elimination of buffers can have negative consequences both for ergonomics and productivity.

4.3. *The automation of assembly strategy*

The automation of component assembly accounts for a large part of the reduction in labour input, although more operator time was needed to monitor and feed the assembly machines. Ergonomically, this monitoring work, performed by specialists, was quite varied but involved regular awkward bending and reaching into the robot to retrieve misplaced components. While the reduction in assembly work removed monotonic reaching and placing movements at the workforce level, this manual assembly remains concentrated on specific workstations. The uneven distribution of ergonomic risk factors in the system highlights the important role of the work organization strategy in determining an individual operator's biomechanical loading profile.

In this case study, technical problems with automating the assembly of some components were identified late in the re-design project. Manual assembly of these parts was therefore required. These additional parts were accommodated into the workstation design by adding a second, elevated, row of components (figure 3). For the operators this resulted in increased numbers of component insertion actions per board over the original design. The increased frequency of repetitions, combined with the higher demands of reaching elevated components, resulted in the increased shoulder loads seen in the biomechanical model. Both time-density of work and load amplitude appear to have been increased by these indirect effects of the partially successful automation attempt. This illustrates how decisions in the technical subsystem can have unanticipated downstream consequences on ergonomics. The automation of stereotyped tasks has the potential to increase productivity without direct negative affects to ergonomic working conditions, depending on the nature of the remaining manual work and the distribution of these work tasks among system operators.

4.4. *Manual assembly workstation design*

The manual assembly workstation design (see figure 3) was conducted within constraints provided by the automation of assembly and transportation functions. These included work rates, the conveyor pathway itself, and the late addition components that could not be automated. The reduction in neck flexion postures observed in video analysis and increased average shoulder elevation seen in the biomechanical model, were consistent with the shift of an operator's attention from the tabletop up to the elevated component racks used in the new system to avoid the conveyor pathway. Shoulder loads in the biomechanical model, considered

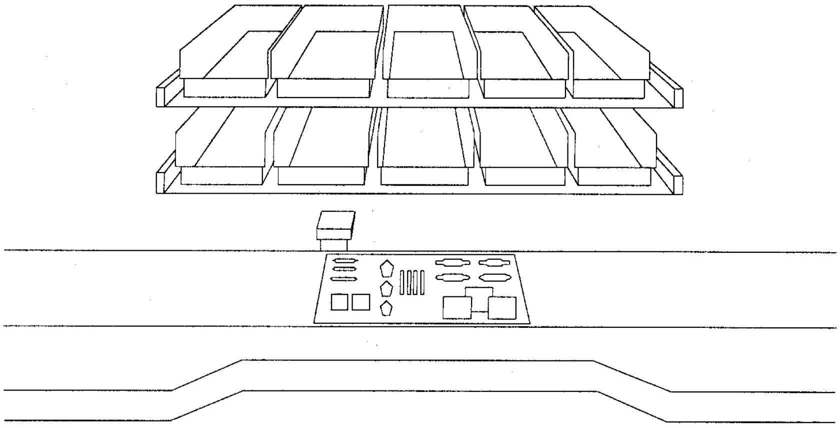

Figure 3. Layout of the second manual assembly station on the new automated line system. Elevated racks were required to make room for the conveyor system and to accommodate parts not fitted for automatic assembly back to the manual assembly process.

relative to female population strength capabilities as a time weighted average, exceeded 14% of maximum when calculated during uninterrupted work. Jonsson (1982), studying muscle activation patterns, has suggested that average (or median) muscular loads should not exceed 10% of maximum capacity. Higher average tissue loading, observed here in the line system, has also been associated with elevated WMSD risk (Norman *et al.* 1998). The ergonomic assessments indicate that shoulder WMSD risk has increased on the new workstation. In the broader study of this population, Kihlberg *et al.* found that 59% of operators reported neck/shoulder stress or disorders related to working at the manual assembly station studied here - the highest rate of any workstation in the system.

The line system workstations were designed, at considerable expense, to accommodate both sitting and standing. We did not observe many operators utilizing this feature. While sit-stand workstations offer variation for the back and leg musculature, they do not necessarily change the repetitive demands for essential job tasks of 'getting' components and 'putting' them onto the circuit board (Winkel and Oxenburgh 1990). Workstation layout decisions will not affect risk related to time-intensity or reduced task variability. Thus, the risk for the body part of primary concern, in this case the shoulder, would be unchanged.

4.5. *General discussion*

This paper provides empirical evidence suggesting negative ergonomic consequences of production system design decisions guided by technical considerations. Thus, the study supports the need for joint optimization of human and technical aspects in production system design, as identified by sociotechnical theory (Clegg 2000, Hendrick and Kleiner 2001, Ingelgård and Norrgren 2001). The findings are also consistent with existing calls to incorporate human factors into decision-making at the earliest phases of the design process (Burns and Vicente 2000). In order to achieve this, it is necessary to understand the linkages between technical aspects of the system and the loads on biological tissues of system operators. The relationships found in this study illustrate some of these linkages. The design process observed in this case, combined with the absence of specific ergonomic performance criteria for designers, allowed for a decision making chain that inadvertently increased risk for system operators. We make, in the next section, both specific and procedural recommendations for minimizing risk while optimizing productivity in production system design.

5. Conclusions

The automation of repetitive assembly work reduced system-level operator exposure to manual assembly work, and thus system-level WMSD risk. It also increased productivity. However, the remaining manual assembly work increased in intensity and monotony due to the automation of transportation functions, which simultaneously increased both productivity and WMSD risk. The early selection of technological solutions reduced biomechanical exposure latitude and could not be overcome by adjustments to the workstation layout. Production system designers and senior decision-makers have decisive influences on the ergonomic quality of their production systems.

5.1. *Implications and recommendations*

The following comments, directed at practitioners, appear warranted based on the results from this case study and on available literature.

Designers should consider both work removed and work remaining when planning automation. While automation of repetitive monotonous work (seen here in assembly automation) can reduce exposure at the system level, it will not necessarily improve the remaining manual workstations. Automating tasks that provide load variation will concentrate operators' biomechanical load onto particular body tissues. Muscular recovery time should be strategically designed into jobs, preferably by including varying tasks in the operators' jobs.

At the organizational level, production system designers have substantial responsibility for ergonomic conditions in their systems. Companies should establish accountability chains within their organizations to generate feedback and learning. Managers should demand specific ergonomic performance indicators, at the operator risk factor level, to provide feedback early in the design process. Production system designers should actively identify and develop strategies that simultaneously enhance both ergonomics and productivity in the system. Operators and technology should be considered jointly from the earliest stages of production system design. Ergonomic thinking in design stages can improve safety and productivity simultaneously with little additional cost.

Acknowledgements

This work has been financially supported by Sweden's National Institute for Working Life, Malmö University College, and W. Patrick Neumann. This project was run as part of the Swedish Cooperative for Optimisation of industrial Production systems regarding Productivity and Ergonomics (COPE) and the Change@Work network, Lund, Sweden. The authors would like to thank Montakarn Chaikumarn, Helena Franzon, Sara Macdonald and Anna Sandell for their assistance in conducting this study. The participation of production operators and management personnel from the study company made this project possible and is gratefully acknowledged.

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PAPER 3

Productivity and ergonomics in parallel and serial flow production

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Submitted for Peer Review

ORIGINAL RESEARCH

Productivity And Ergonomics in Parallel and Serial Flow Production

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Abstract

Purpose: A strategic change from parallel-cell based assembly (OLD) to serial-line assembly (NEW) was investigated in a Swedish company with special reference to both productivity and ergonomics.

Methods: Multiple methods, including records and video analysis, questionnaires, interviews, biomechanical modelling, and flow simulation were applied.

Findings: The NEW system, unlike the OLD, showed the emergence of system and balance losses as well as vulnerability to disturbances and difficulty handling all product variants. Nevertheless the NEW system as realised partially overcame productivity barriers in the operation and management of the OLD system. The NEW system had impaired ergonomics due to decreased physical variety and short cycle times that were 6% of previous thus increasing repetitiveness. Further ergonomic drawbacks in the NEW system included uneven exposure to physical tasks such as nut running and significantly reduced influence over work. The adoption of teamwork in the NEW system contributed to significantly increased co-worker support – an ergonomic benefit.

Implications: Design decisions made early in the development process affect both ergonomics and productivity in the resulting system. While the pattern of physical loading appeared to be controlled by flow and work organisation elements, the amplitude of loading was determined by workstation layout. Psychosocial conditions appear to be affected by a combination of system elements.

Practical Implications: Strategic use of parallelised cellular assembly remains a viable approach to improve performance by reducing the fragility and ergonomic problems of assembly lines.

Value: The interacting design elements examined here provide managers with 'levers' of control by which productivity and ergonomics can be jointly optimised for improved total system performance.

Keywords: Production strategy, ergonomics, system evaluation, human factors, line flow, musculoskeletal disorders, work organisation, cellular manufacturing

1. Introduction

This paper presents a case study of the productivity and ergonomics consequences of a change in production strategy from a parallel flow 'cell' based system to a serial flow line assembly strategy. This case appears consistent with a trend we have observed in Scandinavia to return to line-based production (Jürgens, 1997) after decades of using more sociotechnically based approaches (Forslin, 1990; Engström et al., in press). This trend occurs despite evidence that parallel flow systems can be more effective than conventional line systems (Rosengren, 1981; Ellegård et al., 1992; Engström et al., 1996a; Nagamachi, 1996; Medbo, 1999). These systems have less balance and system losses than serial-lines, and are particularly suited to many-variant, medium-volume production (Medbo, 1999). However, Medbo (2003) has suggested that companies have not fully understood, and thus not fully capitalised, the benefits of long-cycle parallel assembly approaches. This may in part explain the return to short cycle line assembly (Jürgens, 1997). If carefully designed and operated, parallelised production can foster effective work with better physical and psychosocial ergonomics than conventional lines (Engström et al., 1995; Kadefors et al., 1996). Ergonomically long cycle work has potential to provide greater physical variety in activities and increased meaningfulness as the individuals' assembly accomplishment (e.g. a whole engine) is more clear (Jonsson et al., in press). A number of studies have linked the adoption of conventional serial line production systems to poorer ergonomic conditions for operators with increased risk of musculoskeletal disorders (Ólafsdóttir and Rafnsson, 1998; Bildt, 1999; Melin et al., 1999; Fredriksson et al., 2001; Neumann et al., 2002). Work-related illness is an ongoing problem globally and costs about 4% of the World's gross national product with musculoskeletal disorders (MSDs) being the largest single contributer (WHO, 1998). MSDs, the ergonomics focus here, carry substantial direct and indirect costs for companies (Oxenburgh et al., 2004). MSD risk is known to be associated with both physical and psychosocial risk factors in the workplace (Bernard, 1997; Kerr et al., 2001; Buckle and Deveraux, 2002). Poor ergonomics has also been shown to result in increased quality deficits (Eklund, 1995; Axelsson, 2000; Drury, 2000; Lin et al., 2001) – a further negative outcome related to human factors.

The ergonomic literature has presented ergonomic problems as a consequence of management strategies (Björkman, 1996; Winkel and Westgaard, 1996; Vahtera et al., 1997), but the problem is little considered in management literature. In our previous work we applied a simple systems model (Neumann et al., 2002; Neumann et al., 2003) to help examine how strategic decisions, made early in the production system design phase, have consequences for both productivity and ergonomics in the resulting system. The sources of these risk factors in terms of specific production system design elements and operation practices remains less well understood.

The aim of this paper is to identify specific production system design elements and their consequences for productivity and ergonomics. We do this using a case of manufacturing strategy change, from parallel cell-assembly to serial line-assembly work. Secondarily we aim to gain some insight into the reasons behind the change in production strategy that might illuminate the general trend we see in Sweden of returning to line-based assembly.

Production Systems Under Study

This case, in an engine manufacturing company, examines assembly of the same product in both a parallel-cell (OLD) and Serial-line (NEW) production approaches (illustrated in Figure 1). Both systems

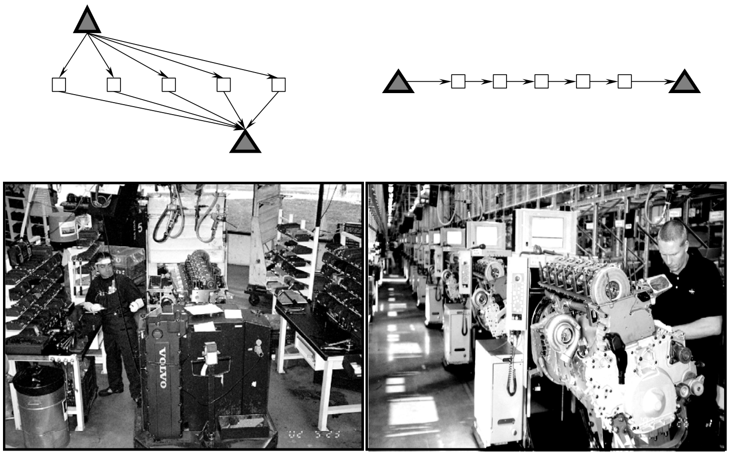

Figure 1: *Flow schematics and workstation pictures for the OLD cell-based, parallel flow assembly system (left) and the NEW serial-flow line system (right). Schematics are abridged to illustrate flow principle with 5 stations (squares) between 2 buffers (triangles).*

operated on strict a 'build-after-orders' approach. In this paper we focus mainly on the final assembly stage in which strategy was changed. The two systems are described here:

The OLD system originally used 18 parallel workstation "cells", operating in three shifts, at which a single operator worked alone to assemble an entire motor. The system was designed for a completion rate of 6.2 motors per cell and shift based on 115% pace on a predetermined motion time system (PMTS). Managers believed not all operators were capable of this pace. When we conducted our measurements six of the parallel stations had been converted to a 'mini-line', used to train new operators on the assembly sequence. At that time cell operators had a daily quota of 5.5 motors (recently increased from 5 / day), regardless of product variants built, and were allowed to stop work once quota was reached. No operator would begin a motor they could not finish that shift – the final 'half' motor of the quota was actually a whole motor completed by two operators together at one station. Hand-steered carts allowed transport and lift-tilt positioning of motors. Parts were supplied to the workstation using a 'kit', connected to the engine cart for transport purposes, which was stocked with all components for the specific variant. Order picking for each kit was a separate job. When each engine was done the operator would manually guide the motor with its now empty kit-cart to the quality control area and collect a new engine and kit from the buffer after the 'middle' section. Since all operators started the shift with a new motor, faster assemblers finishing their first motor earlier, could choose easier variants from engines in the in-buffer – creating a further disadvantage for slower assemblers. Once an operator had reached the quota he/she could stop working but could not leave the plant until the end of the shift.

The NEW system replaced the parallel final assembly with a serial flow of 18 stations designed at an equivalent PMTS rate of 13.9 motors per hour. Automated guided vehicles (AGVs) provided motor transport thus eliminating short walks between assembly cycles. Parts were supplied directly to the line in large crates about 2m from the motors. The AGV included a computer monitor that provided operators with part numbers and assembly sequence information for each particular variant and could confirm appropriate torque applications during assembly. While each workstation required a single operator, operators were grouped into teams of 5-6 and rotated between stations in their team's area at each break. Teams themselves would rotate amongst areas periodically. Team leaders or 'runners' were used to help smooth flow at bottlenecks, with more complex variants and other temporary disturbances.

2. Methods

The assessment strategy included both qualitative and quantitative data intended to provide a rich web of information to illuminate the design issues of interest for matching amounts of assembly work.

Qualitative methods included interviews, discussions and meetings with company stakeholders in order to understand each system's structure, work organisation, and operational characteristics (reported in part above). Documents such as corporate standards and project directives were also examined. All project findings and articles, including this paper, were reviewed by and discussed with company personnel to ensure their accuracy, to enhance our interpretation, and to maintain confidentiality of sensitive company information.

Records/performance data analysis at the system level was evaluated quantitatively using data from the companies own information systems and records. Key indicators included production volume, direct and indirect labour costs, maintenance costs, capital costs, sickness absence rates, and quality deficits. Most of this data was only available at the level of the entire department part of which had no flow strategy change. Some information, such as staffing levels, was obtained by interview with key stakeholders such as supervisors.

Video analysis was used to quantify the amount of operator time utilized in different activities, an indicator with both productivity and ergonomic implications (Engström and Medbo, 1997) for 20 cycles and 11 operators in the OLD system and for 195 cycles across 18 stations with 7 operators (of the original 11 studied) in the NEW system. *Direct work* included any assembly work and included acquisition of components and tools that could be completed without the operator having to move from their assembly position. *Indirect work* included getting components, materials and tools when this required moving away from the product. *Other work* included activities such as paper or computer record keeping, quality control work, and motor transportation. *Waiting* caused by disturbances forcing the operator to stop work such as system or balance losses. In order to check the time costs related to kitting (order picking) in the OLD system 17 cycles from 7 operators of this part of the material supply system were also analysed.

Flow simulation modelling of a parallel (based on the OLD system's original 18 station configuration) and serial flow (based on the NEW systems configuration) were constructed in Automod (Student version 9.1; AutoSimulations Inc, USA). Station utilisation rates (an efficiency indicator) were examined for coefficient of variations (CV) of 0, 10, and 20 percent from the mean cycle time performance, which was based on the 'standard' times, used by the company. The added effect of equipment downtime on system performance was also examined (5% downtime with 10% CV). Balance losses, a feature of serial flow, were not included in this simulation.

Biomechanical Modelling (WATBAK, University of Waterloo, Canada) was used to quantify operators exposure to peak spinal loads. Worst-case scenarios were identified and analysed in both systems. Analysis of video was also used to determine number of repetitions of activities, such as nut running, which imply biomechanical loading and vibration exposure.

Table 1: *Staffing levels (usual # operators per shift) in the new and old system.*

STAFFING	OLD	NEW
Total Operators	**46**	**47**
Picking	6	0
Cells / Line	19	26
USA Motor line	0	4
Other (#/shift)	21	17

Questionnaires were distributed to all available operators in both OLD and NEW systems, with a response rate of 82% and 93% respectively. The sample of operators with experience in both systems included 49 males and 5 females with an average age of 30 years (range 21-44 years) with 4.5 years (2 – 23 years) employment with the company. Question instruments included perceived physical workload assessed using Borg's RP-10 scale (Borg, 1990), pain and discomfort symptoms assessed using a modified version of the Nordic questionnaire (Kuorinka et al., 1987). Psychosocial factors, known risk factors for MSD, were measured using existing questionnaire instruments (Karasek, 1979; Karasek and Theorell, 1990) and (Rubenowtiz, 1997). Additional questions regarding operators' perceptions of the system change were also included.

The Time Point of Measurement in dynamic systems is an important issue. The OLD system had been in operation for almost 10 years before measurement and was running under 'normal' conditions at the time of evaluation. The NEW system had been scheduled to reach full production after three days. This was not achieved and follow-up measures were delayed, by agreement of the joint researcher-company steering group, until 6 months after start-up. Production data from matching months of March & April in each year were used for both systems to control for known seasonal variations in production.

3. Results

Although actual staffing varies on a daily basis, a 'standard' personnel allocation within the systems is presented in Table 1 and shows the elimination of the kit-picking job as well as the addition of variant specific assembly and line-support positions resulting in roughly similar staffing between OLD and NEW systems.

Reasons for the Change were summarised in the project directive (VPT, 2001):

> *"A line will mean it is easier to come to clear the expected 70,000 rate, that we decrease learning time, simplify material supply, make it easier to make other changes (because we skip changing 18 places), have a more social workplace with fewer work injuries and, above all reach a reduced product price".*

Senior managers emphasised the need to increase production volume as having played a key role in the decision to change production strategy. Generally the OLD parallel system as realised was perceived to be inefficient, difficult to manage, provided poor control and support to maintain operators' working pace, and had not resulted in particularly good ergonomics as indicated by sickness & absence records. The line system was seen to have more possibility to develop component specific lift assists for improved ergonomics.

In apparent contradiction to the decision to move to a line, the corporation's own standard on work organisation stated (Backman, 2003):

> *"Serial flows with short cycle times generate waiting times that are not experienced as pauses but as disturbances in the work rhythm. This also generates accelerated work with poor ergonomics as a consequence." (p.2)*

These waiting times were observed in the new system in both the video analysis results and the flow simulation results (see below). These results were predicted by the corporate standard, which discussed alternatives to line production (Backman, 2003):

> *"Leaving the concept of the traditional line means that the system losses are reduced since the time dependence between fitters/operators is reduced"* and *"parallel flows reduce the need of buffers and reduce balance losses." (p.3)*

System Characteristics: Production volume, one of the main aims of the change, increased 12% in the NEW system. Cycle times were 6% of those in the OLD system moving from over 1¼ hours to under 5 minutes. Extra resources were required to maintain quality levels during the run-in period – a common feature of system change. We were not able obtain comparable quality data for the two systems, nor could we isolate the source of quality deficits with respect to ergonomics. Training time was reported as better in the NEW system since it took about a day to learn each station. The time taken to learn all

Table 2: *Comparison of economic performance results including cost breakdowns for each system (left) and the % of difference between the systems (right.)*

NEW vs OLD *% change*	**Cost Item**	**% OLD Total**	**% NEW Total**
+32%	Total Assembly Costs	100.0%	100.0%
+3%[§]	Direct Labour Costs (/motor)	50%	41%
+54%	Other Costs (/motor)	50%	59%
+21%	Indirect Labour Cost	42.2%	38.5%
+81%	Maintenance Costs	3.8%	5.2%
+206%	Capital Costs	4.2%	9.7%
+2455%	Misc. 'Other'	0.3%	5.5%

[§] Labour cost difference is adjusted for a 5% increase in labor rate.

assembly tasks in the system, however, remained roughly the same at about one month.

Economic performance is presented in Table 2. Investment in the AGV system increased capital costs. The start-up of this high-tech system is reported to be responsible for the increases in maintenance and 'other' costs – which combine to over 15% of total costs in the NEW system (Table 2). Labour costs per motor showed 3% increase in this comparison when adjusted for labour rate increases. More detailed assessment of economic factors is currently underway using the cost of labour economic modelling approach of Oxenburgh (2004).

Video Analysis results are presented graphically in figure 2 where total product assembly times are normalised to the OLD system (at 100%). If the order picking (kitting) activities, part of the material supply sub-system in the OLD system, were also included in the analysis then the total operator time per motor in the OLD (+ kitting) system increased to 124% (of OLD shown), still slightly lower than the 128% (of OLD) assembly time in the NEW system. In the kitting system 40% of time was spent acquiring components while 60% of time was spent in transportation and other functions. The performance of the kitting sub-system itself was not further examined. Cycle time variability was 15% (CV - coefficient of variation) in the OLD system. 'Spot' checking of 88 cycles on 6 stations on the NEW system revealed a cycle-time CV average of 13% (CV) across stations (range 5% - 17%) and a CV of 24% if calculated across all cycles and stations together.

Flow Simulation results are presented graphically in Figure 3. Results demonstrate the sensitivity of linear flow to system losses caused by the natural and unavoidable variability in operators' cycle time – at variability levels similar to those observed in this study. The serial flow system model was also more vulnerable to equipment downtime.

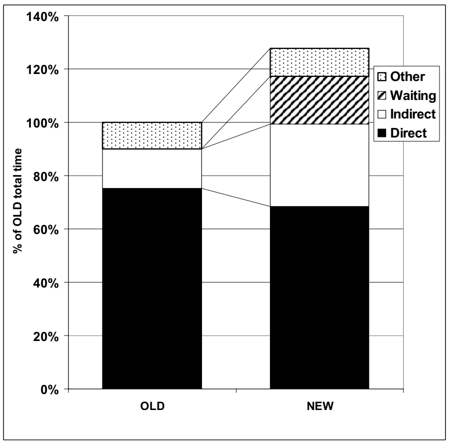

Figure 2: *Results of video based activity analysis for time spent during motor assembly in OLD and NEW systems. OLD system time does not include waiting after quota has been reached. Note the emergence of waiting time caused mostly by system and balance losses in serial flow and increased indirect work related to the increases in walking to get parts.*

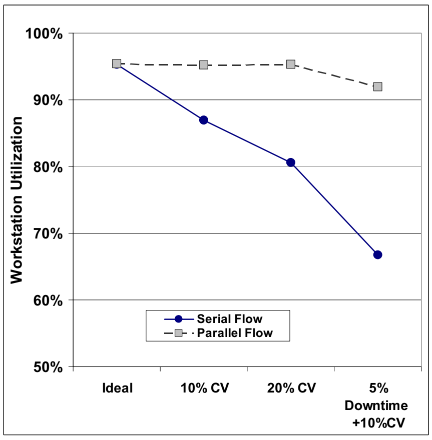

Figure 3: *Flow simulation demonstrates the sensitivity of each flow approach to system losses as a function of cycle time variability (modelled here using a cycle-time coefficient of Variation (CV) of 0%, 10%, and 20%) and additional disturbances such as downtime. Note that mean cycle time is the same for all models.*

Health Records: Sickness absence (SA) records showed this system to have sick-leave rates consistently double of the stated company target. Total SA rates, which include general sickness as well as musculoskeletal disorders, declined slightly from 9% to 8.3% in the comparison period. Men's SA decreased from 7% to 5%. Women, who provided less than 20% of total working hours, had SA rates increase from 16% to over 22%. It was possible not separate musculoskeletal disorders from the company records nor distinguishes between long and short-term absenteeism. Pain in the last 3 months was reported by over 50% of operators in the NEW system for the Neck, Shoulder, Hand-wrist, and Lower Back. Pain reporting rates are summarised in Table 3.

Psychosocial results are summarised in Table 4 for the core indices and indicate significant reductions in decision latitude and influence over work. Co-worker support and teamwork climate indexes, however, showed significant improvements. When specifically asked to compare the OLD vs. NEW systems, 76% of operators perceived the NEW system to have fewer pauses (5% said more) and 56% reported faster working pace (15% said slower). In the NEW system, autonomy at work was seen as worse by 81% of operators (vs. 4% rating NEW better), most rated stimulation as reduced (67% vs. 10%), and variation at work rated lower by 70% (vs. 17%). Fellowship, in contrast, was rated better by 61.5% (vs. 4%). . Perceived physical exertion rates showed a pattern similar to the pain reporting, ranged from 5.3-6.5 ("hard" to "very hard") on the Borg scale, and tended to be lower in the NEW system but were only significantly reduced for the Back (p<0.003).

Table 3: *Percent of operators reporting the experience of pain in previous 3 months for each body part (n=54 pairs).*

	Operators Reporting Pain		
Body Part	**% in OLD**	**% in NEW**	**% Diff.**
Neck	54.7	54.7	0%
Shoulder	47.2	60.4	+28%
Elbow	30.2	22.6	-25%
Hand-wrist	61.5	62.3	+1%
Upper Back	29.4	26.9	-9%
Lower Back	78.8	71.7	-9%
Knees	23.1	20.8	-10%
Feet	32.1	41.5	+29%

Biomechanical loading was observed to be unbalanced between stations in the NEW system. Figure 4 presents the daily total nut-running actions for each station. This indicator is used as a surrogate for both mechanical and vibration loading to the upper limb. We observed both substantial variation between stations and the natural increase of exposure that occurs as production rates increase. Affordability of lift-assists (LAs) was

Table 4: *Psychosocial Index variables from questionnaire instruments (n=54 pairs), statistically significant (p<0.05 on paired T-test) differences are in bold.*

Psychosocial Index (scale range)	OLD	NEW	% Diff	p
Karasek Theorell instrument (1990):				
Psychological Demands (1-4)	2.84	2.90	+2%	0.47
Decision Latitude (1-4)	2.31	2.14	-7%	0.02
Co-worker Support (1-4)	2.83	2.95	+4%	0.03
Rubenowitz instrument (1997)				
Influence over work (1-5)	2.76	2.48	-10%	0.04
Management Climate (1-5)	3.22	3.30	+2%	0.55
Stimulation from Work (1-5)	2.58	2.49	-3%	0.40
Teamwork Climate (1-5)	3.65	3.83	+5%	0.01
Workload (1-5)	3.06	3.21	+5%	0.15

seen as an ergonomic advantage of the NEW system and three were installed. These LAs however, could not reach more distant component variants that then required manual handling and some carrying. The system-wide (across all stations) peak spinal loading was about the same in both systems with 470N shear loading and L4/L5 compression over 2600N experienced while retrieving parts from the bottom of large crates. Unlike the OLD system this only occurred on some stations in the NEW system.

4. Discussion

In this case we see increases and decreases in both ergonomics and productivity indicators. It is important therefore to avoid framing this case as a 'classic confrontation' between LINE and PARALLEL production strategies. Instead we use this system comparison to provide insight into the ergonomic and productivity strengths and weaknesses of these various interacting design elements – including flow pattern, layouts, work organisations, conveyance, and material supply systems. Furthermore production systems are dynamic and subject to continual change and improvement – both systems had potential for improved performance.

Flow strategy & Cycle time -The company appears to have implemented a NEW technical system to overcome productivity limitations caused by the work organisation, specifically the 5 motor quota (later 5.5), of the OLD system. Facing an overriding demand to increase output, management seemed frustrated with what they perceived to be performance barriers in the OLD system. While some production increase was achieved in the NEW, system and other losses inherent in the NEW serial line system reduced expected output during the re-measurement period. Use of 'running' operators, and ongoing work to develop the new team organisation, may reduce the impact of these losses but carry their own costs. The heightened sensitivity of serial flows to downtime, seen here in simulation, also has implications for losses related to slower operators such as beginners, elderly workers, or those returning to work after injury. The system losses observed in the NEW system here both in video and simulation analysis are consistent with reduced performance observed in previous studies of linear flow systems (Rosengren, 1981; Engström et al., 1996b) and in theoretical work (Wild, 1975). That these losses are experienced as waiting time, rather than more ergonomically advantageous pauses, was predicted by the company's own standard and observed in the questionnaire. Waiting may provide time for workers to socialise. The line strategy successfully took control of work pace away from the operators and this resulted in measurable decreases on work autonomy indexes and thus increased risk of disorders. Line systems with short cycle times have long been criticised for reducing operators' control of their work (Ellegård et al., 1992; Eijnatten et al., 1993). The NEW serial flow resulted in greatly reduced cycle times and thus increased repetitiveness and potentially increased MSD risk (Bernard, 1997; Buckle and Deveraux, 1999). Jürgens (1997), in reviewing trends in assembly cycle time in auto assembly has suggested that cycles of about 20 minutes appear to be optimal. Biomechanically, the hazard of a given cycle-time will depend on what work is performed inside the cycle – long cycle times can also have monotonous work but there is more potential for variety. The serial flow system here lead to an uneven distribution of loading which can result in high or repeated physical loading on particular workstations with an increase of MSD risk. The flow strategy appeared here to affect psychosocial risk factors, specifically job control and possibly co-worker support, as well as the operators' pattern of exposure to physical loading (and hence risk) in the system. Once built, changes to this sub-system for improved performance would be prohibitively expensive.

Learning & Kitting - The company perceived the reduced cycle time in the NEW serial flow system as an advantage as it reduced training time needed for a new employee to become productive – although total training time did not change. Engström and Medbo (1992) have discussed the importance of establishing a component kit that supports 'holistic learning' of the assembly sequence in long-cycle assembly work . Groups in both Sweden (Medbo, 1999) and Japan (Nagamachi, 1996) have demonstrated whole product assembly at paces well above 'standard' PMTS times achieved by inexperienced operators with little training. The higher competency of the OLD system operators, who could assemble whole motors, made them attractive for internal recruitment increasing turnover in the system and further increasing the training costs in the old system.

Kitting & Layout - Bozer and McGinnis (1992) have presented a detailed model by which the benefits of kitting, particularly in space utilisation, can be quantified. The argument against 'double handling' of components with kitting hinges both on the efficiency of the kitting process, as well as the extent to which operators using a kit can remain focussed on the assembly task. The OLD system had potential for improved layout of the kit itself – further improving assembly performance, as well as potential to improve efficiency in it's kit order picking sub-system. In the NEW system case racks of components along the line replaced the OLD kits. As a result operators were required to walk repeatedly between product and racking to acquire components, as seen in the video analysis. When product variants required stocking multiple components the extent of walking and carrying along a line can increase dramatically – a function also of product design. This problem was aggravated in this case by the choice of large crates to contain components. In this case one of the heaviest components also had the most variants requiring more space along the line than a lift assist (LA) could reach. Peak spinal loads (a back pain risk factor) for the system were observed on this job, which is now being examined for re-development. LAs were seen as another area in which the OLD system faced barriers – since LAs tend to be component specific there wasn't room for all possible assists. The layout and solitary work organisation of the OLD system prevented the sharing of LAs and purchasing assists for all stations was seen as too expensive. The cost of building LAs drop sharply after the initial expense of developing a suitable LA device (Medbo, 1999). Ergonomically we add a caution that, while LAs can reduce spinal

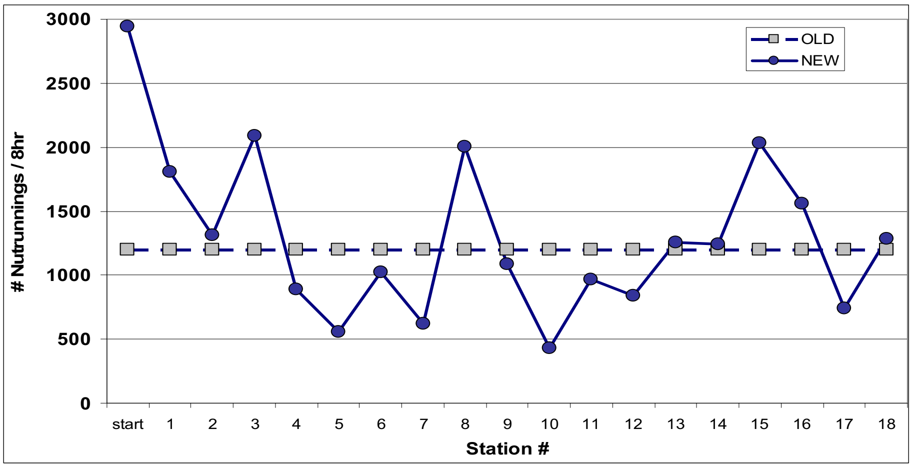

Figure 4: *Nuttrunning, used here as a surrogate for vibration exposure and arm/hand loading, was seen to vary widely across stations in the NEW system (solid line) and were stable in the OLD system (dotted line). Data is based on video analysis and production volumes as designed.*

loading, they can also increase shoulder loading as these muscles are used to stabilise the lift-system in a now longer transfer action (Frazer et al., 1999). In general the aspects of layout, including work tools and methods, appear to have primary influence on physical load amplitudes. Risk due to physical loading can come directly from peak loading, or cumulatively as a function of load pattern over time (Norman et al., 1998). Making changes to load amplitudes, by improving workstation layout, is generally less expensive than changes affecting the entire flow strategy that also influences time pattern.

AGV Technology – The adoption of high-tech AGVs eliminated some operator walking for motor transport and increased the system's capital cost and the cost of buffering in the system. The AGV interface provided an interesting case of computer interface ergonomics in support of the assembly task – the potential for improvement in this area is unexplored in this study. The AGV also acted as a 'marker' for high-tech production – a potential marketing benefit (Engström et al., 1998). AGVs are less flexible than hand-steered carts for routing changes since they require a line be buried in the concrete floor making small route changes expensive. Both systems' carts allowed motor position adjustment although the new AGVs had 'one-touch' controls making this easier. The AGVs also added an element of machine pacing to the work that can also lead to increased muscular activity levels as operators try to match the artificial pace of the system (Arndt, 1987), and may also have contributed to the measured loss of control & autonomy at work, both effects implying increased risk for operators. We observed that the position of the computer monitor on top of the AGV cart, led to the elevation of power-tools – previously suspended above the motor at each workstation – by 10-20cm so as to avoid being hit as the AGV moves through the system. This in turn required higher reaches increasing shoulder demands of the work and is consistent with increased shoulder pain that was reported in the questionnaire. This correctable problem illustrates how separate design elements; in this case technology and station layout, can interact unexpectedly to increase operator risk. Run-in costs of the high-tech AGV system were higher than expected and still observable in the 'maintenance' and 'miscellaneous' financial items at the 6-month comparison point. The OLD and NEW systems represent two different generations of technology in manufacturing. The AGV system - or a stationary alternative – could, for example, have supported parallelised production with regards to assembly sequence, learning, working pace, and handoff of partially completed motors to the next shifts, according to the particular needs of the system (Medbo, 2003).

Work Organisation – In the OLD system the quota, combined with a 'whole engine' rule where operators would only start a new motor if they could finish it within the shift, reduced output considerably over design levels. This OLD work organisation also provided an incentive for operators to hurry so as to reach quota sooner and relax, an effect observed in other studies (Johansson et al., 1993) and possibly a sign of a problem in the control system. Being able to sit after reaching quota reduced prolonged standing in the OLD system, consistent with the lower foot pain reporting levels in the questionnaire (Table 3) and available research (Hansen et al., 1998).

Teamwork was originally a central element of sociotechnical innovation (Eijnatten et al., 1993) and was intrinsic to the long –cycle parallelised assembly approach developed at the much discussed Volvo Uddevalla site (Ellegård et al., 1992; Engström et al., 1995). Here we observed the teamwork approach being applied to the NEW serial flow, and not to the OLD parallel flow system where operators worked alone. This is consistent with the positive results in co-worker support, team climate, and fellowship scales, implying a reduction in MSD risk (Karasek and Theorell, 1990; Bongers et al., 1993) – even though the work was essentially one person per station. Job rotation inside the team was used to enlarge (but not enrich) the shorter cycle work activities – an example of how work organisation can modify the physical loading pattern established by the flow strategy. Rotation may moderate the effects of repeated loading from particular stations – but may also expose all workers in the rotation to risk-generating peak loading situations (determined largely by layout) thus increasing risk for the whole workforce (Frazer et al., 2003). Furthermore, if rotation does not bring the operator to a station allowing recovery of the (over) used muscle groups then it cannot be expected to reduce MSD risk. Upper limb pain frequency was high in both systems and both system required large amounts of hand-arm work to fasten components to engines. Increased activity variety, implying reduced repetitions of particular movements, might be obtained here by moving administrative tasks out to the shop floor for the work teams to manage. Engaging front line employees in development work generally can also provide variety and engagement and has been shown to provide companies with a substantial competitive advantage (Gustavsen et al., 1996; Huzzard, 2003).

General Discussion - This case has allowed us to explore both productivity and ergonomics consequences of production system design elements (See table 5). These elements may provide the 'levers' of control needed for the design of new production systems that can provide superior long-term performance through joint optimisation of human and technical factors. This analysis demonstrates how ergonomic conditions in the realised system are the product of many interacting decisions in the design process and is consistent with our previous case study (see Neumann et al., 2002). The interaction of these elements suggests the need for coordination amongst designers throughout the development process. Separate consideration of human and technical factors, or sub-systems, is unlikely to lead to system solutions

Table 5: *Summary of advantages and disadvantages, in terms of both ergonomics and productivity, observed with key design elements in this case. The dotted line between some elements indicates the tighter coupling of these particular elements.*

Design Element Change	Advantages	Disadvantages
Parallel to Serial Flow	• Facilitated change in work organisation • Production disturbances may provide physiological rest	• Fragile with system and balance losses • Production disturbances not perceived as pauses • Reduced job control
Cycle Time Reduction	• Easier to learn 1 cycle • Easier to tell if work pace matches system	• Reduced physical variey (increased repetitiveness)
Changed System and Workstation layouts	• Increased opportunity for interaction (improved co-worker support) • Not all stations handle heavy parts (e.g. reduced spinal load)	• Difficult to add new components (space limitations) • Lift assists can't reach all part variants • Space shortage results in awkward reach to small parts
Kitting to Line Picking	• Order picking eliminated (positions eliminated) • Lift assists available for heaviest parts	• Operators must walk more to get parts • Lifting parts from large crates causes high loading
Manual to Automated Guided Vehicles (AGVs)	• On screen checklists & logging • Adjustments (if used) can reduce physical load – counts for both carrier systems • No manual cart steering work	• High capital and maintenance costs • Contributes to reduced job control • Reduced physical variation • AGVs interacted with layout to raise height of tools
Work Organisation (solo to team-work + eliminate quota)	• Operators remain 'on-line' for full shift • Team work fosters co-worker support • Eliminate incentive to rush	• 'Runners' need to assist with line flow (positions added) • Work pace steered by system – reduced job control • Reduced work content

that are globally optimal (Burns and Vicente, 2000; Skyttner, 2001; Neumann et al., 2002) and retrofitting to overcome problems from early design decisions can be prohibitively expensive. We observed that the company did not have leading indicators of ergonomics integrated in the management information system – making it difficult for them to judge risk in their factories and provide feedback to design teams. The role of product design in contributing to ergonomics and losses is not explored here but remains a possible area for improvement. While the productivity advantages of parallel flows have been demonstrated (Wild, 1975; Rosengren, 1981; Nagamachi, 1996), this case illustrates how these advantages are not always realised in practice.

6. Conclusions

The performance of the OLD parallel system in this case was compromised by the work organisation and operational control systems as well as limits in the kitting system. The NEW system showed increased risk of musculoskeletal disorders due to increased repetitiveness and physical monotony, as well as poorer psychosocial conditions with elements of machine pacing, and high loading levels on particular stations. The emergence of system and balance losses was observed in the NEW serial system and may have reduced physical workload. The use of team structures in the NEW system improved co-worker support, which implies a risk reduction. Reported pain levels in both systems remain high. While workstation layout determines operators' physical load amplitudes, the flow strategy and work organisation influence the pattern of physical loading. Psychosocial factors appear to be influenced by a combination of flow strategy, work organisation and, to a lesser extent, layout. Design decisions, made early in the development process have substantial impact on both productivity and ergonomics in the resulting system.

7. Recommendations to Practitioners

Based on the results of this study and the related literature we provide the following advice for managers:

- Hybrid system designs, using teamwork and strategically implemented parallel flows, may overcome limitations experienced in both systems studied here.
- Establish indicators and goals for ergonomic performance evaluation that include both physical loading and psychosocial factors.
- Design teams should be held accountable for meeting ergonomic goals jointly with productivity goals. Pay special attention to possible interactions between design elements.
- Engage operators in development processes as part of work variability and 'pain-less' performance improvements – they are the users of the design.
- Work organisation and incentive systems should be designed to support the type of layout/flow system chosen.

Acknowledgements

This work has been conducted with the financial assistance of VINNOVA, project d.nr. 2002-01679 and the Swedish National Institute for Working Life. The authors would like to thank all the Volvo Powertrain Corp. personnel who made this project possible. Thanks also to Gustav Orrsjö. Special thanks, *in memoriam*, to Sigvard Lantz (1951-2004), we miss you.

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PAPER 4

Integrating ergonomics in manufacturing system development - Moving from Reactive to proactive.

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Submitted for Peer Review

ORIGINAL RESEARCH

Integrating Ergonomics into Manufacturing System Development – Moving from Reactive to Proactive

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Abstract

Purpose: To investigate how ergonomic factors can be integrated into a companies' regular development process for the joint optimisation of human and technical performance.

Methodology: An 'action research' stance was adopted with researcher participation in, and support of, the developmental processes.

Findings: Change was slow and marked by setbacks. These tended to be caused by both individual factors (e.g., disinterest, changing jobs, illness etc.) and organisational factors such as inter-group communications barriers and short project timelines that limited the rate of integration of human and technical factors in system design. In the face of these setbacks the resolute production manager, acting as a 'political reflective navigator', was able to steer the initiative through the organisation to establish credibility, overcome resistance, and begin to anchor human factors into the companies' regular development process.

Research implications: The distribution of the design task amongst different groups renders ergonomics, an emergent system feature, very difficult to manage without a structured design process to support its consideration. Approaches to developing such structures is a research imperative for sustainable development growth.

Practical implications: Practitioners may benefit by adopting a "political reflective navigator" stance in trying to adapt and fit the joint-optimisation concept to their company's particular circumstances. Potentially useful approaches include: educational workshops, simulation tools, and design process specifications.

Value of Research: This study illustrates how organisational and individual factors influence ergonomics implementation efforts. It also demonstrates the importance of an internal reflective navigator using insider knowledge in managing the integration of human and technical factors into organisational development processes.

Keywords: Ergonomic intervention, production system design, development work, organizational learning, human factors

1. Introduction

1.1 The Challenge of Ergonomics

Despite decades of ergonomics research, work-related musculoskeletal disorders (MSDs), the single most expensive category of work-related health problem, remain a large problem for afflicted individuals (Pransky et al., 2000), companies (Oxenburgh et al., 2004a), and society (WHO, 1999). Epidemiological research has demonstrated the risk-connection between MSDs and both physical factors; such as highly repetitive work, vibration, awkward postures, and peak & cumulative loading; and psychosocial factors such as job demands, individual control, and co-worker support (e.g., Karasek and Theorell, 1990; Bernard, 1997; Norman et al., 1998; de Beek and Hermans, 2000; Buckle and Deveraux, 2002). Despite this knowledge, little has changed. While many successful case studies of ergonomics interventions exist (e.g. Aaras, 1994; Hendrick, 1996; GAO, 1997; US_Federal_Register, 2000; Oxenburgh et al., 2004a), systematic reviews have not found the effect of intervention attempts to be generally consistent when evaluated with the rigor of bio-medical scientific tradition (Westgaard and Winkel, 1997). Since few of these intervention studies included process evaluations, it is difficult to determine why many projects had no major impact on disorders. Karsh et al. (2001) have highlighted this problem:

> *"A pressing problem that has plagued ergonomic intervention research is the lack of understanding as to why seemingly identical interventions work in some instances but not in others… We propose that research pay special attention to various implementation approaches to ergonomic interventions."*

From an organisational change perspective this is a classic problem. Success rates for 'organisational culture' change, for example, are reported to be as low as 19% (Smith, 2003). Clegg and colleagues (2002), in a large international survey, found that between 50-75% of implementations of modern manufacturing technologies were not successful. These failures appear to be less a failure of the technical system itself but rather a failure to accommodate the social sub-system (Nadin et al., 2001) – a failure to integrate ergonomics into system design. We have begun to apply systems thinking (Senge, 1990; Skyttner, 2001) to consider how to integrate human factors into these complex systems, an approach not generally taken by ergonomics consultants who tend to focus on immediate physical workplace problems (Whysall et al., 2004). The aim of this paper is to investigate how ergonomics might be integrated into a company's regular development process, with special attention to barriers and assists in achieving such integration.

1.2 Points of Departure

In this section we describe the theoretical and empirical basis of our intervention approach. These 'points of departure' also provides the framework in which we subsequently interpret the results of our intervention efforts (Toulmin and Gustavsen, 1996).

A system model - Figure 1 presents a systems model describing how MSD risk factors and eventual disorders emerge as eventual outputs, along with productivity and quality levels, from the production system development process. By 'systems' we adopt Skyttner's definition of 'a set of interacting units or elements that form an integrated whole intended to perform some function' (Skyttner, 2001). The model presents a long chain of consequences beginning with strategic decisions (level 5) in the design of the production system (level 4) that, once operational in the production system (level 3), can lead to risk for operators (level 2) and subsequently to MSDs (level 1) as an unintentional side-effect of the production process. While there is relatively little information on the ergonomic consequences of management strategies (Björkman, 1996), 'downsizing' has been linked to increased MSDs and ill health (Vahtera et al., 1997) as have 'lean' production approaches (Landsbergis et al., 1999), linking levels 5 to 1 in the model. Our previous work has found the model (Figure 1) useful in understanding how specific design elements, such as system flow and automation strategies chosen early in the design process (level 5), can have a large effect on MSD risk (level 2) in the system (Neumann et al., 2002; Neumann et al., working paper). These elements tend to be central to the system design and thus appear to be 'locked-in' by the size of the investment in the decisions (Neumann et al., 2002; Neumann et al., working paper) making change difficult. Better cost-effectiveness could be achieved if human factors were considered early in design choices where the 'leverage points' of ergonomics can be found (e.g. Burns and Vicente, 2000). Unfortunately, ergonomics is often considered late or inappropriately in the design process (Perrow, 1983; Skepper et al., 2000; Imbeau et al., 2001) and emerging problems are usually delegated to the health and safety service who are generally trained to focus on the risk factor level (level 2). This isolating organisational structure has been described as the "side-car" approach to health and safety and is criticised as being ‘too little too late’ (e.g. Helander, 1999; Jensen, 2001, 2002). There appears therefore to be an organisational gap between Engineering’s influence on, and the Health and Safety Ergonomists’ accountability for, human factors in design and operation of production systems (Figure 1). The problem posed here is systemic and solution development must engage stakeholders throughout the system in order to overcome counterproductive side-effects of organisational (system) boundaries in responsibility and accountability (Senge, 1990).

Process development - While a number of ‘ergonomics process’ models have been published (Hägg, 2003; Joseph, 2003; Moreau, 2003; Munck-Ulfsfält et al., 2003), it is not clear how these models might be customised and implemented in a particular company. If we look to the quality field for examples we find that the mere adoption of an ISO9000 process has little correlation with quality performance until the ideas behind these programs are ‘fit’ to the company (van der Wiele et al., 2000). Thus we see a need to anchor ergonomics processes into the organisation so that the principles can be implemented – not just the forms filled out. Success in TQM program development appears to be related to duration of implementation period (Taylor and Wright, 2003). With this rationale we pursue an evolutionary approach to the development of ergonomics capability inside the specific organisation that is meaningful for the unique sets of individuals involved, applied in daily practice, and suited to their formal and informal organisational structures (Toulmin and Gustavsen, 1996).

Feedback is a key aspect for systems control theory (Skyttner, 2001) and organisational

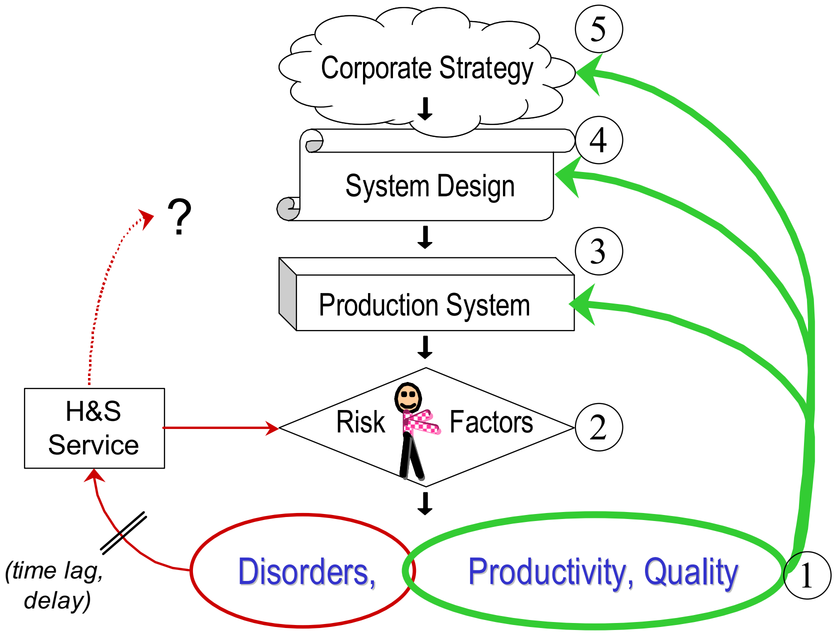

Figure 1: *Simple systems model illustrating how strategic and design decisions (5 & 4) shape the production system (3) and thus influence both risk factors (2) as well as ergonomic and productivity outcomes (1). Feedback into design & development process (5, 4) of productivity and quality knowledge is often tight (right side arrows) while disorders, which occur with delays and lags, are often handled by the Health and Safety Service with weaker communications to design teams (left side arrows). (Adapted from Neumann et al. 2002)*

change (Bateman and Rich, 2003) perspectives**.** As the systems model (Fig 1) illustrates; feedback on ergonomics is limited for designers and strategic decision makers who, at these higher levels, are increasingly isolated from their system's ergonomics, and may also lack tools (Imbeau et al., 2001) and procedures for handling the ergonomic implications of their work. It is little wonder therefore that these important stakeholders often doubt the utility of ergonomics in improving system performance (Helander, 1999; Baird et al., 2001). One barrier here may be the lack of appropriate ergonomics indicators (e.g. at risk factor level 2 from Figure 1), which are generally much less precise and frequent than for productivity measures. Feedback is further inhibited by the use of trailing indicators such as sickness absence, which suffer from both lag and delay (Figure 1) compared to available leading indicators of risk (Cole et al., 2003), and are unspecific as they include non-work related sickness (e.g. flu, colds). Without unambiguous indicators and mandates designers find it difficult to accommodate human factors objectives even if standards are present (Wulff et al., 1999b, a). There is a need therefore to improve the use of ergonomics indicators and, as in the earlier quality example, to fit these indicators into the processes of work system design and operations.

Engaging stakeholders in joint optimisation - While sociotechnical systems theorists have long discussed the need to engage technical and work organisational actors directly (Eijnatten et al., 1993) this has proven difficult to operationalise and the 'gap' remains. Figure 2 illustrates how ergonomics and other performance factors may interact. By identifying solutions that result in both good ergonomics and good productivity (top right Fig. 2) higher total system performance can be achieved (de Looze et al., 2003). There is a growing body of evidence to support the convergence of organisational performance and quality of working life (Huzzard, 2003; Oxenburgh et al., 2004a). In Sweden for example, evaluation of the massive Swedish Working Life Fund demonstrated superior company performance when working life and performance objectives were pursued jointly than when productivity was pursued alone (Gustavsen et al., 1996). This same study also observed a broad mobilisation of stakeholders as an important element of the change process. Rubenowitz (1997) has suggested engaging technical personnel as a critical element for ergonomics intervention, an aspect also noted to by Westgaard and Winkel (1997) who emphasize also that company ownership of the change process is crucial to obtaining impact. By emphasising the joint optimisation modelled in Figure 2 it may be possible to engage both stakeholders with technical foci and those with human foci in the development activities.

In summary we see a need to customise the application of ergonomics principles to fit the particular organisation and its development processes. In this paper we investigate three elements which our literature analysis suggests may support this effort: 1) adopt an evolutionary developmental approach to

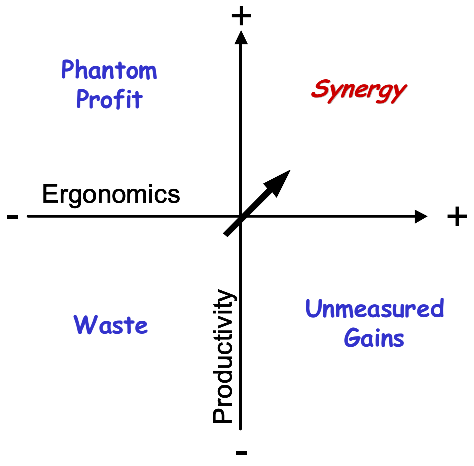

Figure 2: A simple 2 dimensional model illustrating how a 'navigator' can attempt to steer development. A synergy effect may be achieved if ergonomics and other productivity aspects are optimised jointly (top right). Although good ergonomics may have unmeasured gains(bottom right) not immediately visible in productivity data, poor ergonomics may compromise anticipated productivity - phantom profit (top left).

continuously integrate ergonomics considerations into daily design and operational practice (closing the 'gap'). 2) improve the utilisation of ergonomic indicators in the organisation, and 3) actively engage all stakeholders in development of better solutions with a 'double-win'.

2. Methods

The research team adopted an action research stance throughout the project in which researchers participated in company development activities (Toulmin and Gustavsen, 1996; Reason and Bradbury, 2001). The strength of this longitudinal case-study approach lies in the ability to follow the development of the process continuously, in 'real-time', and from a close embedded position as it evolves. This avoids the reconstructive nature of post-hoc interview investigations. Researchers participated actively in meetings providing information from the workplace assessments as well as from available research. Researchers also engaged in informal discussions with various stakeholders on how, for example, the initiative might be coordinated effectively. Through these discussions we, as researchers and in collaboration with company personnel, began to operate in the role of 'organisational activists' (Jensen, 2002) or 'political reflective navigators' (Broberg and Hermenud, 2004) in the effort to establish broad support for, and participation in, the process (Gustavsen et al., 1996). This paper can be thought of as a close examination of what happens in the 'liquid phase' in Lewin's classic (1951) unfreeze-change-refreeze model; although dynamic companies today are never fully 'frozen' in terms of operational processes (Hatch, 1997).

There is a tension in action research between the researchers' need to participate meaningfully, so as to be embedded in the process, and the need to prevent the development agenda from either overwhelming the research agenda (Huxam and Vangen, 2003) or becoming dependent on the researchers (Siemieniuch and Sinclair, 2002). In the face of this tension, researcher participation is a balancing act. In order to avoid that the process or participants become over-dependent on the researchers we routinely emphasised to company personnel that *"You're the ones driving the bus! We can help, but this is your process"*. We focus here on helping the company *develop their own ability* to deal with ergonomics issues in their regular work. As 'bus-driving instructors' we tried both to heighten each persons 'driving' skills, by presenting ergonomics issues and consequences in existing system designs (Neumann et al., working paper), while at the same time trying to encourage other stakeholders to 'get onto the bus', by bringing ergonomics issues into new or existing development arenas in the organisation.

Data collection was in the form of field notes from meetings, discussions, and observations taken throughout the intervention process. Meetings and interviews were audio recorded if possible to provide a backup to note taking. Recordings of key meetings were shared with other research team members to obtain their observations. Four people from the research team were directly engaged in the intervention effort and included both ergonomic and engineering skill sets. Whenever possible more than one researcher would attend meetings to allow dialogue and reflection inside the research team on how the process was evolving. Researchers visited the site about once each week over the intervention period. This paper reports on the process after 18 months. We strive to extract potentially useful lessons from this specific case that might be applicable in other cases with similar circumstances (Pålshaugen, 1996). The complex reality of organisational change can never be fully represented in a linear narrative (Sørensen et al., 1996; Toulmin and Gustavsen, 1996). Instead we present 'vignettes' that illustrate key aspects of the process. These are presented with short 'reflective commentaries' that provide interpretation and connect the observation to our theory and 'points of departure'. In this sense we create a dialectic between the empirical case and theory (Yin, 1994; Greenwood, 2002).

3. Results

3.1 The Case Story

Case context: The impulse for this project came from the production manager (PM) in an engine manufacturer with a high profile in Swedish industry. The company had recently installed a line-based production system after over a decade of using individual 'cell' based parallel flow assembly; an approach developed in Sweden in the 1980's (Kadefors et al., 1996; Jürgens, 1997; Engström et al., 1999). A detailed comparison of these two systems, conducted in an earlier phase of the research project, demonstrated how strategic decisions in the production system design determined system ergonomics (Neumann et al., 2003; Neumann et al., working paper). Following researcher reports on this analysis the senior production manager (PM) wished to generate improvement actions based on the researchers' analysis. At this point, the PM made a clear vision statement for a sustainable work system: *"operators should be able to continue to work in these systems up to retirement"* without getting disorders. The researchers and company jointly obtained funding for a research and development program with the objective to develop a *"change process which can increase the companies own ability to create a sustainable work system by optimising both effectiveness and ergonomics"*. As part of the project, the company has agreed to spread knowledge gained from the process to other industries in Sweden. The initiative was launched under the label 'Production Ergonomics' (ProErg).

Reflection – We entered the organisation in the 'production' department through the senior manager responsible for daily operations across the site who answers to the site manager. The PM appears to maintain a long-term view while dealing with the daily trials of production. Engineering – responsible for system design – is a different department with different leadership. Product design activities are based in a different city. We appear to have strong support from one senior manager and tacit support from his boss.

Initiation Phase - The process was initiated with the formation of a steering group, with representatives from many organisational stakeholder groups including production managers from other product systems. The initial meeting included discussion of objectives of the initiative and a review by researchers of the system analysis conducted previously. The steering group was seen to be too large to effectively develop specific action plans. A temporary 'Analysis Group' was formed and charged with assessing available information and identifying priority areas for action. This temporary group included a representative from production, engineering, union, health and safety service, and the researchers. In a series of discussions, the analysis group decomposed the production ergonomics 'problem' into specific topics and clustered these into related aspects which were then assigned to one of three groups (see Figure 3): 1) a "Measurement" group' responsible for improved information handling, 2) A "Future" group to develop improvements to the work organisation and the production system, and 3) a "Return to Work" group for faster rehabilitation. The 'Future' group, which had the broadest mandate, began establishing sub-groups, often with personnel closer to the shop floor, to tackle specific problems or activities. For example the 'Future' group had formed a team to implement ergonomics improvements based on an existing ergonomics audit. This sub-group, lead by the Ergonomist and engaging engineers, operators and production supervisors, proceeded to make over 30 improvements in the existing system that could be changed with low cost. Some problems were 'locked in' by the design creating high costs for retrofitting. These items would have to be negotiated through the company's regular investment channels. Over this period the Return-to-Work group developed a new procedure for managing work absenteeism and improving return to work processes. The 'Measurement' group, unlike the other two groups, was assigned to an individual who had not been involved previously in the development process. This group was slower in initiating activities, as extra time was needed for personnel to understand the initiative and prepare to act on it.

Reflection - Structurally this breakdown of the ergonomics 'task' made sense to the company. Organisationally, however, there was little involvement of engineering groups who have substantial control over ergonomics in the system. While engineering was represented in the steering and analysis groups the initiative was not taken up and remained essentially a 'production' issue isolated from system designers. In retrospect we see problems with communications here. For those participating in the process right from the start the rationale behind the effort was clear, but for those not previously involved the ProErg initiative appeared as new tasks that were additional to – and not integrated with – with their 'regular' work. Progress appeared best in areas where individuals were closely involved with deciding on necessary action and when the process drew on existing improvement processes.

Problems Emerge -Immediately after summer holidays we observed a dramatic slowdown in activity levels. Many meetings were cancelled or postponed. Only a few of the sub-groups appeared active. At this point we learned that each of the three group leaders had been, or was about to be, transferred to new positions. Problems also emerged in some of the project sub-groups as the process began to intersect with other activities. In the case of the engineering led 'Futures' sub-group, for example, the engineer responsible felt her role was unclear: since she already had more projects than could be completed on time, why was she being asked to decide on new "ergonomics" projects? The engineer's supervisor suggested she wait until specific project requests were generated by someone else. At about this time the safety engineer, who had been coordinating and driving the larger ProErg process from the company side left work on sick leave and, sadly, died in January 2004. This marked a low point for both researchers and the production ergonomics process generally.

Reflection - A number of both personal and organisational factors appeared to create barriers for the process in this period. ·Over the project normal life events such as promotion, career changes, retirement, divorce, marriage, cancer incidents, childbirth, and death were all experienced by individuals involved in the process. These events appeared to influence ability and/or willingness to take on a role in the newly created development groups. In this case the ergonomics impulse was not sufficiently anchored in daily routine that it continued following the disappearance of a key individual and was not seen as an organisational necessity for stakeholders struggling to perform their 'primary' duties while balancing other life demands. Organisationally the engineering groups

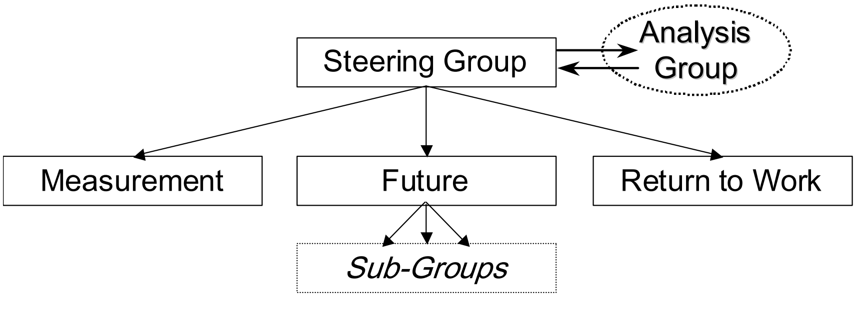

Figure 3*: Schematic of groups formed during the initial ergonomics process development phase. This structure later dissolved as personnel changed positions.*

remained distanced from the process and engineers on the front line did not experience strong support for the initiative from their managers. Thus the process remained a 'Production' initiative that was suffering from the turbulences of ordinary life.

Identifying New Opportunities - Recognising the slowdown, and aware of difficulties of having new staff pick up the tasks of the ergonomics development work, the production manager (PM) and researchers reviewed the situation in the fall of 2003. The PM arranged a presentation of the original system comparison results to the companies' senior management team, which included the site manager (SM) and senior representatives from engineering, finance, and personnel. The PM wanted to inform and engage the other senior managers. In this meeting it emerged that, for the engineering department, the primary focus was on the development of new production systems – not retrofitting existing systems where budgets were already depleted. The site manager called for a workshop to be held so that the knowledge gained from the production system evaluation could be spread to the engineering group designing the next generation production system.

Reflection - Here we see the PM acting as a 'political reflective navigator' to gain support for the vision generally and for this attempt to realise the vision in cooperation with the research team. By having researchers present 'hard' data on both technical and ergonomic performance the PM helped establish credibility for the process and created a forum for information exchange and dialogue with system developers.

New arenas emerge - The workshop provided the first forum in which the ergonomics and productivity effects of production system design elements could be presented to the engineering teams engaged in production system design. Unfortunately the senior site manager could not attend the workshop and this caused a delay in obtaining his support for a course of action. Ongoing discussions with managers and engineers resulted in development activities in a number of arenas. Simulation, both of system flow and ergonomics, was already a growing issue in the company and was encouraged by the intervention team. The research team provided demonstration analysis of how ergonomics could be handled using both flow simulation (Medbo and Neumann, 2004) and biomechanical modelling tools (Neumann et al., 1999b). We observed, however, that when a design team was presented with a production concept which diverged from the given assignment as framed by senior engineering managers, that the team felt itself lacking authority to explore the new concept without approval at a higher level – even though the alternative appeared to have both better ergonomics and productivity. Unfortunately no forum existed at that time for such a discussion. Engineering management saw the development of ergonomics capability as too heavy a burden for the system design team given the tight timeline and budget of the current project. Development activity in this area was subsequently initiated by the new manager of the production-engineering group both as part of 'virtual manufacturing' developments and also through examination of how ergonomics is handled during the design process.

Reflection - In this period we see an increased understanding and acceptance of ergonomics criteria by engineering managers, facilitated by the focus on future, rather than existing, production systems. The time-pressure of the company's development projects, however, create a barrier, even at relatively early stages, to integrating ergonomics into development – it was already almost too late to develop the current design project's process. The distribution of the design task between different design groups began to become apparent at this stage (Figure 4) – a place for potentially counterproductive systems effects. At this point we observe the engineering department initiating ergonomics development essentially independent from the production led initiatives.

Integration –After further reflection the PM decided to integrate the 'Pro-Erg' initiative into the 'Assembly steering Group', an existing group responsible for overseeing all development projects using the company's international 'Global Development Process' (GDP). The GDP is a gate system for managing product development (e.g. Cooper, 1990) which specifies all items that must be accounted for or accomplished before the project is allowed to proceed to the next stage. The PM saw integration of ergonomics into the GDP, a move that would involve stakeholders at the company's international level, as a way to ensure that these factors were accounted for at the earliest development stages as part of regular practice. From this point onwards a Health & Safety service representative, either an ergonomist or safety engineer, was included in this management 'steering' group that oversees the GDP. Initially, however, the procedures and routines of this group were not oriented towards ergonomics and the language used by the engineers was perceived as 'foreign' to the ergonomist and health and safety engineer (and researchers). One of the specific ergonomics actions planned through this group is an educational plan by which engineers, managers, and supervisors can increase knowledge and establish communications on how human factors are to be handled. Another element in building ergonomic routines into development projects is the establishment of specific goals for ergonomics against which proposed design solutions can be compared.

Reflection – Placing health and safety personnel into the development steering group helped the production manager signal the importance of this issue in development projects. We observed the PM operating more independently and arguing more confidently and with increased understanding for ergonomics during this period. Communication barriers between different professional groups should be expected and take time to overcome. While Ergonomists are at the table, there remain at this point no formal (eg GDP) process elements ensuring the ergonomics issues are actually dealt with by the group.

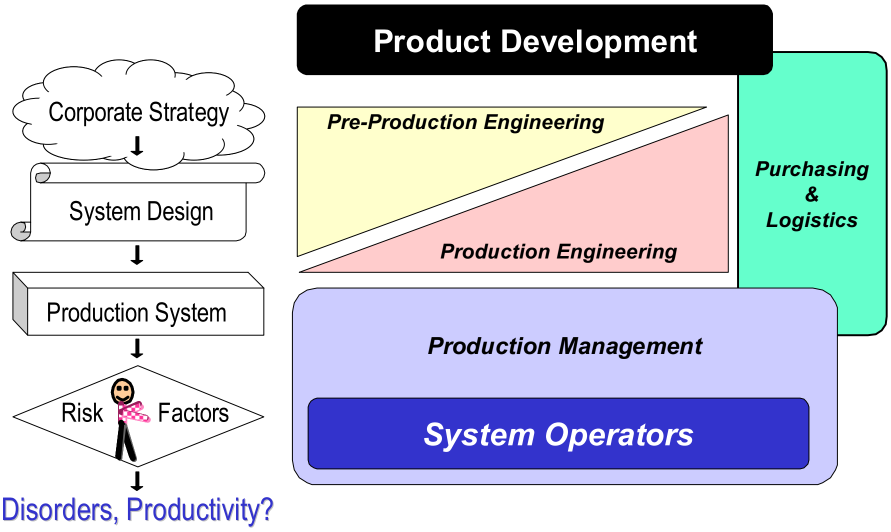

Figure 4: *Stakeholder map illustrating key organisational groups positioned according to their role in the development process as modelled from Figure 1. This illustrates where in the development process key groups are predominantly active and have authority in determining the design, with eventual ergonomic consequences.*

3.2 Stakeholder Analysis

During our interaction with the new system design team we gained a deeper understanding of the various stakeholder groups that influenced system design, and hence system ergonomics. This is illustrated in relation to the original system model in Figure 4. Product development, which is based in a different town from the manufacturing facility, determines the assembly task. Pre-production engineering, operating on strategic instructions to build a serial 'line' production system with a given capacity for example, arrange system layout and fit in available space as well as a rough setting of assembly sequence. Production engineering, working most closely with daily production set physical workstation layouts and final balance of tasks between workstations. Purchasing and logistics are responsible for the timely supply of all components to the system and shipment of motors from the system to customers. These last two groups are considered jointly due to their joint responsibility for the use of large crates in component supply that can create ergonomics problems in the resulting systems. Finally it is the production group, along with production operators who are exposed to risk, that are responsible for the daily operation of the resulting system.

By 'mapping' these stakeholder groups onto the original system model we were able to better understand how influence on system development was distributed in the organisation (Figure 4). Groups influence ergonomics directly in the tasks they define and, crucially, indirectly through the interaction of their respective design contributions from which ergonomics problems can emerge. Emergence; a system property that only becomes apparent in the interaction of system elements, is a useful concept from systems theory (Skyttner, 2001). Emergent properties can be difficult to manage in design since influence is dispersed amongst design groups - no one is in control of ergonomics. Thus we see that 'engaging engineering' is not a simple task but rather involves a number of different sub-groups who must communicate, across organisational boundaries, to manage the interaction of (or emergence in) their combined design tasks. While pre-production engineering and production engineering habitually work closely together, other groups such as logistics, purchasing, and product design are more distant and have not been engaged by the ProErg initiative.

4. Discussion

Although a number of improvements were identified and implemented in the existing system, the initial phase of the change effort did not manage to anchor ergonomics into daily practice and, similarly to Bamford & Forrester (2003) , wound down quickly when key members left. Individual factors (e.g. promotion, or long term sickness) had a dramatic impact on the initiative. The initiatives structure, chosen by the company personnel, rested primarily on production personnel. Engineering, although part of the planning, was only marginally involved and initial engagement of this key group was weak. Opportunities here generally consistent with the literature may include: establishing a mandate and tradition of attention to human factors (Ekman Philips, 1990), fostering social rather than only technical focus in design teams (Kilker, 1999), improving available knowledge (Neumann et al., 1999a; Skepper et al., 2000; Hägg, 2003), ensuring that the need for change is understood (Bateman and Rich, 2003), establishing indicators for ergonomics (Neumann et al., 2002), and adopting suitable design tools by which available knowledge might be used (Broberg, 1997; Imbeau et al., 2001; Jensen, 2002). These factors may help overcome what has been called a clash of perspectives between ergonomists and design engineers (Kirwan, 2000). A number of these opportunities are currently being explored and developed by both production and engineering groups. Engaging operators themselves, the system users, in the production system design is another area where learning can be achieved by communicating across organisational boundaries (Noro and Imada, 1991; Kuorinka, 1997; Maciel, 1998; Haines et al., 2002).

In the face of setbacks, we observed the benefits of a strategic and reflective approach, similar to the 'political reflective navigator' described by Broberg & Hermenud (2004), but from a position inside the organisation. In a series of steps, by no means complete, the PM was able to internally navigate the company's particular circumstances in order to secure support from senior managers and to engage engineering directly in these efforts. In doing this the PM demonstrated increased process knowledge with regards to ergonomics; indicative of transformational learning in which new knowledge allows a reframing of the integration problem that extends beyond just gains in ergonomics information (Mazirow, 2000). This was achieved, at least in part, through the critical reflective dialogues between the PM, researchers, and other company personnel (Mazirow, 2000). We highlight the importance of the PM's insider knowledge in navigating the companies' organisational dynamics and in 'opening doors' to existing developmental arenas where human factors are being determined. The firm resolve of the PM to reach his vision has been crucial in the survival of both the initiative and the research project in general at this site, is noted as a success factor in organisational change (Smith, 2003). The workshop conducted for the design team appeared helpful in raising awareness and acceptance of the ergonomics challenge. Workshops have been described as a multi-purpose tool that can support sociotechnical design (Axtell et al., 2001). The PM sees further ergonomics training as one way to engage groups, such as product development who have not yet been reached by the process, as illustrated in the 'stakeholder map' (figure 4). The organisations absorptive capacity (Mukherjee et al., 2000) with regards to ergonomics appears to be negatively influenced by the high pressure and short time-lines of engineering projects which create resource barriers, a noted change inhibitor (Bateman and Rich, 2003), to adding new constraints and complications such as human factors into system design. In the face of this barrier the integration of ergonomics into the project management system, the GDP, appears to be one way to regularise the consideration of ergonomics in every project. The necessary political-organisational manoeuvring to achieve this, including the crucial activation of all key stakeholders associated with improved organisational performance (Gustavsen et al., 1996), has not yet been accomplished and the process still appears to rest heavily on the PM. The rate of change observed in this case suggests that making substantial change using an evolutionary approach may take many years. While no end-point exists, 3-5 years may prove a reasonable minimum in this case (Gustavsen et al., 1996), which is currently just passed the 1½ -year mark.

While the joint consideration of productivity and ergonomics issues was promoted, and often verbally accepted by managers, this concept proved difficult to operationalise. In the joint optimisation model presented by de Looze et al. (2003) this integration was achieved by persons *external* to the company. In this case, there appeared to be a tendency to continue with existing analysis approaches and developmental paths in which ergonomics and productivity were considered separately – the gap is difficult to close. The research team is now engaged in demonstration projects that are intended to show how, in practical terms, human and technical performance factors can be jointly considered via flow simulation (Medbo and Neumann, 2004), material supply redesign, and economic modelling (Oxenburgh et al., 2004a; Oxenburgh et al., 2004b). These approaches have the potential to foster communications regarding ergonomics between groups using unambiguous indicators – money, or units per shift. However, as we observed, even if such a project demonstrates a potential gain, embedding it into an already running project is inhibited by tight time-lines and lack of senior manager buy-in. It remains to be seen if the company can take up and use these approaches independently in their development work.

5. Conclusions

- A deliberate process of 'political reflective navigation', here by an internal agent not the ergonomist, helped accommodate organisational dynamics and allowed for opening doors to existing arenas of development inside the organisation where human factors are determined.
- The evolutionary approach to integrating ergonomics into the organisation, even with strong support from the production manager, was slow and marked by setbacks. A single navigator cannot make progress alone.
- Developmental barriers may be at organisational levels (e.g. inter-group — barriers, communication gaps) or at individual levels (e.g. work overload, pending retirement, life events).
- Intervention groups that are outside of regular development groups are vulnerable to disruption from, for example, reorganisation.
- Lack of engineering engagement in the initial process development created barriers when engineering personnel became involved in the change effort.
- The workshop appeared to be a good method to provide information, solicit support, and initiate dialogue with the engineering design team; although if top management is not directly involved then delays in decision-making will result.
- Constructing a stakeholder map helped us understand that not all design groups with relevant control over ergonomics have yet been reached by the process.
- Engineering teams work to the mandate given by senior managers – if innovative designs are to be developed senior managers must sanction them.
- Tools such as computer simulation appear to have good potential in providing designers with quantified indicators they can use to consider ergonomics simultaneously with other production concerns.

Acknowledgements

This work has been conducted with the financial assistance of VINNOVA - the Swedish Agency for Innovation Systems, Project d.nr. 2002-01679, and the Swedish National Institute for Working Life. The authors would like to acknowledge the partnership of the Volvo Powertrain Corporation, Skövde plant, Sweden. This paper is dedicated, *in memoriam*, to Sigvard Lantz (1951-2004).

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