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Discrete event simulation as an ergonomic tool to predict workload exposures during systems design

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A B S T R A C T

This methodological paper presents a novel approach to predict operator's mechanical exposure and fatigue accumulation in discrete event simulations. A biomechanical model of work-cycle loading is combined with a discrete event simulation model which provides work cycle patterns over the shift resulting in a load-time trace for the entire shift. This trace was tested with four different muscle endurance-recovery model pairs yielding a fatigue-time history for the entire shift. An electronics assembly case with shift-long perceived fatigue data was compared to the simulation model results. Sensitivity testing of the input work-rest ratios found the best correlation ($r^2 = 0.84$) at 17% of the modeled rest level. The need for this adjustment is discussed in terms of limitations of available muscle endurance and recovery models. Muscle model limitations notwithstanding, this approach allows system designers to understand the mechanical exposure and fatigue-related effects of proposed alternatives in system design stages and can contribute to 'Virtual Human Factors' approaches for pro-active ergonomics capability.

Relevance to Industry: This paper demonstrates an approach to quantifying operator exposure patterns and fatigue levels using dynamic simulations of the proposed operations. This allows system designers to understand the ergonomic impacts of proposed alternatives in system design. Design level tools allow early stage application of ergonomics where costs are lower and solution options are greatest.

1. Introduction

Integrating human factors into the design of new work systems is a challenge for practitioners (Jensen, 2002). The inclusion of human factors in an early stage of design allows a broader range of solutions to be considered, since there are few constraints. It also allows any design changes to be done at lower cost when compared to retrofitting changes once a system is built (Miles and Swift, 1998). One of the barriers to such proactive ergonomics work is the lack of tools supporting production engineers to incorporate system-level attention to human factors in their design work (Broberg, 2007). One problem is that, in the design stage, there are no observable human operators involved yet. Current human factors methods rely heavily on data collection from the worker, either through observation, direct measurement or questionnaires (Neumann et al., 2007). There is, therefore, a need for human factors tools that can be used "virtually" to evaluate health hazards in early stages of the design of the system - virtual ergonomics tools (Perez and Neumann, 2013). While considerable research and development in this area has been directed to digital human models (DHMs) and other assessment tools to be applied at the workstation level (e.g. Bäckstrand et al., 2007; Chaffin, 2005; Lämkull et al., 2009), less attention has been paid to system level simulations that would allow designers to understand the time domain design implications on the human workers of system level design options. Time aspects have been noted as a critical issue for musculoskeletal health (Wells et al., 2007), but are generally underdeveloped in virtual tools.

One of the tools used regularly by engineers to understand system dynamics in the early design of new work systems is Discrete Event Simulation (e.g. Banks et al., 2005). Discrete Event Simulation (DES) is the representation of a system in terms of sequence and times of the process' stages, in which the state of variable(s) change at *discrete* points in time (Banks et al., 2005). The DES process involves the creation of a model based on a series of mathematical assumptions that dictate the ways in which *entities*

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will interact with the system. DES has been recognized as a tool with many applications in manufacturing and service industries, ranging from the analysis of system design alternatives (Neumann et al., 2006; Neumann and Medbo, 2005) and business modeling (Hlupic and Robinson, 1998), to the optimization of resources (Legato and Mazza, 1999) and cost evaluation (Spedding and Sun, 1999). Although DES is widely available and applied in industry to predict system performance and identify improvement opportunities, human factors are seldom addressed in this modeling approach (Baines et al., 2004, Baines and Kay, 2002). Focus group research has shown that barriers for ergonomists to applying DES as a VHF tool may include unfamiliarity with the approach, they have a hard time seeing DES as a tool with applicability in their field, and they may also not fully trust its results (Perez, 2011; Perez and Neumann, 2013). Similarly engineers may not have an explicit mandate for ergonomics (Broberg, 2007; Perrow, 1983), and thus are not motivated to integrate HF aspects into their DES modeling work.

Some studies on DES have been conducted from an ergonomic perspective. For example, Walters et al. (2000) analyzed the impact that fatigue and rotation schedules have on military operations, Neumann and Medbo (2005) used DES to evaluate workers performance and cumulative spinal load in assembly tasks, Kazmierczak et al. (2007) combined DES and digital human models for the performance analysis of work systems, and Baines et al. (2004, Baines and Kay (2002)), explored the integration of age, circadian rhythm, and personality aspects on DES models of manufacturing system performance. To the authors' knowledge no example could be found in the literature that utilized DES as a primary tool to directly predict some of the effects of the exposure of workers in the system, such as the mechanical exposure pattern or accumulation of muscular fatigue. However, other virtual methods have been attempted to minimize the effects of workers exposure to systems, such algorithms to optimize job rotations (Carnahan et al., 2010). The time-related focus of DES makes it particularly suitable to examining the ebb and flow of demands on the workers which will vary with configuration of the flow of the system and the dynamics introduced by stochastic system elements like machine downtime or workers' performance variability (Neumann et al., 2006).

The method described in this paper allows for the description of mechanical exposure patterns over a whole shift and, subsequently the interpretation of these patterns in terms of fatigue based on existing fatigue models. Muscular fatigue has been associated with multiple negative effects both in workers and systems. Fatigue and the factors that contribute to its manifestation – such as mechanical exposure, load variation, cycle times, task duration, and (lack of) pauses – have been associated to health related issues (e.g. Chen, 1986; Sluiter et al., 2003; National Academy of Sciences, 1999; Newman, 2001). Muscular fatigue is also considered a precursor of human errors and resulting accidents and losses of quality and efficiency (Bosch et al., 2013, Eklund, 1997). At the operator level, muscle fatigue has been linked to a decline of performance, increased reaction times and the slowing of the sensory abilities (Åhsberg et al., 1997, 1998). Fatigue has also been associated with reductions in motor control and force fluctuations (Enoka et al., 2003).Furthermore, Björklund et al. (2000) showed diminished proprioceptive acuity following low-intensity work to fatigue and also impaired movement accuracy has been reported during fatigue (e.g. Jaric et al., 1999; Missenard et al., 2008). All these performance decreases, quality losses, human errors and health related problems associated with fatigue may translate into huge monetary costs for governments and companies (National Academy of Sciences, 1999; Rose et al., 2004; Ricci et al., 2007; Rose et al., in press).

Muscular fatigue can be measured in an "objective", quantified, way thanks to different devices and methods (Kankaanpää et al., 1997; DeBusk et al., 1979; Sluiter et al., 2009; Zenz and Berg, 1966; Bosch et al., 2007). In the absence of human workers in the early design of work systems however, the challenge is to find a means of prediction rather than measurement. Since muscular fatigue results from periods of work interspersed with periods of rest, we would need to predict the effect of both. One approach is to apply existing models of maximum endurance time (MET) and rest allowance (RA). MET represents the maximum time that a muscle can sustain a load during an isometric exertion (El ahrache et al., 2006), and is calculated as a function of a fraction of Maximum Voluntary Contraction (*f*MVC) – the fraction of the peak force produced by a muscle as it contracts. When the worker reaches the MET, it is assumed that he has also reached 100% level of fatigue implying an inability to maintain the load levels. Using empirically derived MET models and exposure time, one may predict the level of fatigue. Such prediction models can be found in the literature; some are considered "general" and some of them are specific to different body parts such as shoulder, elbow and hands (see the review of El ahrache et al., 2006). We note here that this work applies existing fatigue models, but does not redress any underlying weaknesses of existing models. As these models improve they can be embedded within the proposed predictive approach.

The rest allowance (RA) is defined as the time needed for adequate rest following a static exertion, and is generally expressed as a percentage of holding time, defined as the time during which a static exertion, static posture, or a combination of both is maintained without interruption (El ahrache and Imbeau, 2008). One may compare the RA with the actual rest periods (within a designed work system) and predict the recovery. Examples of RA models are in Rohmert (1973), Milner (1985), Rose et al. (1992) and Byström and Fransson-Hall (1994).

The aim of this study is to develop and evaluate a methodology to simulate the production system and consequent work-load patterns of operators over a shift. Then, subsequently, to predict the levels of muscular fatigue in the shoulder region throughout the working day by combining a DES model of a real industrial system with existing empirically based MET and RA models. This approach is evaluated by comparing modeled results to empirically gathered data in the case of an electric shaver assembly system.

2. Methodology

The fatigue modeling approach was developed in the context of a previously studied production system, following the methodology illustrated in Fig. 1. Based on the case from industry, this project was initially divided into a biomechanical analysis to quantify workloads at the workstation level, and a DES model to obtain system level time patterns of production cycles. The DES model followed the process description of the industrial case, including task times and postures, technical system specifications, workstations times and product flows and variability. Existing MET and RA models were then used to calculate the accumulation of fatigue and the recovery obtained by workers throughout the work-shift. Fatigue level over time was finally calculated by subtracting the recovery obtained from the fatigue accumulated in each work cycle. Each one of the components of Fig. 1 is further explained in the following sections.

2.1. Industrial case

The industrial case concerned the final assembly of electric shavers in one of the production lines at Philips in the Netherlands. This production line consisted of twelve workstations as seen in Fig. 2. The cycle times at the first and last workstation were 12 s, on