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An adaptive control model for assessment of work-related musculoskeletal hazards and risks

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There is growing evidence that the domain of work demands (e.g. physical demands, mental demands) as characterized through work elements (e.g. weight of load, frequency, horizontal distance, height of lift, work duration, and twisting angle for lifting demands; complexity, work duration and number of occurrences for mental demands) can interact to precipitate hazardous conditions which potentially result in musculoskeletal injuries and illnesses. Research efforts to date have focused largely upon singular aspects of the domain of work demands with reference to human effort and injury/illness risk assessment. Thus, the complex interactive effects of the entire set of work demands on risk outcome measures have been neglected because of the difficulty such endeavours pose. The main objective of the present work is to develop a foundation for a comprehensive work system model enabling occupational health and safety professionals to understand and evaluate how the complete spectrum of work demands (i.e. physical and mental demands, physical/social/organizational/individual growth environment conditions) interact to influence human effort, and subsequently affect hazards and, thus, perceived and actual risk. The intention is to provide a systematic and standardized approach to complex work system hazard identification and risk assessment for prevention of musculoskeletal disorders.

1. Introduction

1.1. *Human performance optimization*

The guiding principle of human performance improvement is to balance work demands with worker abilities and needs to maximize performance measures. This optimization of human performance is the common goal of work improvement efforts in industrial settings. Management, which is responsible to corporate shareholders, is continually striving to increase revenue by improving the quantity and quality of output. At the same time, ergonomists and safety specialists seek to reduce the risk of injury and damage loss by modifying worker interactions with physical and mental job demands as well as the physical work environment. Occupational psychologists attempt to reduce the detrimental effects of workplace demands

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by empowering the worker within the organization. Occupational health professionals, including occupational physicians and health nurses, evaluate workers for 'fitness-for-duty' and seek to minimize morbidity and lost time that may result from injuries and illnesses. Although all parties seek to optimize human performance, typically each does so by focusing on isolated variables (primarily the variable of expertise) within the complex and dynamically changing systems (Karwowski *et al.* 1994a).

This paper aims to develop a comprehensive work system model, to optimize human performance in the workplace, which captures the individual and interactive effects of these singular variables. To accomplish this goal, an integrative work system model is presented. 'Performance' in this paper will be described in terms of health and safety measures with the goal of risk quantification of workplace hazards. 'Risk', a common assessment parameter in health and safety analysis, quantifies the degree of harm with respect to likelihood (e.g. probability) and severity (e.g. consequences) in response to workplace hazards (Cox and Cox 1993, Manuele 1997). A 'workplace hazard' is defined as an event or situation with the potential for harm (Cox and Cox 1993). To be effective, work system hazard/risk assessment must address all components of the work system as well as their interactions (Karwowski and Jamaldin 1995).

1.2. *Nature of work system hazards and harms*

Traditionally, harm has been generally interpreted as resulting from physical hazards such as those produced by physical task demands (i.e. biomechanical, physiological) and by the environment (e.g. nuclear, radiological, biological, chemical, physical). Work-related musculoskeletal disorders (WMSDs) have been widely acknowledged as a major part of occupational harm, resulting from the acute and cumulative exposure to physical task demands (Centers for Disease Control 1987), and are among the most prevalent cause of lost time injuries and illnesses in almost every industry and, importantly, are among the most costly (Bureau of Labor Statistics 1995, National Safety Council 1995).

The National Institute of Occupational Safety and Health (NIOSH) has conservatively estimated the cost of occupational musculoskeletal disorders as $13 billion annually (NIOSH 1997a) and has devoted extensive resources in the investigation of risk factors for WMSDs (NIOSH 1981, 1996, 1997a, b, c, Waters *et al.* 1993). Recognizing that further research is needed, the National Occupational Research Agenda (NORA), established through a collaboration of NIOSH and over 500 stakeholders in public and private sectors for guiding health and safety efforts, identified low back disorders and upper extremity disorders as two of its 21 critical priority areas (NIOSH 1996).

Recently, the concept of work hazard has been expanded to include non-physical hazards, specifically, psycho-social, work organization, and mental demands. These hazards include both the interactions among job content, work organization and management, work environment and organizational conditions, and the workers' competencies and needs (International Labour Office 1986). Work-related mental demands pose challenges which, if excessive, form a source of hazard (e.g. Hancock and Warm 1989).

Occupational 'stress', the harm resulting from psycho-social and work organization hazards as described in its respective literature, is generally chronic in nature, persisting for a period of time during which the harm may be cumulative or progressive. Evanoff and Rosenstock (1994) reported that estimates of direct and indirect medical costs associated with occupational stress in the US have ranged from $80–150 billion annually. NORA also named organization of work as one of its 21 research priorities (NIOSH 1996).

A number of recent studies present evidence of the adverse health effects of interactive relationships among physical task demands, mental task demands, and the physical/social/psychological/organizational environment conditions has been suggested through several studies. WMSDs have been reported as exacerbated by the occupational environment (Ulin and Armstrong 1992, Armstrong *et al.* 1993, Bongers *et al.* 1993, Chaffin and Fine 1993, Kuorinka and Forcier 1995, Moon and Sauter 1996, Smith and Carayon 1996, NIOSH 1997a, b). Devereux (1998) confirmed the interactive effects of physical and psycho-social work demands on the prevalence rates of musculoskeletal disorders. However, such interactive effects are themselves contingent upon factors such as age, skill, and fitness, since personal characteristics have also been cited as additional contributors to the development of WMSDs (Fraser 1989, NIOSH 1997c).

1.3. *Study objectives*

Due to the highly interactive nature of multiple hazards comprising work systems, it is essential that any health and safety assessment instrument be predicated on the explicit acknowledgment of all known elements and their potential and actual relationships with each other. While zero risk is an optimal goal, effective risk can be minimized to levels acceptable to the individual worker and organization members. Thus, a model for hazard and risk assessment must clearly describe and assess all fundamental elements, their relationships with each other, the potential for both acute and chronic exposure and the harm that may result (Karwowski *et al.* 1999, Yeung, *et al.* 1999). In this context, work system assessment refers to: (1) the characterization of the domains of work demands (i.e. physical/mental demands and physical/social/psychological/organizational environment conditions) with corresponding outcome measures (i.e. effort/perceived risk/actual risk); and (2) the assessment of the relationships between work demands and outcome measures in order to optimize human performance with respect to safety and health as manifested through the abatement of risk associated with the development of WMSDs. To accomplish these goals, an overview of a such a work system model is presented. The detailed system components and adaptive control model operation are also discussed. This is preceded by an overview of job analysis and system safety techniques.

2. Overview of work hazard and risk assessment techniques

Safety engineers, ergonomists, and industrial hygienists have historically approached the investigation of the work system for hazard and risk evaluation using a spectrum of investigational methods. As the benefits of each of these strategies are realized, efforts to analyse the work system have correspondingly developed many forms and structures. Principally, these efforts can be clustered into two general groups, which are: (1) job analytic techniques, and (2) system safety techniques. The following subsections provide an overview of job analysis and system safety techniques and evaluate their progress with respect to occupational hazard/risk assessment.

2.1. *Job analysis techniques*
Job analysis techniques have traditionally been used to characterize work demands and their effects on workers. In one of the most recent works, Shoaf *et al.* (1998) suggested that the term 'job analysis' has become outdated as the scope and complexity of 'jobs' have increased. Rather, the evaluation of jobs is more accurately referred to as 'work system assessment'. Here, 'work system assessment' is used throughout to address the traditional 'job analysis' concept, as well as advanced work-related hazard/risk assessment. As indicated earlier, work system assessment includes the characterization of work demands (i.e. physical/mental demands; physical/social/psychological/organizational environment conditions) and outcome variables (effort/perceived risk/actual risk).

Work system assessment may be applied to any unit of work, that is, to tasks, jobs or occupations. A 'task' describes a distinct part of a job, and a 'job' is defined as all the work carried out by a worker or group of workers (British Standards Institution 1959). Therefore, a job may consist of one or more tasks. An 'occupation' refers to jobs of a general class without regard to organizational lines (McCormick 1979). Shoaf *et al.* (1998) grouped job analysis techniques into one of three classification systems: micro-assessment methods, macro-assessment methods, and comprehensive methods.

Micro-assessment methods are specialized in technique and narrow in scope. They focus typically on one work domain or one of its specific subsets. Examples of micro-assessment techniques are: analysis of lifting demands and their effects on workers (e.g. Chaffin and Park 1974, Snook 1978, Liles *et al.* 1984, NIOSH 1991, Marras *et al.* 1993, Waters *et al.* 1993, Karwowski *et al.* 1999); analysis of mental demands (Hart and Staveland 1988, Reid and Nygren 1988); and psycho-social assessment (Hackman and Oldham 1976, Karasek and Theorell 1990).

Macro-assessment methods are not as detailed as micro-assessment methods and typically involve the evaluation of a particular work demand domain or may span across more than one work domain. A typical macro-assessment method utilizes a checklist approach in the form of a questionnaire. Examples include, but are not limited to, the work of Newman (1977), Keyserling *et al.* (1992), and Guo *et al.* (1996).

Comprehensive methods incorporate characteristics of both micro-assessment and macro-assessment methods. The Position Analysis Questionnaire (PAQ; McCormick *et al.* 1969) and Arbeitswissenschaftliches Erhbungsverfahren zur Tatigkeitsanalyse (AET; Rohmert and Landau 1983) are examples of comprehensive job analysis methods. They are among the most thorough systems in the literature, especially because they characterize the entire spectrum of work demands. The PAQ and AET, however, lack many of the detailed findings established within the last two decades and, thus, do not possess a sufficiently comprehensive framework for hazard and risk assessment at this point in time.

2.2. *System safety techniques*
System safety hazard/risk evaluation techniques have been largely devoted to analysis of the physical environment. System safety techniques, which address occupational hazards, are process-based. They serve as regimented methods of analysing system design to ensure the intended operation and mitigate possible failures. Thus, system safety hazard evaluation covers a wide spectrum of potential and existing

hazards. In contrast, non-process based techniques (e.g. air or water sampling) evaluate only existing physical work-related hazards.

The following is a summary of the most common process-based hazard evaluation techniques (Gressel and Gideon 1991):

(1) Checklists are among the simplest forms of hazard evaluations. They can identify recognized hazards and ensure compliance with accepted design standards. Checklists can be applied to equipment, procedures or materials.
(2) Preliminary hazard evaluation analysis lists the hazardous materials, equipment components, and process operating conditions. As each hazard is identified, the possible causes, consequences and corrective measures are listed.
(3) 'What If' analysis can identify both hazards and their consequences and help develop possibilities for potential hazard reduction. The analysis procedure usually starts at the beginning of the process and asks a series of questions concerning process upsets or malfunctions. Additional questions based on the initial analysis may be formulated.
(4) Safety reviews are conducted to identify plant conditions and procedures that may have deviated from the intended design.
(5) Failure Modes and Effects Analysis (FMEA) checks each process component individually and describes the function of each component and all of its potential failure modes. The method then determines the causes of these failures as well as the effects.
(6) Fault Tree Analysis (FTA) determines and displays the cause of a major unwanted event. This method starts with the top or end event and develops a logic tree showing the causes through the use of 'AND' and 'OR' gates.
(7) Event Tree Analysis (ETA) is similar to FTA in several ways. As in FTA, a tree structure is developed to outline the events of a hazard scenario. While FTA develops a vertically oriented tree logic, an ETA tree is constructed horizontally and begins with an initiating event and moves forward rather than beginning with the end event.
(8) Hazard and Operability Study (HAZOP) is a powerful evaluation technique in terms of identifying complex failure scenarios that involve multiple independent events. By using the plant equipment and instrumentation drawings, the process is broken into small segments or nodes, such as the line connecting a pump to a storage tank. Deviations of the process from normal operating conditions are evaluated by applying a series of guide words to the node. Recommendations for improvements or for more study are based upon the likelihood and consequences of the deviations.

In addition to hazard identification, most of the above mentioned system safety techniques provide probabilistic risk quantification (e.g. ETA, FTA, HAZOP). They are, however, limited because of their unaccountability for the role of human behaviour, particularly human error (Feyer and Williamson 1998).

Human reliability analysis techniques (e.g. influence diagrams, human cognitive reliability models, technique for human error rate prediction) have attempted to improve system risk assessment by quantifying human error probability (Kirwan 1990). Still, the development of risk assessment techniques has failed to realize the enlarged definition of work hazard described above in two respects. First, these techniques are designed to address acute hazards. Acute hazard exposure usually results from human error or technical failure and can be characterized as an 'off–on' switch (Cox and Cox 1993). Hazards resulting from chronic exposures, to which it is much more difficult to assign a probability value, are largely neglected. Secondly, the domains of organizational and psycho-social hazards have been generally disregarded with respect to their contribution to overall system risk. These omissions represent serious deficiencies in the current system safety hazard/risk assessment techniques.

2.3. *Need for a work system hazard/risk assessment model*

The level of risk depends on the intensity, frequency and duration of the multifaceted array of factors which characterize any given work system, as they relate to the workers' capacity to respond to work demands in a specific environment (Karwowski and Jamaldin 1995). The acknowledgment of the interactive nature of physical and non-physical (i.e. cognitive, psycho-social and organizational) work system hazards by the scientific and occupational health communities, as well as the magnitude of the resulting harm to workers, businesses and the economy, warrant the need for an instrument which assesses the integral effects of all system elements (Karwowski 1991, Karwowski *et al.* 1994d, Genaidy *et al.* 1999). NIOSH (1997c) recognized that, in general, knowledge of the relationships between risk factors and the level of risk is still fundamentally incomplete. The magnitude of this problem and the recognition of its impact creates a pressing demand for the work system hazard/risk assessment instrument that assimilates all system elements.

3. Description of work system model components

The work system described in this study consists of three primary components: work demands, worker, and outcome measures (i.e. perceived and actual risk), as well as their relationships (figure 1). A description of these components and their relationships is given below.

3.1. *Work demands*

Work demands include both work content (i.e. the physical and mental job demands) and work context (i.e. the physical, social, individual growth and work organization environment).

3.1.1. *Definition of variables*: The physical demands component describes the set of activities that require combined dynamic and static muscular contractions while the body is maintaining a dynamic posture (e.g. walking, running) or a static position (e.g. sitting, standing). Physical demands have been classified, for epidemiological reasons, into two categories: (1) object handling activities such as lifting, lowering, pushing, pulling or carrying consist of moving objects with one or both hands and the use of upper and lower extremities, and action of the trunk; and (2) extremity-postural work which describes extremity and head work either in a fixed or dynamic lower body position, such as sitting and crawling.

Mental demands represent the workload imposed by the job tasks on the worker's perceptual and cognitive capabilities. One way in which mental work can be categorized is as skill-based, rule-based or knowledge-based according to the classification system developed by Rasmussen (1983). Skill-based behaviour evolves as a series of prearranged, ordered steps in a well-rehearsed routine. Rule-based behaviour is invoked when a situation is identified as belonging to a familiar class of problems through which the solution steps are based on prior experience.

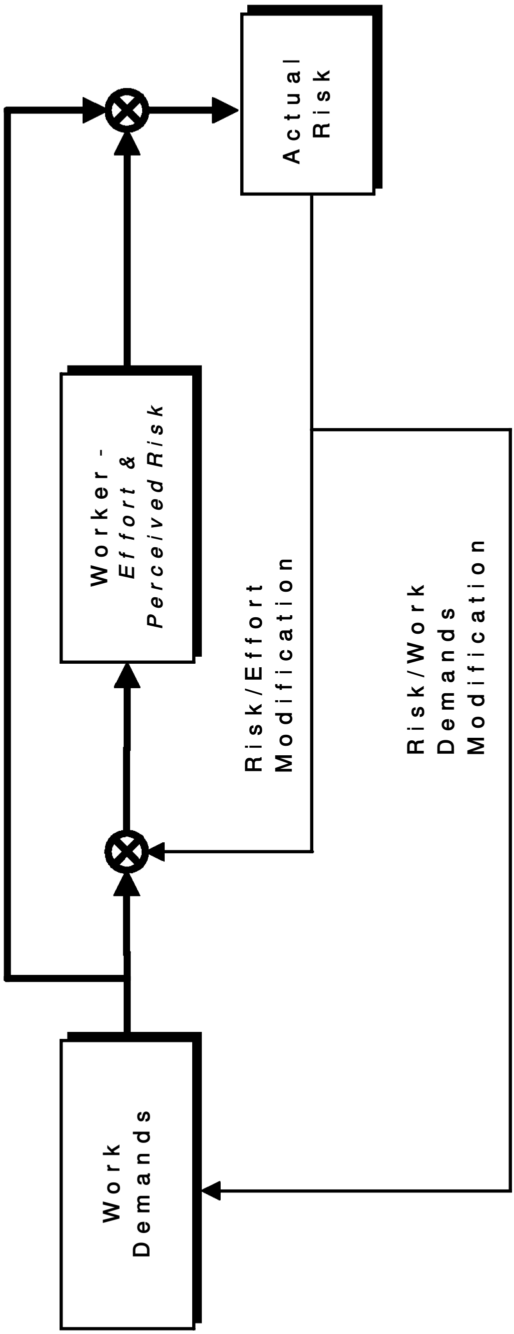

Figure 1. Work system components.

Knowledge-based behaviour occurs in an unfamiliar situation in which the problem cannot be simply and immediately classified and, therefore, extensive trial and error iteration is required to determine the solution.

Work context refers to those environmental conditions that affect a worker's ability to perform, but does not specifically relate to work input or to work output transformation, as in the case of physical and mental demands. Physical elements represent the physical environment in which the work tasks are performed. These elements can impede the worker's long-term or short-term ability to perform the job activities.

The social, individual growth, and work organization environments describe those variables that collectively form the non-physical work setting. The social aspects include relationships with co-workers, management, and family (Elo 1986, Gardell 1987). The individual growth aspects refer to an individual's growth needs as described by Maslow's Hierarchy of Needs (1943). Work organization is the objective nature of the work process and deals with the way work is structured and managed (e.g. shift work, job structure within the work process or organization; Cox and Cox 1993).

3.1.2. *Hierarchical structure of work demands*: The work demand profile is structured as a hierarchical framework (see figure 2). Figure 2 provides an example of the physical demands hierarchy structure. Two global work demands reside at the top of the hierarchy, that is, work content and work context. Below the top layer, classifications describe the composition of the next lower layer. For example, below the 'work content' layer lies the physical and mental job demands. The next lower layer describes the groupings which constitute the physical and mental demands.

The lowest level of the hierarchy represents the most detailed descriptions, that is the work elements characterizing the demand classification. For example, weight of load, repetition, horizontal distance, height of lift/lower, time duration and twisting angle refer to work elements which describe lifting demands of the object handling demands in the physical demands layer of the work content layer.

It is important to structure the work demand profile within a logical framework, as it will allow users to obtain varied levels of information details. For example, ergonomists and safety engineering specialists employed in an environmental health division of a large corporation may be interested in the information provided by the bottom layer of the hierarchy (i.e. the most detailed level of information) as they attempt to design and implement control strategies aimed at the minimization of risk in the workplace. Alternatively, a higher level manager in the division may be interested in more global aspects of information provided at higher layers of the hierarchy in order to communicate a more comprehensive overview regarding hazard/risk to other corporate officers, shareholders or potential customers.

3.2. *Worker*

The worker represents the individual performing the job with their associated personal characteristics, abilities, capacities and needs serving as the conduit through which the work demands are processed into an effort level. Work demands act as an input to the worker who, in turn, performs an activity to transform a work object or information into a desired product.

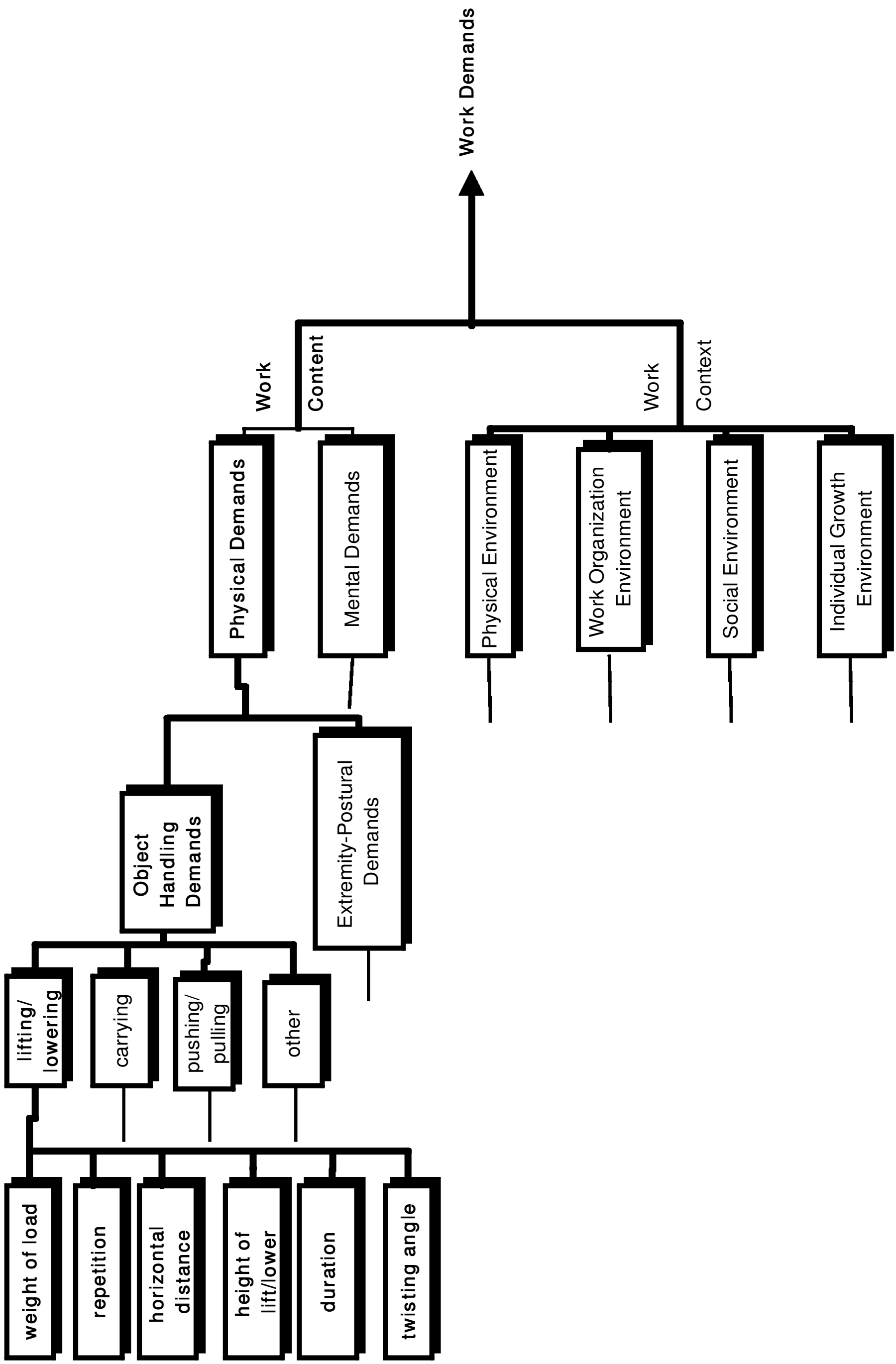

Figure 2. Hierarchical structure of work demands.

Although jobs vary tremendously, there are four operational functions (see figure 3) that are fundamental to all jobs and virtually every form of human activity. These are: (1) sensing (i.e. information receiving); (2) information storage; (3) information processing; and (4) decision/action functions (McCormick 1979). Therefore, the worker functions within the context dictated by the work setting, transforming the job demands into the desired product by generating an effort level as they expend energy.

Traditionally, job performance (i.e. the manner in which the worker meets the challenges of the work demands) has been described rather simplistically. Vroom's (1964) 'Performance $= f(\text{Ability} \times \text{Motivation})$' model has long served as the archetypal formula to specify the relationship between the individual worker and their performance output. This study endeavours to enrich this description by characterizing the worker's effort level (i.e. physical, cognitive, emotional) in association with their own individual qualifications and the required qualifications as determined from the job demands.

3.2.1. *Modes of information processing and output selection*: The way in which all workers handle the challenges of work demands, regardless of their individual capabilities, can be viewed as governed by three primary modes of processing—cognitive, emotional and physical. The work object (i.e. information about a work task) is a stimulus, is rendered as an object or entity through its sensory qualities and can be stored in memory as a function of those perceived qualities. Such hybrids of representation and actual stimulation become the input to the cognitive and emotional processes (see Gaillard 1993). Cognitive (i.e. rational) processing transforms sensory information input into motor and/or vocal output using formal and logical operations. Emotional processing is influenced by feelings which inherently contain impulses to act. The logic of the emotional processing is associative; it takes elements that symbolize a reality, or trigger a memory of it, to be the same as reality (Goleman 1995). Emotional appraisal of a situation is automatic and instantaneously contains impulses to act.

Generally, there is a balance between emotional and cognitive processing, as emotion feeds and informs cognitive processing, and the cognitive processing, in turn, refines and regulates the impulses of the emotional input (Goleman 1995). Positive emotional states, such as in mildly enthusiastic states, are capable of enriching the cognitive processing. At the extreme, positive emotional states can disable cognitive processing, as in manic states. Negative emotional states can moderately affect cognitive processing, as in the case of a bad mood, or can disable it, as in the case of severe depression.

Figure 4 depicts a hypothetical representation between cognitive processing and emotional processing. Cognitive processing is optimal when emotions are in a moderate state (i.e. not very positive, not very negative). When emotions are overwhelmingly positive, such as in an hysterical excitement, or overwhelmingly negative, such as in an angry rage or depression, all energy is devoted to the extreme state with little remaining for cognitive effort. Generally, however, there is a lack of an integrated construct in the scientific literature which permits a complete understanding of the architecture of human information processing. Further research is needed on this issue to advance understanding and provide integrative information. Recent integrative works on stress, workload, and fatigue have begun

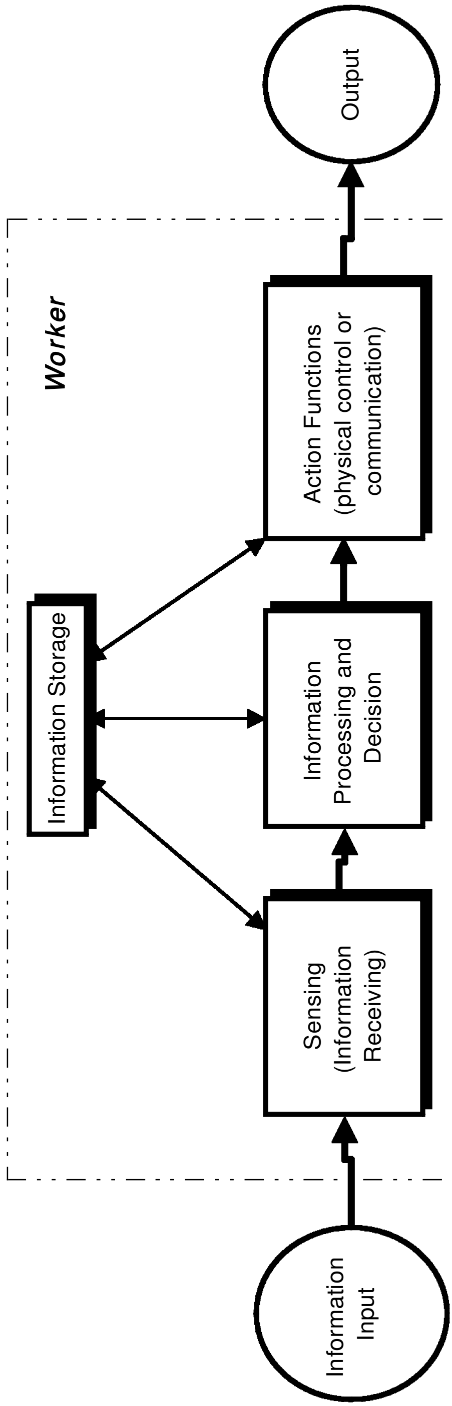

Figure 3. Basic operational functions in human work activities (adapted from McCormick 1979).

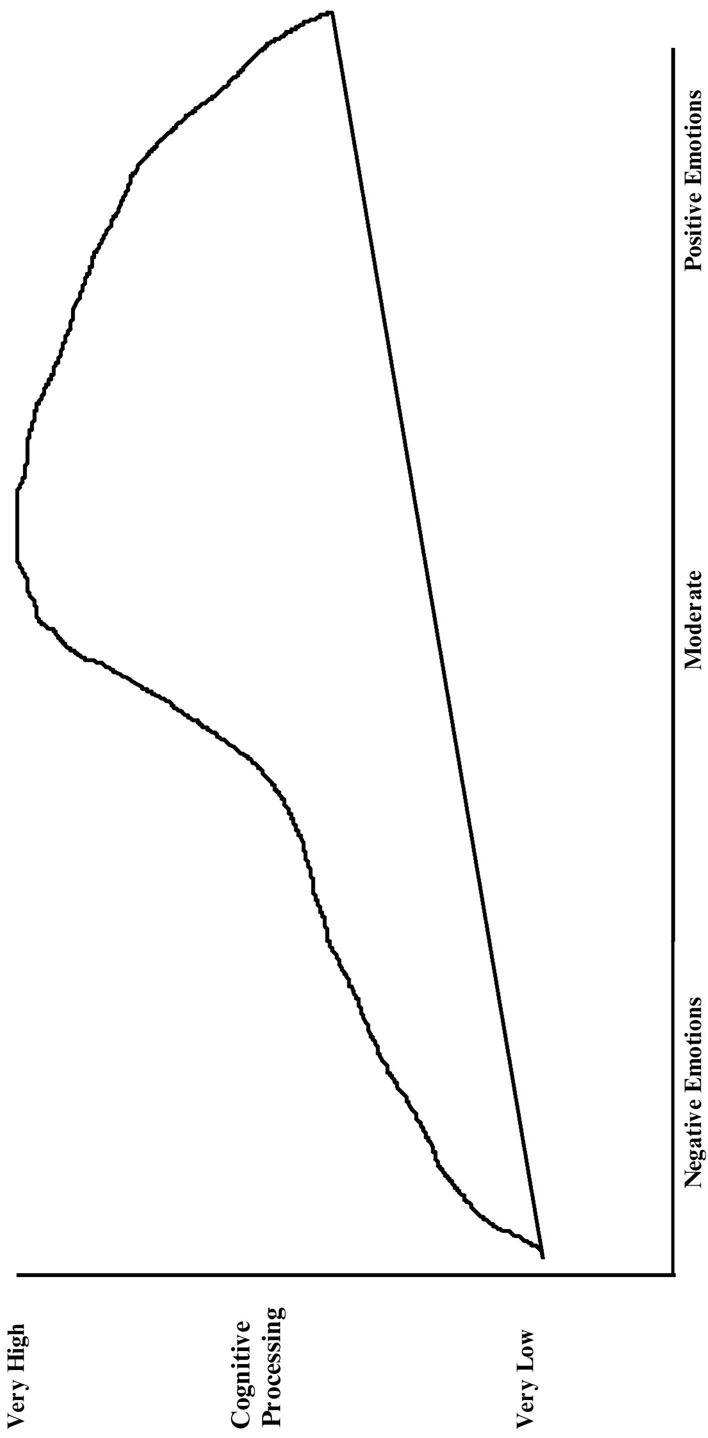

Figure 4. Hypothetical representation of cognitive processing and emotional processing.

to seek this relation (see Gaillard 1998, Hancock and Desmond 1998, Tepas and Price 1998)

After information is processed, an output is selected and a response is produced by muscular contraction of differing body parts, including the complexities of speech. The response results in transformation of the work object or information toward a desired form. Since physical loading consumes energy for this object transformation process, the worker's energy state is influenced by the physical load. This, in turn, indirectly influences the capacity for information processing. For example, if physical loading is within moderate limits, it may produce a positive emotional state that can enhance and improve mental capacity available for task execution, thereby reducing the negative effects of irrational processing. Alternatively, if physical loading is not pleasurable or is distasteful, a resulting negative emotional state may reduce or decrease the cognitive processing capacity available for task execution.

3.2.2. *Effort*: Effort is defined as the amount of energy an individual expends (Porter and Lawler 1968). Based on work experience, effort can be described as a function of the interaction of the worker energy states, worker qualifications (e.g. motivation, skills, abilities), and required work qualifications. For example, if the performer has the required motivation level and abilities to perform a certain task, but the performed energy state is dominated by physical fatigue due to inadequate sleep or illness, the resulting effort level will be very low or inhibited. Indeed, the worker energy state is a complex interaction of emotional, physical and cognitive states (figure 5). Moreover, the motivation force is affected by internal human needs, as well as external work demands.

Effort can be classified according to the nature of the challenge presented, via work demands, into the domains of the muscular, the cognitive and the emotional. Muscular effort refers to the physiological energy expenditure resulting primarily from physical job demands. Subjective ratings of physical effort have been found to be valid, reliable and highly related to actual metabolic costs (Hogan and Fleishman 1979, Hogan *et al.* 1980). Cognitive effort refers to the energy expended through mental processing resulting from mental job demands (Hart and Staveland 1988). Emotional effort refers to energy expended from processing feelings and their inherent impulses to act, regarding all facets of the work demands.

Cognitive effort and emotional effort are closely related. Harmony between them can enrich human performance (Cszentmihalyi 1990, Hancock 1997). Alternatively, discord can impair and even incapacitate the worker. There is also a close connection between the physical and emotional/cognitive effort domains. When someone is exerting a high level of physical effort in response to challenges presented by physical work demands, the worker's cognitive and emotional energy states may be directly affected. Physical abilities required by the work affect individual growth motivation, fatigue and satisfaction (Hogan and Fleishman 1979, Fleishman 1984). A consequence of the physical exertion is the slowing of the cognitive processes, which in turn may lead to exertion of an extra amount of cognitive effort in order to process the required information (see Vercruyssen *et al.* 1989).

3.3. *Health and safety performance measures*

The work system model's output is the performance resulting from worker effort. The output of interest emphasizes the quantity significant to the user. Therefore,

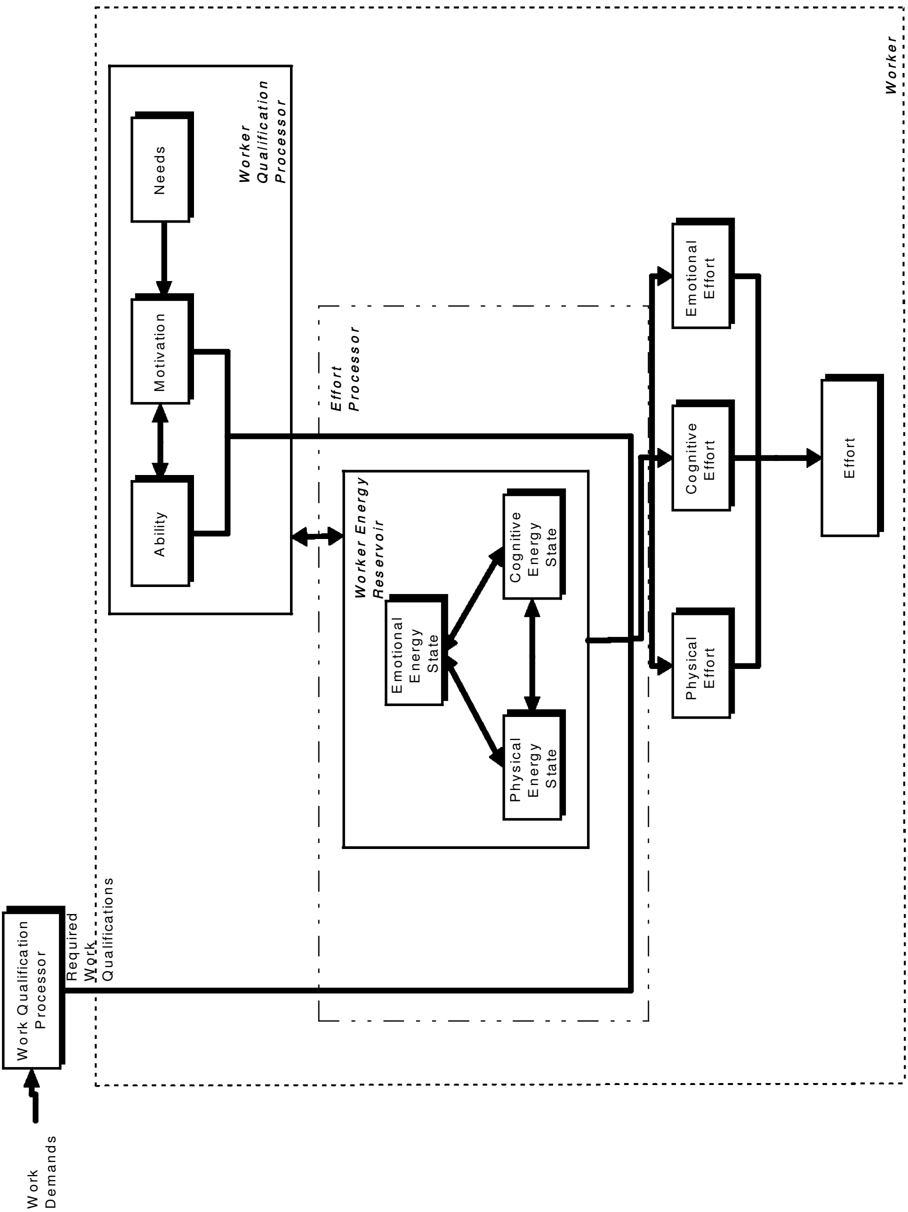

Figure 5. Effort as a function of worker energy state, worker qualification and required work qualification.

these outputs may assume the form of various parameters. As this study focuses on the health and safety of the work setting, the outputs of interest are the risk perceived by the worker and the actual risk to the worker in the system.

Risk, in a broad and contemporary sense, expresses the potential harm caused by hazards present in all aspects of the work system. It can be classified into perceived risk and actual risk. Perceived risk is the level of internal risk the worker experiences in response to the level of effort exerted and may or may not be equal to the actual risk. Perceived risk is subjective and is, therefore, influenced by numerous judgemental biases such as familiarity, controllability of hazard and time scale over which any resultant harm may occur (Cox and Tait 1998). Therefore, it is contextual, as it is filtered through personal attitudes, experiences, values and education (Petersen 1996). Actual risk is the true risk present in the work system, regardless of the worker's awareness, and can be calculated through a quantitative risk analysis measure.

Perceived risk can be further categorized according to the mode of processing the risk is borne out of, rather than the type of harm the risk can cause, as the harm may assume several forms (e.g. physical, cognitive, emotional). This distinction is especially important in the area of emotional risk, although the areas of physical and cognitive risk also exhibit interconnections to other areas, as would be expected in a complex system.

3.3.1. *Perceived risk*: Perceived physical risk refers to the subjective risk the worker assumes with respect to their body structure (e.g. muscles and bones) and physiology (e.g. respiratory, sensory systems). For example, if a worker believes there is little risk associated with a heavy, repetitive lifting task, the perceived risk is low. Accordingly, the perceived risk will impact the decisions the worker makes regarding the way in which the job is performed.

Perceived cognitive risk refers to the subjective risk the worker assumes with respect to the mental job demands. For example, a worker may agree to assume several knowledge-based job assignments to be performed concurrently. The high level of mental processing necessary to execute these tasks represents a primary risk to the worker's thinking capabilities (including cognitive and memory processes), but the worker may also experience physiological disorders (e.g. cardiovascular as a result of chronic effects) as a result of accepting the cognitive risk (Hancock and Warm 1989).

Perceived emotional risk refers to the subjective risk the worker assumes regarding the expression or repression of their feelings and their impulses to act on them. Perceived emotional risk arises in response to the interconnectedness of the work system characteristics. For example, a worker who is fatigued due to a high level of physical or mental job demands, annoyed due to family scheduling problems as a result of having to work overtime, and hot as the air conditioner may not be working correctly, may be more likely to risk verbally assaulting a co-worker's character after a disagreement than a worker without such problems and discomfort.

3.3.2. *Actual risk*: Actual risk, the objective risk the worker is exposed to, equals the product of frequency and severity of harmful effects (Goetsch 1996, Wentz 1998). There are several methods of quantifying actual risk (see Cox and Tait 1998). Frequency can be calculated as the number of occurrences per 100 full-time workers over a 1-year period for: (1) lost workday cases; and (2) restricted workday cases (Goetsch 1996). Severity can be computed as the number of lost workdays and restricted workdays per 100 full-time workers over a 1-year period. Actual risk may then be calculated as the weighted sum of lost and restricted workday cases.

4. Description of work system model operation

4.1. *System overview*

The model of the work system proposed for WMSD hazard/risk assessment (figure 6) represents a complex adaptive control system. While these models depict the main components which describe the work system relationships, the myriad factors which characterize the work demands and the worker sub-systems demonstrate the system's complexity. This multitude of factors interacts to produce effort and risk. Consequently, numerous variables and relationships within each sub-system can be manipulated to vary the effort and risk output parameters for WMSD study.

Self-regulation in living systems is mediated by feedback control mechanisms (Smith and Smith 1987). As the work system is a living system, feedback control is used to describe the effects of output parameters which serve to change input variables. Wiener (1948) defined the term 'cybernetics' as that referring to the study of feedback-controlled guidance in both living and non-living systems. Smith (1979) asserts that cybernetics can serve as a fundamental approach to the study of social factors and social human factors design in occupational safety and health. Smith (1979) also acknowledges that the interactions between human behaviour and the physical, social and organizational properties of the work environment provide the basis for understanding the operational hazards in work. The cybernetic model detailed in this paper further develops these ideas by specifying work system components and explicitly describing their interrelationships.

Adaptation is an interactive process implying the response of one entity to the actions of another (Hancock and Chignell 1987). The work system is adaptive as its participants adjust, based on changes in the work demands as well as the effort exerted, risk perception, and risk knowledge. Adaptation occurs to modify system parameters to compensate for changes in the process. In general terms, adaptation results from a three step sequence. First, a standard or goal is set for the output parameter. Next, the actual output is assessed with respect to the target. Lastly, adjustments are made to the system parameters in response to the error (target—actual) to minimize deviation. The mismatch between work demands and available resources (i.e. actual capabilities of the human operator) when within the zone of adaptability can be compensated for through adaptation, therefore controlling the error signal to remain within acceptable boundaries (Chignell and Hancock 1986). Figure 7 illustrates the task demand and capacity mismatch relationship.

Specifically, in the case of the work system, adaptation occurs through two groups of respondents, namely, the worker and management. The worker controls the effort acceptance level and the risk acceptance level. In regulating these parameters, the worker takes into account changes in the system inputs and 'learns' based on experience. Management controls a large set of the factors which characterize the work demands and, therefore, affect the stimulus for effort and risk outcomes. In regulating these parameters, management takes into account changes in system outputs, also with an accompanying learning experience.

Risk acceptance level is based on the perceived and actual risk inputs. The worker adjusts their behaviour according to influences of internal and external

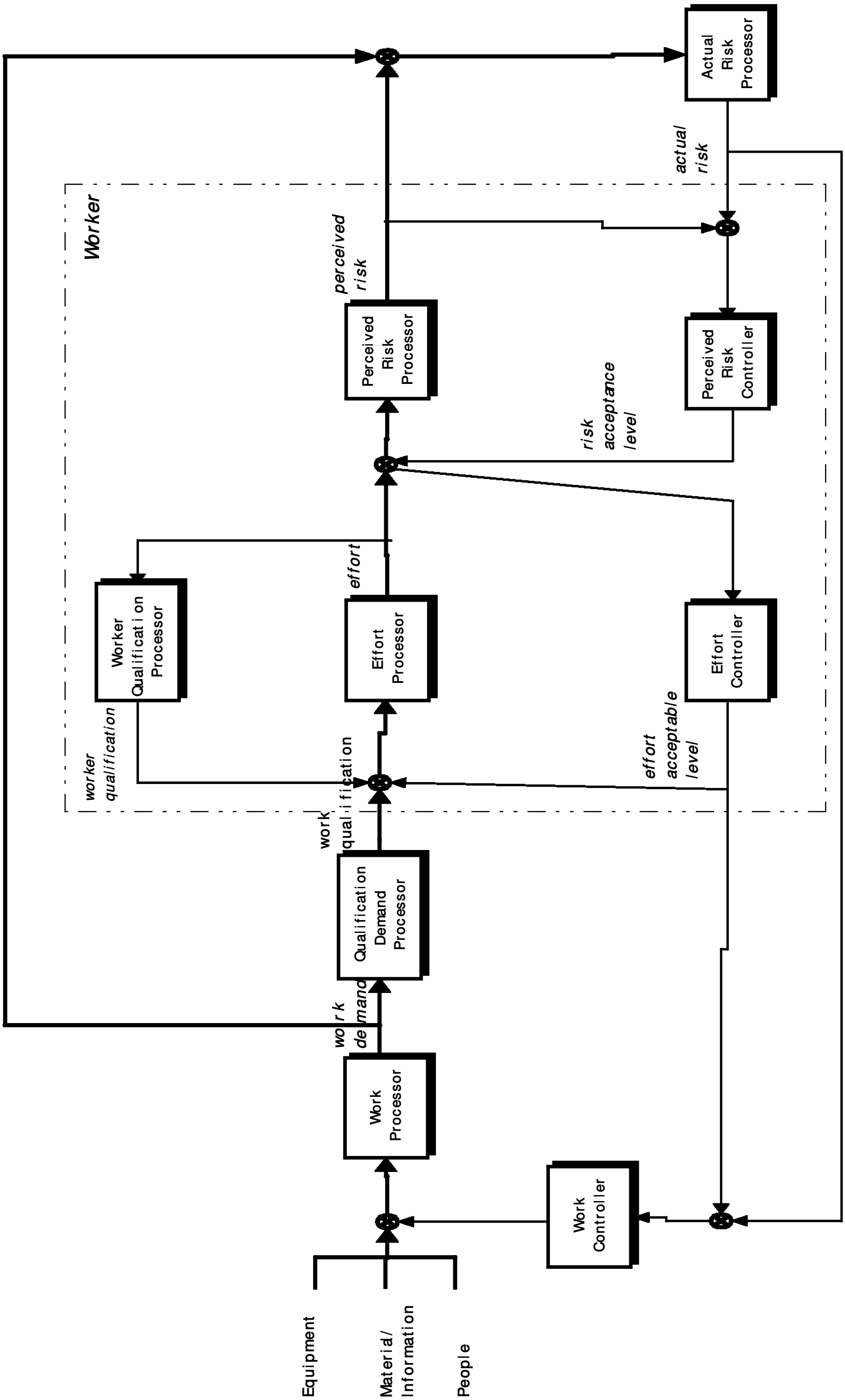

Figure 6. A cybernetic work system model.

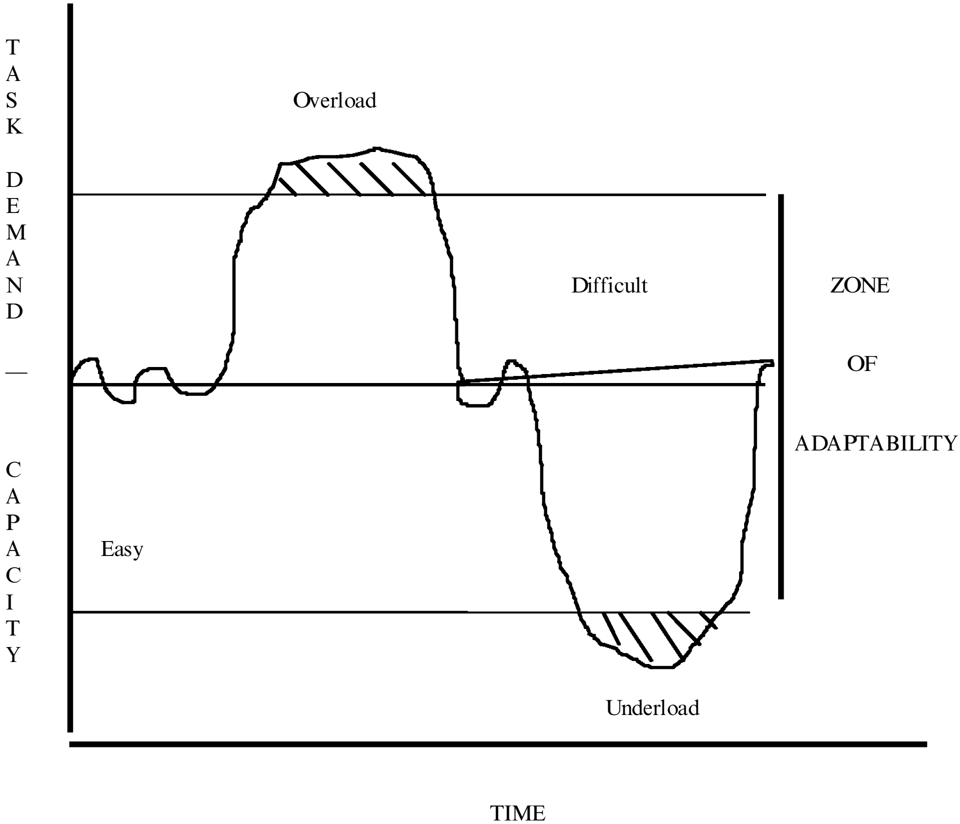

Figure 7. Task demand and capacity mismatch relationship (adapted from Hancock and Chignell 1987).

variables. Internal variables are those which characterize the worker, such as their attitude toward risk (i.e. risk taker or conservative), motivation for performing the activity and individual needs (e.g. acceptance by peer group). External variables are those which characterize the nature of the risk, such as time frame of consequences (i.e. immediate or long term), media coverage, and controllability. Both internal and external variables affect the worker's physical, cognitive and emotional modes of information processing to form the adapted response.

Similarly, the worker can adjust their effort level to set an effort acceptance level based upon previous knowledge of the effort required to perform the work activity and the determined risk acceptance level. To set the effort acceptance level, the worker must first establish the risk acceptance level. This information is fundamental to the effort regulation process. The effort acceptance level is affected by the worker's physical, cognitive and emotional energy states as well as motivation, ability and needs.

While workers regulate their responses to work demands through effort acceptance level (i.e. how hard the worker is willing to try) and risk acceptance, management regulates the stimulus to the worker (i.e. the work demands). These factors are typically manipulated after assessing the actual risk and worker effort levels (i.e. performance) to achieve a desired result. Many aspects of the factors creating the work demands can be altered by management including working hours, temperature of the environment, break schedule, number of tasks defining a job, difficulty of tasks defining a job, and degree of worker autonomy over the work process.

4.2. *Work system model*

4.2.1. *Operator definitions*: The components of any system include input, processor, output, control and feedback (Murdick 1975). Three types of operators are depicted in figure 6: processors, controllers and comparators. Processors function to produce the given output parameter. Therefore, processors represent the activity or activities that transform the input into output. Controllers represent the activity or activities that serve to determine the deviation of the target output from the actual output and adjust the system parameters in response to this error. A glossary of the processor and controller functions is given in table 1. The

Table 1. Glossary of building blocks for work system model.

Building block	Description
Work demands processor	Transforms inputs of people, material and equipment, effort and actual risk into work demands. Regulated by management, based upon appraisal of effort and actual risk outputs.
Effort processor	Transforms inputs of work demands and perceived risk into effort. Regulated by worker, based on such variables as worker energy state, motivation and ability.
Qualification demands processor	Transforms input of work demands into required work qualification. Job content and job context determine the qualifications to execute work activity.
Worker qualification processor	Transforms input of worker's effort into worker qualification. The worker's effort level is influenced by, among other variables, their ability to perform the work activities. These abilities, determined by the worker's education, skill and training, form the basis for the worker's qualifications.
Perceived risk processor	Transforms inputs of effort and actual risk into perceived risk. Regulated by workers, based on such variables as familiarity of activity and benefit of outcome.
Actual risk processor	Transforms inputs of perceived risk and work demands into actual risk. Determined by job content (e.g. task difficulty, weight of load handled) and context (e.g. duration of work day, noise level), as well as the manner in which the activity is executed (i.e. as guided by the worker's perceived risk).
Risk controller	Regulates inputs of perceived risk and actual risk to produce risk acceptance level. Performed by the worker and influenced by variables such as the individual's risk attitude and benefit of outcome.
Effort controller	Regulates inputs of effort and target risk to produce target effort. Performed by the worker and influenced by variables such as motivation and energy state.
Work controller	Regulates inputs of target effort and actual risk to Work Demands Processor. Performed by management to alter aspects of job content and job context with the intent of varying effort and risk outcomes.

comparator, the circular symbol containing an 'x', describes the error detection between the input and variable which is being fed back.

4.2.2. *Model operation*: In the cybernetic work system model, work qualifications act as the inputs to the worker. In general, qualifications refer to the knowledge, skills and abilities (KSA) acquired through education, training and experience. The KSA dimensions are widely used by human resource specialists for job selection and training programme development (Schneider and Konz 1989, Fleishman and Reilly 1992, Wooten 1993).

The required qualifications for a given job are derived from the work demands (i.e. job content and job context). They identify the characteristics an ideal candidate for the job should possess. Workers who will perform the job tasks, however, possess their individual set of abilities, that is, the actual worker qualifications.

If the worker's actual qualifications are greater or less than those required by the work qualifications, a mismatch occurs (i.e. deficiency or surplus in worker capacity). In the case of a deficiency, the amount of mismatch may be reduced or possibly eliminated by experience, education, on the job training or augmented assistance from the machine system itself (Hancock and Scallen 1996). In the case of surplus, the amount of mismatch may be minimized by increasing the difficulty of, or dynamically adding additional work demands. This process of dynamic task allocation is one which is currently under intense scrutiny (see Parasuraman and Moulou 1996). The amount of mismatch affects the worker's effort level. When worker qualifications are less than required, he/she may react by overexertion. When worker qualifications are greater than required, he/she may become bored and exert a lesser effort. Performance may be optimized by matching as closely as possible the required and actual worker qualification parameters.

The proposed model's relationships can be expressed through the following seven equations:

$$\text{Effort} = f_1\ (\text{Required Qualifications, Worker Qualifications, Effort Acceptance Level}) \quad (1)$$

$$\text{Perceived Risk} = f_2\ (\text{Effort, Risk Acceptance Level}) \quad (2)$$

$$\text{Actual Risk} = f_3\ (\text{Work Demands, Perceived Risk}) \quad (3)$$

$$\text{Risk Acceptance Level} = f_4\ (\text{Perceived Risk, Actual Risk}) \quad (4)$$

$$\text{Effort Acceptance Level} = f_5\ (\text{Perceived Risk}) \quad (5)$$

$$\text{Work Demands} = f_6\ (\text{Equipment/Material/Information/People, Effort Acceptance Level, Actual Risk}) \quad (6)$$

$$\text{Required Qualifications} = f_7\ (\text{Work Demands}) \quad (7)$$

As demonstrated through the model's relationships, the required work qualifications, the worker's actual qualifications and the effort acceptance level determine the level of effort the worker exerts (1). Next, the worker's effort and risk acceptance level (i.e. the level of risk the worker accepts) yield the perceived risk (2). Actual risk is determined from the worker's perceived risk (as it influences task execution) and the nature of the work demands (3). The worker's risk acceptance level is based on their perceived risk as well as the actual risk (4). Similarly, the worker's effort acceptance level is based on the risk level he/she accepts, that is, the perceived risk

(5). Therefore, the totality of the work demands can be described as the raw inputs (i.e. equipment, material/information, people), the actual risk and the effort acceptance level (6). The work demands act to produce the required qualifications ideally possessed by the worker (7).

4.3. *Relationships between work system model components*

Balancing work demands with worker abilities and needs represents a homeodynamic condition, where the worker strives to maintain a state of balance within limits based upon natural laws governing their existence. Any stimulus or attempt to alter that state is met with an innate response to maintain an acceptable status. The stimulus is or creates 'stress' upon the organism, system, culture or organization. The response is 'strain'. Welford (1973) observed that strain arises whenever there is a departure from optimum conditions (i.e. a condition that the worker is either unable to correct or cannot easily correct). It is postulated that workers perform best under conditions of moderate demands and that performance will be 'suboptimal' if the demand is 'too high' or 'too low'.

4.3.1. *Feedforward elements*: Three major elements form the feedforward path of the complex work system—the work demands, the worker and the performance outcomes, perceived risk and actual risk. In this path, the work demands serve as an input to the worker, who, in turn, processes these demands, producing the effort and risk outcomes. The worker affects these outputs physically, cognitively and emotionally. In order to optimize the performance outcomes, variables within the work system must be manipulated. Therefore, aspects of the work demands and the worker function as the modifiable factors for the minimization of work system hazard/risk.

4.3.2. *Feedback elements*: The feedback elements of the complex work system are the adaptations which allow the change of conditions within the domain of a given component's control. Adaptations are made to compensate for incompatibilities between system components. There are two primary feedback loops: risk/effort modification and risk/work demands modification.

The risk/work demands adaptations represent those factors in the work content and work context that can be modified based on the knowledge of risk involved in meeting work demands. For example, if management learns that a consultant's evaluation has shown a particular worker to be at high risk (i.e. actual risk), management may then choose to modify aspects of the work environment (e.g. job rotation, training).

The risk/effort modifications represent those factors that can be adjusted by the worker. These modifications, in turn, could increase or decrease the level of worker effort. For example, if a worker feels at risk of injury, and then learns that the given work activity has very low risk, the worker may choose to exert more effort to accomplish the tasks.

4.4. *Example of model utility*

The following example illustrates how the framework of the cybernetic model could serve as a foundation for research of WMSDs in the industrial environment. Suppose a researcher is assigned the task of studying the incidence of WMSDs in a software development company. The epidemiologic study will use a prospective longitudinal approach and seek to classify risk factors for neck-related disorders. The study, following a group of workers (both exposed and non-exposed) forward in time for a period of 5 years, will calculate the rate of new cases.

The cybernetic work system model can be used to facilitate the development of this study in several ways. First, the model allows for the accounting of factors (e.g. social support, job role clarity, home demands) not traditionally examined that may clarify the link between these factors or combinations of factors and the incidence of the WMSD. Secondly, as the cybernetic model specifies general associations between parameters, the study can test hypotheses to characterize the relationship. For example, the relationship between worker perceived risk of WMSDs and actual risk has not been investigated.

Furthermore, the analysis of numerous work system factors considered in the cybernetic model may reveal evidence of an effect modifier (e.g. age for tendinitis) or a confounding factors (e.g. diabetes for carpal tunnel syndrome) which could alter the way in which future studies are conducted.

5. Concluding remarks

An effective work system hazard/risk assessment instrument must address all components of the work system as well as their interactions result (Karwowski *et al.* 1999, Yeung *et al.* 1999). Identification of work hazards and risk serves as the foundation for management decision-making regarding work system design and safety assessment settings. The work hazard description and risk quantification can then establish a basis for preventative/corrective action, through all stages of the work system's life cycle. Accurate description of WMSD hazards also plays a significant role in the success of the intervention efforts, such as prioritization of areas for job redesign, identification of populations at risk, benchmarking, and communication programmes. The present work provides a comprehensive description of an adaptive control work system model for WMSD hazard/risk assessment purposes and, thus, provides a theoretical framework for future research.

While the primary objective of a comprehensive work assessment instrument is hazard identification and risk quantification, due to the breadth and depth of data required to fulfil this objective, numerous other purposes may be served. These include, but are not limited to:

(1) Design of the most appropriate medical examinations by occupational medicine specialists. A work demands model yields task descriptions which serve as inventories of various occupations. These inventories form a database which can be used as a functional capacity checklist of essential job tasks, therefore aiding medical specialists. Evaluation of an individual's capabilities for a specific job, as demonstrated in a pre-employment health screening, is problematic without such data Additionally, an inventory of job tasks serves to identify workers who participate in hazardous tasks and, therefore, alerts medical specialists to monitor such workers for adverse health effects.

(2) Design of rehabilitation and return-to-work programmes by health practitioners. Work system analysis provides information to classify which tasks are essential and which are non-essential regarding execution of a job. Critical tasks can be used to provide input to physical therapists as recommendations for therapy guidelines. Later, the critical tasks can serve as the

performance criteria for determining when the worker possesses sufficient capability to return to work.

(3) Decision making with respect to work restrictions and provisions of reasonable accommodations by occupational medicine physicians, human resource specialists and business managers. In recent years, there has been considerable government attention regarding the needs of the handicapped and disabled in the active workforce. As a result, medical selection procedures for job candidates has undergone considerable scrutiny. A worker's limitations with respect to a given job can only be evaluated relative to a detailed description characterizing the nature of the essential tasks. Work system analysis provides a means for collecting and classifying this information.

(4) Improvement of work processes by industrial engineers, business managers, supervisors and work teams. To understand the complex operation of a work system, all aspects must be defined and their interrelationships described. This knowledge, which is a prerequisite for improvement efforts, can be provided by a work system analysis instrument.

(5) Planning and scheduling work activities by business managers, supervisors, industrial engineers and work teams. Work system analysis can provide detailed information regarding the difficulty, frequency, duration and variability of job demands, as well as describing the environmental work setting. This information yields a precise depiction of job attributes, which in turn improves the accuracy of predicting project duration and efficiency in the coordination of various work activities.

(6) Documentation of work requirements by human resource specialists for personnel purposes such as selection and compensation. Work system analysis can provide a written record of a job's task demands and ability requirements. This information serves as a screening tool for job placement by matching potential candidates to job requirements. The listing of job tasks can also assist in the compensation process by supplying a list of job performance criteria that can readily be evaluated.

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