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Mechanical exposure concepts using force as the agent

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This paper presents a model that addresses mechanical exposure with regard to the development of musculoskeletal disorders, defines exposure concepts, unifies a variety of exposures, and includes the concept of human activity. When force is used as an agent, concepts related to the measurement, transformation, and interaction of the agent with tissues can be developed for use in epidemiologic exposure assessment and hazard assessment. The importance of tissue response in the exposure modeling process and in the creation of exposure indices is highlighted. Unfortunately, the response of tissue to forces of varying amplitudes and time variation patterns are largely unknown and thus reduce the possibility to develop optimal exposure assessment metrics. Although the paper argues that an exposure index at the tissue level may be the most powerful, considerations of resources and current knowledge make exposure indices based on external exposure or internal exposure preferable choices.

Key terms epidemiology, ergonomics, exposure indices, internal exposure, musculoskeletal disorders.

The terminology and concepts of exposure have not been consistently applied in the area of ergonomics and the epidemiology of work-related musculoskeletal disorders. In fact Zartarian et al (1) note that terms such as exposure and dose are often used interchangeably even in the more longstanding field of occupational epidemiology. Checkoway (2) suggests that the meaning of these terms can differ across various fields (such as pharmacology, risk analysis, or epidemiology). This variation makes it is difficult to compare research results that have employed different terms to describe exposures. Even more difficult is the interpretation of research that uses similar terminology but applies different definitions to the terms employed.

Recently Lioy (3) proposed an exposure analysis model in an attempt to unify the concepts of exposure within environmental epidemiology. Zartarian et al (1) presented an in-depth review of exposure concepts and their definitions and suggested a common language for use in exposure studies. We draw on the work of these authors in describing a model of mechanical exposure for use in musculoskeletal epidemiology and risk assessment in ergonomics, using force as the agent.

Previous terms used in hazard assessment and in exposure assessment for musculoskeletal disorders have included ergonomic exposure, physical exposure, risk factors, biomechanical assessment, and mechanical exposure. We use the term mechanical exposure (4), as physical exposure is too broad, there being a large number of physical agents (5), while ergonomic exposure restricts the scope of ergonomics too narrowly. Several models that include many aspects of work (eg, psychosocial factors) have conceptualized the relationship between the work environment and the development of musculoskeletal disorders (4, 6–8). This paper has a much narrower focus and addresses concepts needed for unambiguous mechanical exposure measurement.

Many "exposures" are described in the literature on the epidemiology of musculoskeletal disorders. For example, Bernard (9), in an extensive review, has identified a wide range of what are termed exposures or sometimes risk factors, including forceful exertions, posture, static posture, repetition, vibration, and cold. In order to understand, study, and better define the relationships between work and musculoskeletal disorders, we need to define the agent(s) and ask how the variables are

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related in an exposure model. Furthermore, in order to examine exposure, we must clearly define both the agent and the target (of interest) (1). Moore & Wells (10) used an early form of this exposure model by working backwards from postulated injury mechanisms in tissues of the distal arm, such as tendon strain, friction work on sheaths, and static muscle activation, to create exposure measures for the cumulative trauma potential of manual jobs.

Internal exposure is a concept identified in several models (4); however, it is sometimes argued that the use of the term is not consistent with usage in other fields of occupational epidemiology (11), in which exposure is outside the person or occurs at the point of contact between the person and the environment (2). Use of the concepts "dose" and "burden" for mechanical exposure may be misleading, since force does not accumulate as chemical dose and burden do. That is not to say that the "effects" of force on tissues cannot accumulate.

The role of purposeful activity is rarely seen in exposure schemes although occupational hygienists are aware that workers can hold their breaths in areas with high concentrations of vapors or that the strenuousness of the work affects ventilation and thus also the inhalation of particulates. With musculoskeletal disorders, the strategy used by a worker (eg, a squat or stoop in combination with a lift) can affect loads on tissues. As well, internal states, such as the co-contraction of antagonistic muscles, can become important.

The aim of this paper is to present a model that addresses current issues relevant to the development of musculoskeletal disorders in exposure assessment, define exposure concepts across a variety of mechanical exposures, and include the concept of human activity. The exposure model we present includes the concepts of injury mechanisms at the tissue and cellular level, the natural history of disorders, and health outcomes. However, it is beyond the scope of this paper to provide an in-depth description of all these concepts.

Mechanical exposure model

Terminology and definitions

In this paper, we describe the concepts of mechanical exposure with respect to the development of musculoskeletal disorders by employing terminology commonly used to describe other physical agents and concepts from the literature on inhalation, skin, or ingestion exposure (1, 3). Our intention in doing so is to describe mechanical exposure using reasonably established and accepted terminology to further communication and research in this field. We define these three concepts and include definitions for all the concepts used in our model in table 1.

Agent. The concept of an agent, "… a chemical, physical, mineralogical or biological entity, which may cause adverse effects in a target after coming in contact with the target [p 273]", is an important component of risk modeling and exposure assessment (1). Examples of agents include a charged particle in cell mutation and cancer, fibers in mesothelioma, dust in asthma, and benzene in liver cancer. We focus on the agent of force as a factor in the development of musculoskeletal disorders. While force may not be the only agent, we suggest it is a key factor for many musculoskeletal disorders (8, 13). There can be exposure in the case of human contact with something in the environment that results in force(s) on the person and that defines the exposure path. Forces of interest include a weight to be lifted, a chair to sit in, a computer mouse to manipulate, and vibration from a handheld tool, or simply work in a gravitational field. It may even be that most of the force is produced solely from within a person from co-contraction of antagonistic muscles when contact is made with a computer mouse or keyboard.

The agent in our examples is a (time-varying) force, which comprises the exposure (external and internal) and which can be described by the following three dimensions: the amplitude of the force, its frequency (or more generally its time variation pattern), and the duration of the exposure (4). Figure 1 shows schematically how a force time history is mapped with respect to these three dimensions of exposure.

Target. The target can be a "physical, biological or ecological object [p 273]" (1). Since we have chosen to examine the agent of force, we define our target as the human tissues of interest that are acted upon by this agent.

Exposure. Contact or interaction between the agent and a target is considered exposure (1). Therefore exposure can only be defined in the context of the agent, the target, and the path (1).

Description of a mechanical exposure model

The proposed model allows discussion of a wide range of mechanical exposures in industrial and office occupational settings, including hand–arm and whole-body vibration. Noise-induced hearing loss could also be encompassed by the model.

Although "psychosocial exposures" (14) are not explicitly included, the influence of many workplace psychosocial factors is reflected in the model. For example, a "fast workpace" or "hectic" work can be manifested as a

Table 1: Terms and definitions for a model of mechanical exposure with force as the agent.

Name	Figure 2 location	Definition and description
Agent	A	A "chemical, physical, mineralogical or biological entity which may cause adverse effects in a target after coming in contact with the target" [Zartarian et al, 1998 (1)]. In this model the agent is force.
Target tissue	B	A "physical, biological or ecological object" [Zartarian et al, 1998 (1)]. In this model we define several human tissues as targets. These tissues are thought to be affected by the agent of force.
Exposure (human contact)	C	In the most direct sense, exposure involves the contact or interaction between an agent and a target. Here we define exposure as any and all contact between the worker and the agent from the environment, for example, grasping a vibrating tool or lifting a mass. The nature of the physical agent is such that, even if it enters some tissue(s), it may or may not affect the target tissue(s). Target tissues can be defined at any level depending on the disorders or purpose of interest.
Job description	D	Description of the goals required of the worker, including details about potential interaction with force(s). Organizational controls that may act as constraints should be documented.
Environment (description)	E	Any aspect of the environment producing or resulting in force (the agent) that can potentially make contact with a worker. This could be a vibrating tool, a load to be lifted, or work in a gravitational field or in zero gravity.
Activity	F	Any overt (observable) activity, including that involving (or leading to) interaction between the worker and the agent. Job description alone may lead to biased or incorrect estimates of this interaction. This is sometimes called "work-style".
Work strategies	G	The manner in which the worker attempts to achieve the goals of the job description within the constraints of the environment and their own capabilities. This manner is a main driver of activity. This concept includes the particular motor patterns used in the job.
Potential contact	H	We define potential contact as an estimate of contact with the environment based only on information available from the environment but with no observed activity.
Internal exposure	I	We add this concept to explain the nature of the agent within the human body (both target and nontarget tissues). The unit of measurement does not change from exposure to internal exposure and is *newtons*. Rather than to use the term "dose", we suggest using "internal exposure".
Transmission and transformation	J	The transfer of the agent (force) through various tissues to the target and any changes that occur during this transfer. We have added this concept to our model to allow for a detailed description of the changes that the physical agent may undergo as it travels to the target tissues.
Injury mechanism(s)	K	Any processes that result in tissue damage or dysfunction as a result of the agent's interaction with that target tissue. With a mechanical agent such as force it does not make sense to talk of accumulation or elimination of force. However the outcome (eg, tissue damage) of the interaction of force with the target tissue(s) may be cumulative.
Biological effect	L	Any observable outcome of the interaction of the agent with human tissues. Chemical exposure models discuss the biologically effective dose. We can speak of the biological effect and describe the tissue damage. A biomarker can be used to estimate the biological effect, as well as internal exposure or injury mechanism [Vine & Hulken, 1995 (12)].
Natural history of disorder	M	The natural history of a disorder represents any and all processes that perpetuate the disorder to a point at which it is recognizable and leads to early expressions of injury. This concept is linked to the feedback loops indicated in our model (figure 1). Any model addressing the natural history of the disorder would have to include reparative and protective processes, as well as any processes that result in further damage to tissue. This aspect differs slightly from the chemical exposure model concept of "early expression of disease". This difference exists, in part, because many of the health outcomes resulting from exposure to force are not known as diseases and are difficult to diagnose in the early stages. We have included the concept of early expressions of injury to address this difference.
Early expressions of injury	N	Refers to any symptoms that can be observed and conceivably linked to the agent.
Health outcome	O	Any expression of injury that causes individual pain, discomfort, or reduced work capacity.
Exposure index	-	A descriptive statistic calculated upon the time history of an exposure measure (ie, a single number representing a time history).

change in the time variation pattern of force. "Deadlines" can be manifest as a period with no breaks.

We identify the following three regions of interest in the mechanical exposure model: (i) outside the body, (ii) inside the body between the interaction of the person and the environment (such as hands holding a mass) and the target tissue, and (iii) the target tissue, specifically the interaction of the agent with the target tissue. Mechanical exposure refers to the force as interaction of the person and the environmental agent (force). Internal exposure describes the agent, force, as it acts on and undergoes transmission and transformation through the body to the target tissue. The agent then interacts with the target tissue and a biological response, positive or negative, can occur. Figure 2 shows a schematic presentation of the model.

Outside the body. Many features of the environment can lead to exposure to the physical agent, force. A description of the environmental source and the work activities is necessary to understanding exposure. In fact, the human body is in constant contact with (exposed to) forces, as a result of living in a nonzero gravitational field (15).

Not only is it important to describe the physical attributes of the environmental source accurately (eg, a vibrating tool), but how the worker interacts with this source must also be considered.

One way of examining how a worker interacts with an environmental source is to look at the job description.

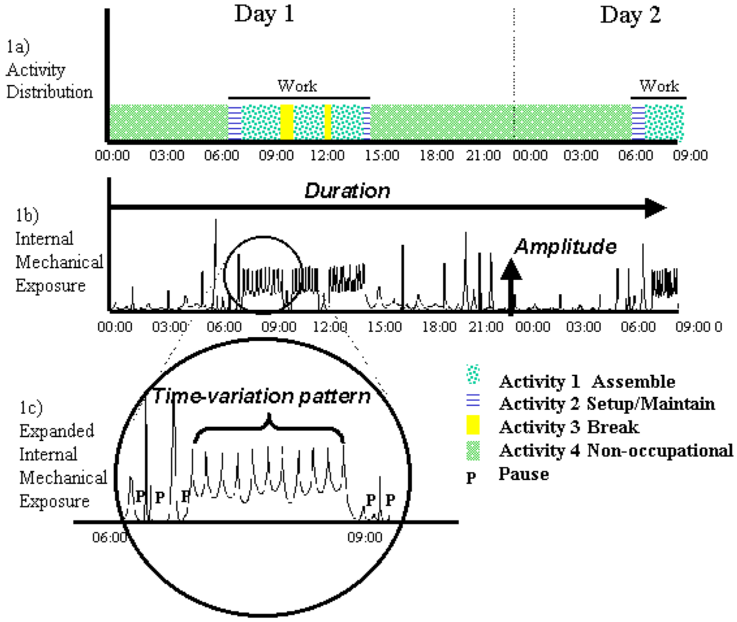

Figure 1. Schematic presentation of a time history of the agent "force" exerted on a person and its characterization by three dimensions of amplitude, time-variation pattern, and duration.

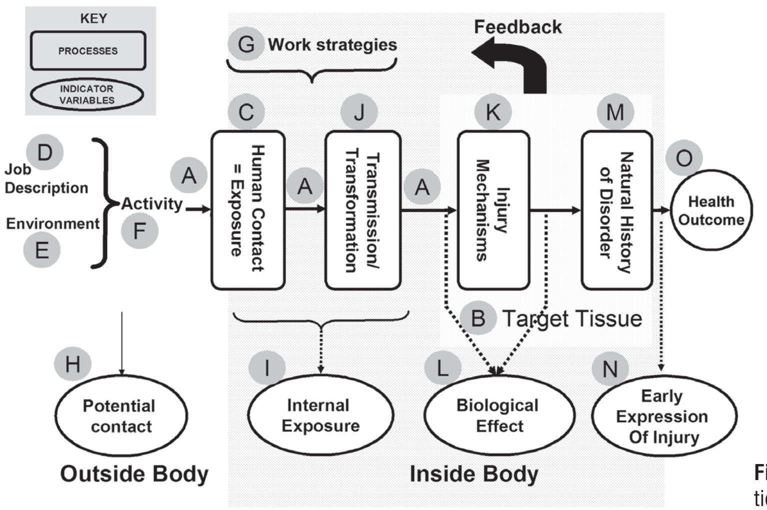

Figure 2. Proposed mechanical exposure model. Additional details available in the text.

We found that we could estimate exposure without the presence of a person only on the basis of the job description and the physical (force producing) characteristics of the environmental source. We call this estimate potential contact or interaction. The potential contact is the "amount" of the agent that is potentially available to act on the target tissues—perhaps as characterized by a box weight. For example, in a study of the exposure of scaffolding workers, van der Beek & Frings-Dresen (16) estimated mechanical exposure from administrative records and their knowledge of scaffolding parameters like mass.

We suggest that, where possible, it is important that the activity of the worker in the environment be observed if the contact with the source is to be understood fully; examining the job description, behavior, and environmental source is simply an indication of "potential contact" and may or may not predict mechanical exposure well.

Inside the body. We use the term internal exposure once contact has been made and force has been transferred to human tissues. We refrain from calling this state dose. Using the term internal exposure also reflects the fact that the nature of the agent does not change as it enters the body (ie, it is still a physical agent measured in the same units of force as outside the body). This is not to say that the force is unaffected as it enters the body. In fact, using the term internal exposure allows us to describe any damping or additive effects that occur as a result of interaction with body tissues. The point(s) of contact and the target tissue define the exposure path. The forces at contact could possibly be considered to be propagated through the body as strain in tissue, as stress in the tissues, or as forces. We have chosen to consider the agent as force since the transmissibility of force allows a simpler approach. [See later examples.] Tissue strain, however, plays an important role in the interaction of force with the target tissues.

Posture (one aspect of activity) may itself result in force on internal tissues from the action of gravity acting on segmental masses and resulting joint moments of force. Moving the arm, even with no applied external force, requires muscular forces to accelerate or decelerate the limb segments. The strategy of the person may change the nature of the contact or interaction with an environmental source. Strategies may also involve different levels of muscle co-contraction, creating loads in addition to those of gravity (even without a load). At the contact point and along the exposure path, as it passes through body tissues, force can be characterized by a time-varying amplitude or pattern.

One further concept we examine in our model is that of work strategy. The strategy of the worker may change the nature of the contact with an environmental source. Strategies may also involve different levels of muscle contraction possibly changing the amount of the agent reaching the target tissues. At the contact (exposure) and as it passes through body tissues (internal exposure), force can be characterised by a time varying amplitude or pattern.

Target tissues. Once we have determined the time history of forces acting on the target tissues, we can begin to consider injury mechanisms.

The effect of the forces on the target tissue can be characterized by several injury mechanisms, such as strain in articular cartilage and change in the expression of matrix metalloproteinase (MMP) (17) or parathyroid hormone related protein (PTHrP) (15), bone strain and modeling or remodeling rate (18), or trabecular buckling

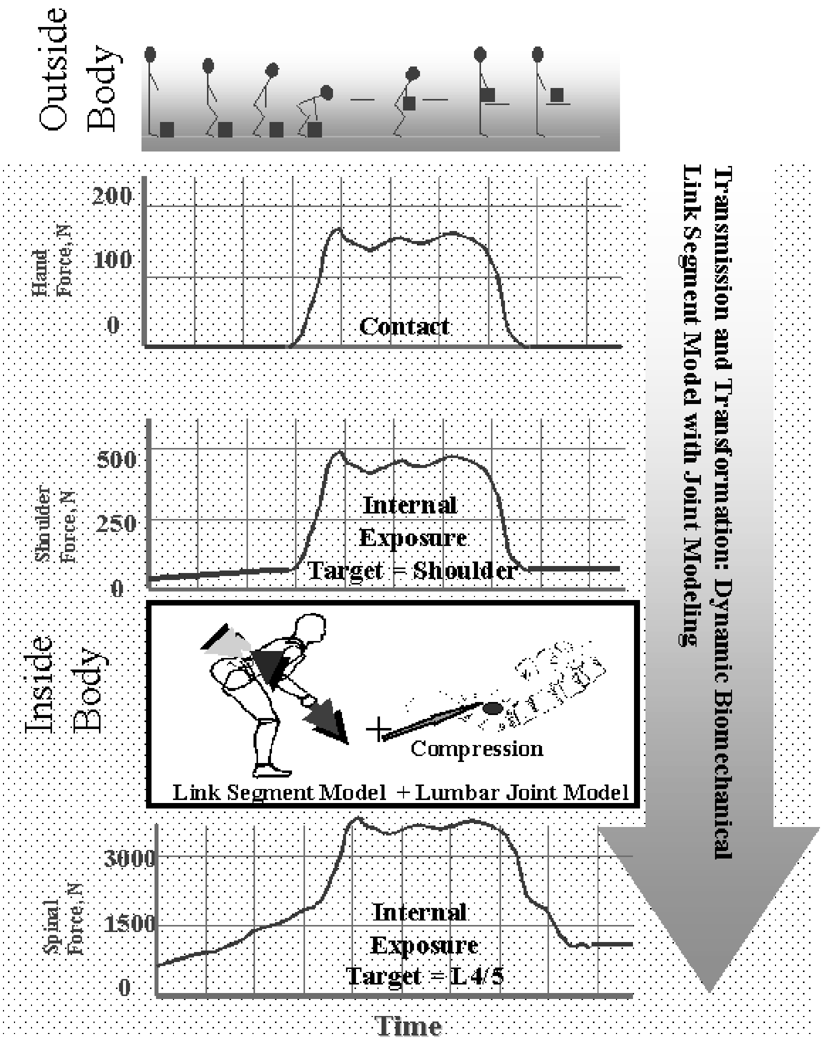

Figure 3. Schematic presentation showing the relationship between the exposure and internal exposure for a manual materials handling task. Dynamic link segment modeling, as well as joint modeling, were used to estimate the transmission and transformation of the forces from the contact point to different points in the skeletal linkage. The used transmission and transformation methods have been described by McGill & Norman (27, 28).

(19) (figure 3). In the case of bone and articular cartilage, the process of mechanotransduction, or how cells detect strain and transduce it to a cellular response is central. Not all musculoskeletal disorders can be understood through the use of this approach; reduced blood flow with resulting localized muscle hypoxia (20) or increased tissue shear stress in hand–arm vibration resulting in damage (21, 22) may need modified approaches.

Since, in many cases, it is not possible to monitor changes directly in the target tissues, we may require biomarkers to help us determine if tissue changes have occurred.

A biomarker can originate from within the target tissues or from other related tissues (such as blood). If a biomarker or effect is not known for a particular disorder, we may be able to identify the early expressions of injury. Since many musculoskeletal disorders are not easily diagnosed in early stages, the natural history of the disorder should be considered when possible. The concept of health outcome may extend beyond the target tissues. Secondary processes may also cause deleterious processes in other target tissues. However an exposure situation may not necessarily lead to injury. With the agent of force, it is possible that a training effect could result. This training effect may be protective against injury and depend a great deal on the amplitude, time variation pattern, and duration of the forces. Knowledge of the time and tissue response characteristics of musculoskeletal tissues is therefore important if better exposure measures are to be developed.

If the injury is progressive, it will eventually lead to an expression of injury (given that exposure continues or was sufficient to initiate tissue damage). The health outcome represents the report of pain or a diagnosis (or medical suspicion) of an injury, disorder, or response if available. We consider this broad definition of health outcome because the classification of musculoskeletal disorders among workers has not been consistent. For example, a recent review has shown that classification systems for musculoskeletal disorders in workers are not consistent in the disorders they classify or in the criteria used to define the disorders (23).

We have also incorporated feedback into the model. This feedback can arise from the target tissues or from other tissues and may have an impact on various processes and structures. Armstrong and his colleagues (6) referred to feedback as a cascade effect. Potential feedback loops can be initiated by factors such as pain, fatigue, or discomfort. This feedback may modify the forces exerted upon tissues several ways. A change in work strategy, whether conscious or not, can increase or decrease grip force on a handheld tool. The injury mechanisms can change the ability of tissues to share force. The natural history (or progression) of the disorder may also change the transmission characteristics or the injury mechanisms. Fatigue or pain can change the lifting strategy from one supported by muscles to one supported by passive tissues.

Examples of force as an agent

We now describe three examples of mechanical exposure in which force is considered the agent. For each example, we define the target tissue(s) and describe the concepts that comprise our model. These examples serve to illustrate how the concepts of our model are operationalized. We describe each of them according to the three regions of our model (outside the body, inside the body and target tissues). Note that, although we propose that force is the agent in all three examples, the target tissues differ, as do the characteristics of the force.

Hand–arm vibration

Consider a person using a vibrating hand grinder (figure 4). Vibration is an example of exposure to a physical agent and the musculoskeletal consequences. We suggest that, for vibration, force can be considered to be the agent. Its time variation pattern includes high frequencies (10–20 000 Hz) rather than the low frequencies (0–10 Hz) commonly found in the examples of manual materials handling and mouse use. In this example, we discuss two possible targets, the digital nerves and the acromio-clavicular joint, and highlight some issues of transmission and transformation.

Outside the body. We can describe the hand grinder specifications [eg, root-mean-square (RMS) acceleration of 20 m/s^2] and the job description (grind "*x*" number of parts per shift)] as part of the environment (figure 4). Vibration exposure is usually quantified by the acceleration of the tool (22). We could argue that, in fact, the agent is force and the amplitude and frequency of the force applied to the hand–arm system should be used as the exposure measure (although measurement of acceleration is a more convenient surrogate). Work strategies can play a substantial role in exposure to the agent of force. Strategies can include the use (or avoidance) of protective equipment or clothing. The presence of gloves in this example would likely change the forces acting on the hands. Work strategies can also dictate the exerted handgrip force that will affect the transmission of vibration (force) to the hand–arm.

Inside the Body. We consider two different target tissues in this example. One is the digital nerves (fingers

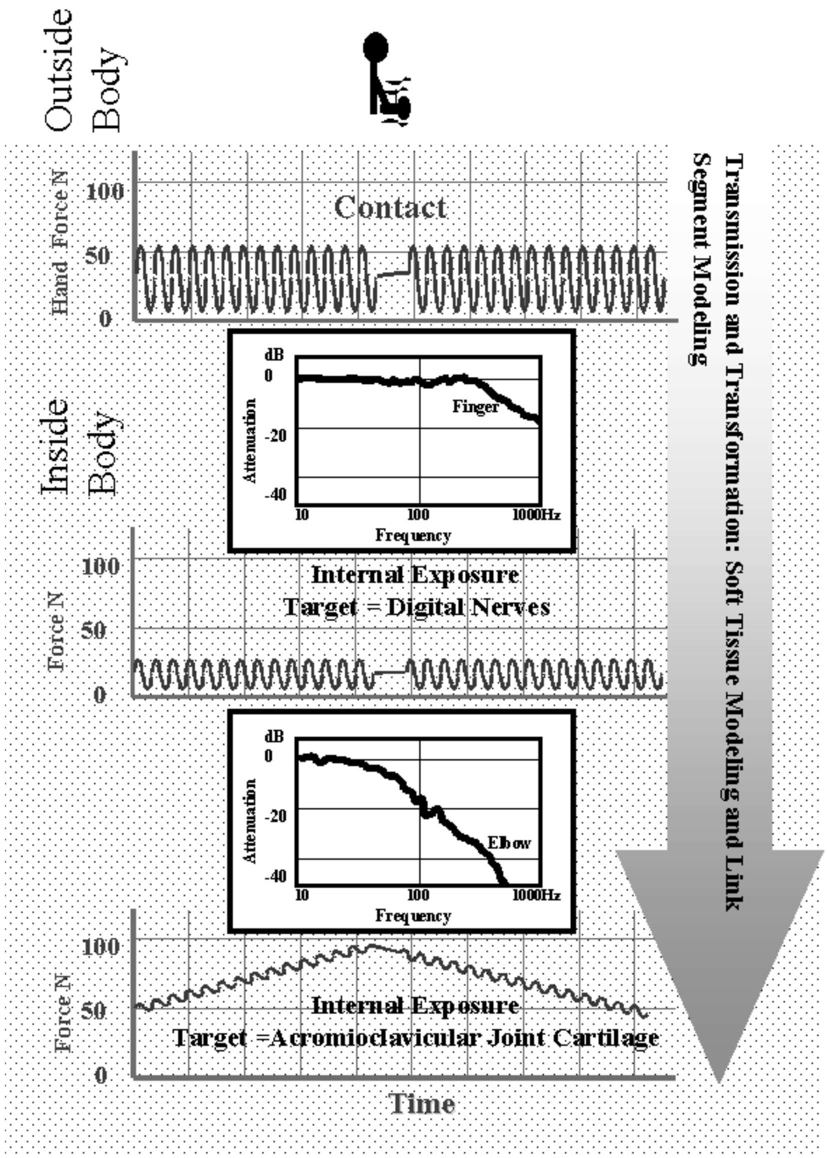

Figure 4. Schematic presentation showing the relationship between the exposure and internal exposure for a manual task with a vibrating tool. Dynamic link segment modeling, as well as transfer functions, were used to estimate the transmission and transformation of the forces from the contact point to different points in the skeletal linkage. The transfer functions were drawn on the basis of the findings of Kihlberg (25).

and hands) and the other is acromio-clavicular joint cartilage (24). This represents a multiroute example in which the agent potentially acts on different target tissues and travels to these tissues via different routes. The route to the digital nerves acts via skin and subcutaneous fat. The force transmission (transformation) characteristics of these tissues must be evaluated to determine the internal exposure of the nerves. This internal exposure is defined by the transfer function of the tissues. The route to the acromio-clavicular joint cartilage includes skin, subcutaneous fat plus bone, ligaments, and cartilage (including synovial fluid), as well as the potentially moderating effects of the muscles and tendon attachments along the pathway(s) to the acromio-clavicular joint cartilage. Figure 4 shows the transfer functions between the hand and different locations in the upper limb (25). Note that the tissues attenuate higher frequency force variation and the force may be of small amplitude by the time it reaches the acromio-clavicular joint cartilage (figure 4).

Target tissue. Energy absorption by the tissues is used as a measure of injury potential (22) although it does seem to be related to a heating effect (21). A marker for damage would be peripheral vasospasm (an effect). If no effect is observable, we must use a biomarker to determine whether the injury is present or ongoing. In order to understand the exposure better, we must also try to determine the recovery period for the target tissues; that is, our model must be able to account both for time or duration characteristics and for aspects of the amount of force (peak accumulations, etc). This procedure requires in-depth knowledge of dynamic tissue behavior and characteristics.

Low-back loading during manual materials handling

Now consider a worker who is required to unload boxes from a truck, and the target is the L4/L5 lumbar motion unit (figure 3).

Outside the body. The worker has a job description that, for example, involves unloading a truckload of boxes. The environment dictates the positions, shapes, and masses of the boxes. The environment further defines other constraints, such as deadlines or quotas, pay structure, workplace culture, etc (26). These factors interact with or influence the work strategies adopted by the worker. The work strategies involve high-level processing of information based on previous experience, current physical condition (including injury mechanism feedback), cultural conditioning (work, society, and family), and assessment of the physical characteristics of the job.

Another aspect of the environment that may influence the contact is the physical space which contains the boxes, in this example a truck. If this space is constrained and requires non-neutral postures, the force applied at the hands may be the same but, as we see in the next section, the internal exposure may differ. The space available may also change the strategies employed in lifting or moving the boxes.

The interaction of the person with the environment is described by gravitational forces and the contact forces with the boxes or truck sides and is of the form of a time varying force. These decisions of how to perform the task within constraints (or work strategies) may be protective or they may be deleterious with respect to the exposure (possibly increasing the force or minimizing the force that reaches the target tissues).

Inside the body. The transmission and transformation steps from the contact at the hands to the target tissue have been described in the literature (27, 28) The transmission through the linkage to the lumbar spine can be predicted using dynamic-link segment modeling (27). Even with no external forces on the hands, accelerating the limb segments and, of course, the presence of a gravitational field requires forces to be generated within the body tissues. Models of the lumbar spine can be used to distribute the loads between different tissues in the lumbar motion unit, such as bone, disk, muscle, tendon, or ligament (28). If high frequencies of loading (shock, rapid loading or whole-body vibration) are involved, then the system transfer function can be used to predict loads experienced in the lumbar spine (eg, for loading via the feet) (29). Forces will exist in many other tissues, such as those in the shoulder, due to the transmissibility of the forces (figure 3). The force at the target tissues (in this case the L4/L5 lumbar motion unit) is again characterized as a time varying force.

Other features of the person's activity influence the process of transmission and transformation, especially the postures adopted. A flexed trunk with no load on the hands creates compression forces at the lumbar spine that are similar to those created by holding a heavy load close to the body. The effects of posture are therefore conceptualized as part of the transmission and transformation process. Posture also becomes an "effect modifier" (ie, effects on target tissue differ at different levels of posture because posture affects tissue tolerance) (19). The person's work strategy can be characterized by the co-activation of antagonistic muscles of the trunk, and this co-activation increases the compressive load on the lumbar motion unit.

Target tissue. Tissues have many injury modes. A lumbar motion unit can suffer end-plate fractures and trabecular bucking (19) due to compressive loads with high amplitude and low-frequency time-variation patterns, spinal creep with low-frequency components ("static loads") and long duration, avulsion fractures with high force, high-frequency time-variation patterns (short rise times), disk herniation from load of long duration with flexed postures ("static postures") (19). The time dependency is notable in that most biological tissues are viscoelastic. Take the example of spinal creep, which can be a precursor to loose ligaments, which, in turn, lead to compromised spinal stability and therefore to injury. Spinal creep is the dynamic response of the lumbar motion unit subjected to a time history of compression forces. In exposure models for the inhalation or absorption of chemical agents, there can be an accumulation of the agent, and a burden (quantity) of the agent is meaningful. Here force itself is not stored; instead the creep is the cumulative result of the strain induced by the internal exposure. The maximum spinal shrinkage (as a result of the creep) can be a viable biomarker of the response to the mechanical exposure (30). Figure 5 shows how this description of mechanical exposure in manual materials handling fits into the proposed model.

Computer mouse use

In this example, we consider an office worker interacting with a visual display terminal by using a computer mouse. The trapezius muscle is the target tissue of interest in this example.

Outside and inside the body. The story here is substantially the same as in the manual materials handling example. However, because the amplitude of the loads exerted upon the hand is so low with mouse use, the neuromuscular system has more degrees of freedom available for its response. The load at the target tissue

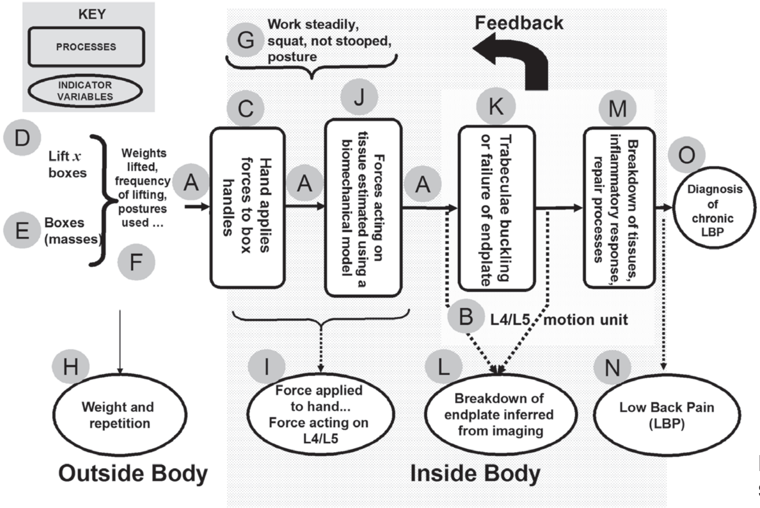

Figure 5. Proposed mechanical exposure model describing manual materials handling.

is more variable and therefore less predictable, and it depends on external conditions (31). The characteristics of internal exposure at the trapezius and supraspinatus muscles during work with video display terminals are thought to be "static" (ie, a low amplitude force that is maintained at an almost constant value for substantial portions of the day without returning to zero). We chose these shoulder muscles as an example of target tissues well aware that several other tissues may be origins of disorders with computer mouse use.

Target tissue. For the shoulder muscles two types of injury mechanisms have been suggested (32, 33). For the supraspinatus muscle, generation of muscle force leads to elevated intramuscular pressures. Elevated pressures lead to a reduction in blood flow (32). A reduced blood flow may lead to localized hypoxia and damage to muscle fibers. For the trapezius, the low force levels are created by a small number of active low-threshold motor units. These small motor units can fire uninterruptedly for substantial periods of time, and they have been dubbed Cinderella motor units (33). As a result, they can suffer local metabolic crises with muscle cell damage and lead to muscle pain (34). In this example, the ability to define the natural history and the exact mechanism of injury may not be possible. Nonetheless the model may help us to understand these exposure response concepts better. Figure 6 illustrates how this description fits with the proposed model.

Exposure indices

We consider an exposure index to be a descriptive statistic that represents the exposure measure in question.

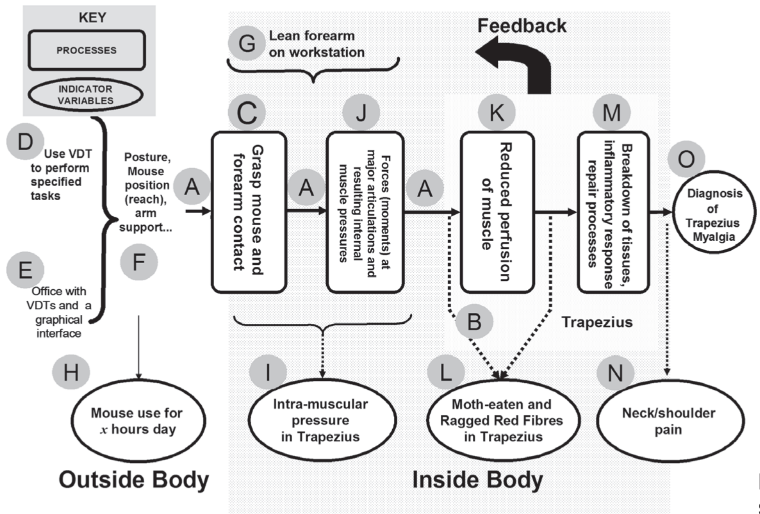

Figure 6. Proposed mechanical exposure model describing computer mouse use in an office environment.

An example for manual materials handling could be cumulative load (24) or the maximum weight lifted. We can create exposure indices for any of the three regions in the exposure model, outside the body, inside the body, or in the target tissue. Appropriate questions include "Is there a force threshold before an effect occurs?", "What is the nature of the recovery or restorative process?" and "What is its time constant?"(35). Neutra & Pizzo (36) explored some of the relationships that may exist from the viewpoint of a different physical agent, electromagnetic fields (EMF). For example, with a tissue response that has no threshold and has a very long time constant, an integral of the internal exposure may be a useful index (37). If the transformation and transmission is approximately constant across the work conditions of interest, then an integral of exposure, such as weight lifted per day or per lifetime (24), may be a good exposure index. The extra precision potentially obtainable if an exposure index is computed from a modeled tissue response may not be cost-effective or even possible.

If there are nonlinear or threshold effects or the time constant of the response is short compared with that of the exposure, then simple models based upon exposure may be misleading (37). If there is a J-shaped relationship between internal exposure and injury risk for which there is tissue atrophy at low levels of internal exposure, adaptation via growth at moderate levels, and disorder due to micro-damage and inflammatory responses [for bone see the work of Bloomfield (18)] at high levels, then using an exposure index based upon a tissue response model may provide a better link between work conditions and musculoskeletal disorders. Thus the common suggestion that exposure is *dose (internal exposure) × time* may not be appropriate for some mechanical exposures. The preceding suggestion argues that exposure assessment should be based upon the best available evidence as to tissue response and injury mechanisms.

An example of the creation of exposure indices at multiple levels can be seen in the work of Norman (38) and Krajcarski [unpublished data: Krajcarski S. Implementation and evaluation of challenge-recovery modelling as a time-history sensitive ergonomic exposure assessment tool for work-related musculoskeletal disorders of the low back (master's thesis). Canada (ON): Department of Kinesiology, University of Waterloo; 2000]. The challenge was to develop exposure indices for a case-control study of low-back pain. Postures and loads were determined for a shift based upon observation and measurement for periods of 2–8 hours for over 300 workers. Exposure indices were based upon the observed contact of workers with the environment (weights lifted or push force exerted). The exposure indices included the usual and average load lifted per day.

Internal exposures were determined according to a quasi-dynamic link segment model and a lumbar joint model to estimate lumbar compression in newtons. It should be recalled that the effect of posture is included in the estimation of these internal exposures. The internal exposure was a force time history with units in newtons for one shift and thus included all dimensions of mechanical exposure (4). Two exposure indices determined from these internal exposures included the peak daily load and the cumulative (integrated) load over the shift, in this example about 480 minutes. In the multivariate logistic model, the exposure indices, based upon the internal exposure, were prominent and tended to exclude variables associated with posture (39).

Krajcarski [unpublished data: Krajcarski S. Implementation and evaluation of challenge-recovery modelling as a time-history sensitive ergonomic exposure assessment tool for work-related musculoskeletal disorders of the low back (master's thesis). Canada (ON): Department of Kinesiology, University of Waterloo; 2000] went further and calculated a modeled biological response, based on a first order transfer function, as a representation of the spinal tissues' response to loading. The modeled response was a time history for the whole shift. Two exposure indices were calculated on the basis of the modeled response (ie, the value of the response at the end of the shift and the peak value during the shift). He found that the exposure indices based on the modeled biological response were the best discriminators between those who reported low-back pain and those who did not.

This paper has shown that exposure indices, based upon the agent force, can be created from potential or actual exposure, from internal exposure, and from modeled tissue responses. The two aforementioned studies suggest that exposure indices based upon modeled tissue responses may have a stronger relationship with musculoskeletal disorders than those based outside the person. This assumption does not consider the significantly greater resources required, the constraints involved, and the limitations of our understanding of tissue responses to loading. It perhaps points the way to exposure indices in the future when real-time monitoring of loading (40) can be achieved together with a better understanding of tissue injury.

Other measures of exposure used in the epidemiology of musculoskeletal disorders

We note that there are many exposure indices used in the epidemiology of musculoskeletal disorders that are apparently not based upon force. Among them postures and electromyograms are primary factors. Posture has been an important variable in both hazard assessment and in epidemiologic studies because it is a predictor of tissue loads due to gravitational or postural loading and can also affect tissue tolerances (41, 42). We have argued that the effect of posture is accounted for in the transmission component of the model, where it modifies the effects of any external loads. Posture could thus be seen as a predictor of internal exposure.

Electromyography is sometimes used as a measure of exposure (43). Electromyography (EMG) monitors the electrical activation of the muscle fibers in the neighborhood of the electrodes. Surface electrodes are generally employed in field studies. If processed to estimate force (joint moment), the EMG, it can be argued, is an internal exposure measure. If a mean power frequency shift is used, then it can be viewed as an acute tissue response. A measure such as static load (44) or RMS amplitude, expressed in microvolts or as a percentage of a maximal voluntary electrical activity (MVE), can be thought of as a biomarker for internal exposure. A measure such as an EMG "gap" (45) falls somewhere between the internal exposure (muscle force) and a biological response, as was found in the section on mouse use. The EMG has been used predominantly in office settings and on the trapezius muscle. The office setting is where measures of internal exposure derived from posture alone (postural load) appear not to capture muscle force well due to the difficulty of measuring the posture of the multi-joint–shoulder complex and the influence of other (nonmechanical) factors (31).

If multiple exposure measures are analyzed in a single study, the issue of their relative position in the exposure model "chain" becomes important. Basically, one should not mix exposure measures from different parts of the exposure model in the same statistical analysis of exposure–response relationships. Neumann (39) suggested that posture preceded lumbar spine forces in the causal chain and opted for the analysis of postural and force exposure data separately.

Summary

In this paper we present a conceptual model of mechanical exposure using terminology consistent with that developing in occupational epidemiology. It highlights the importance of (i) the work environment, (ii) the transmission and transformation of forces acting upon the musculoskeletal system, and (iii) knowledge of tissue response in the exposure modeling process and the creation of exposure indices. The response of tissue to forces of varying amplitudes and time-variation patterns are of prime importance in this regard and are largely unknown. Although we argue that an exposure index at the tissue level can be useful, considerations of resources may make exposure indices based on external exposure or internal exposure preferable choices.

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