External load and the reaction of the musculoskeletal system — A conceptual model of the interaction

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ARTICLE INFO
Article history:
Received 24 May 2012
Received in revised form 14 March 2013
Accepted 8 April 2013
Available online 23 July 2013

Keywords:
Musculoskeletal disorders
Musculoskeletal load
Psychosocial factors
Exposure
Dose-response

ABSTRACT
This paper presents a conceptual model of the interaction between the human body and external factors influencing the musculoskeletal system (biomechanical load, vibration and psychosocial factors). The interrelationship of parameters that define each external occupational or non-occupational factor and their combination creates exposure. Exposure influences the human body modelled as a mental system and a musculoskeletal system, and results in responses leading to improved or impaired structures of the musculoskeletal system. The reaction to external factors expressed as a response depends on personal traits. The results of this study are a basis for insights into how external physical and psychosocial risk factors influence the mechanisms responsible for whether body structures improve or are impaired. The model is intended to be filled in with mathematical equations that describe quantitatively phenomena related to processes caused by external load, with consideration of personal traits. This paper discusses ways leading to mathematical formulas, which would explain the phenomena included in the model quantitatively.

Relevance to industry: The relevance of this study to industry consists in providing, through the use of the proposed model, after a quantitative verification, safety levels that can result in improved work and workers protect against MSDs. By considering both occupational and non-occupational activities, the model can help to protect workers holistically.

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1. Introduction

Disorders of muscle tissues and their surrounding structures, i.e., musculoskeletal disorders (MSDs), indicate health problems of the locomotor apparatus. MSDs are impairments of body structures, such as muscles and tendons, joints, cartilage, ligaments, nerves, the skeleton and blood vessels. They mostly result from the cumulative effect of long-lasting load of various magnitude. A wide range of external factors in the work environment cause MSDs. In addition to work, aspects of the daily life can contribute, too. Therefore, MSDs depend on both occupational and non-occupational factors (Habib et al., 2011).

Numerous epidemiological studies, which sought to identify external factors positively or negatively associated with the development of MSDs in various body parts, proved that biomechanical load (Punnett et al., 2005), vibration (Bovenzi, 2008) and psychosocial factors (Smith et al., 2006; Huang and Feuerstein, 2004) were important.

Heavy physical work, e.g., lifting and carrying, pushing, pulling and manipulating heavy load, is a classic task leading to the development of MSDs (Hoogendoorn et al., 2002; van Niewenhuyse et al., 2006). Very specific tasks, like handling patients (Smith et al., 2006), were found to pose risk for the low back too. However, office work (Choobineh et al., 2011) or work at an assembly line, packing small objects, etc., i.e., work which mostly involves upper limbs in repetitive tasks with static load of the back also causes musculoskeletal disorders (Bosch et al., 2007). Systematic reviews confirmed repetitive and forceful movements of the upper limbs as risk factors for the development of MSDs (van den Windt et al., 2000).

Those studies linked physical effort associated with postures, exerted forces and time sequences to the development of MSDs. On the other hand, physical effort during training programs with heavy load resulted in outcomes beneficial for the human body. Rooks et al. (2002) showed that a program of strength training effectively improved muscle strength and cardiovascular endurance. Strength and endurance training as well as stretching and fitness training were effective in decreasing pain and disability in women.
with chronic, nonspecific neck pain (Ylinen et al., 2003). Similarly, coordination and endurance training for patients with chronic low back pain proved to be effective treatment (Johannsen et al., 1995). Vouri (1998) justified physical activity and summarized its effect on physiological responses. He emphasized positive effect of moderate daily physical activity. Thus, physical load induced by biomechanical measures related to posture and exerted forces can result not only in impaired body structures leading to MSDs but to improved health as well.

The impact of vibration is also dichotomous. Numerous studies on the negative impact of vibration on muscles have focused on the effect of whole body vibration (WBV). It is well-documented that exposure to WBV is a risk factor for low back pain (Burdorf and Sorock, 1997; Tiemessen et al., 2008; Lis et al., 2007). Similarly, Heaver et al. (2011) and Astrom et al. (2006) showed hand-arm vibration (HAV) to be a major risk factor for the development of MSDs in workers who use grinders, drills, saws, hammers and other vibration tools. Regular and frequent exposure to HAV leads to the HAV syndrome (HAPS) (Youakim, 2010; Bovenzi, 2008; Mahbub and Harada, 2011).

On the other hand, vibration can be a beneficial factor, e.g., for patients with spinal cord injury (Murillo et al., 2011). Exposure to vibration can improve the rehabilitative effect (Jackson et al., 2008; Ahlborg et al., 2006). Vibration can be effective in improving balance (Wunderer et al., 2008; Mani et al., 2010) and bone mineral density (Rehn and Nilsson, 2008). It is also used in sport applications (Cardinale and Bosco, 2003). Supporting exercise with vibration has been shown to be effective not only in improving muscle strength (Roelants et al., 2004; Rehn et al., 2007) and muscle power (Cochrane and Stannard, 2005) but also the ability to jump (Cochrane et al., 2004).

Workload was proved to depend on the type of task and to stem not only from physical factors but also from psychosocial ones. There is a growing awareness of the link between occupational psychosocial factors and MSDs (Bongers and Kremer, 2002; van der Windt et al., 2000). Studies seem to confirm the hypothesis that a poor psychosocial situation results in higher reports of symptoms in the wrist/hand, shoulders (Bongers and Kremer, 2002; Eatough et al., 2012; Wahlstedt et al., 2010) and low back (Eatough et al., 2012). However, psychosocial factors may or may not be associated with impairment of human body structures. According to Karasek’s model (Karasek et al., 1998), psychological demands of work combined with control are a combination of factors that are either harmful or beneficial, i.e., produce either negative or positive stress. A combination of those factors creates a level of demands necessary for effective performance to take place as opposed to a level at which a combination of factors produces excessive mental load and the effect of this exposure is harmful. Chiang et al. (2010) showed that job demands might not be stressful, particularly if a person has control over responsibilities and receives sufficient support. That proves that psychosocial external factors, too, can both harm and improve health.

Interactions between factors are also important. Vibration in conjunction with biomechanical load caused by awkward postures, excessive force and repetitive movements, was proved to be the cause of the development of disorders like carpal tunnel syndrome (Bovenzi et al., 2000). Awkward postures with additional whole-body vibration (WBV) increase the risk of low back pain even four times compared with the sitting posture only (Lis et al., 2007). Combined exposure to physical and psychosocial workload also increases risk of musculoskeletal injuries (Koeboe et al., 2006; Devereux et al., 2002). External factors interact not only among themselves but also with the personal traits of an individual (Huang et al., 2002; Kumar and Kumar, 2008), which also contribute to the development of MSDs (Burdorf and Sorock, 1997). Thus, predicting the influence of external factors at the level of an individual is difficult. Negative outcomes of psychosocial factors may be decreased by resources related to physical, psychological, social or organizational aspects (Schaufeli and Bakker, 2004).

Understanding and establishing mechanisms leading to impairment or improvement of health condition is elusive. However, it is not only the interaction between factors that makes precise conceptualizing of the causation between factors and outcomes. Proper criteria would discriminate positive and negative influence. Thus, (a) a conceptual model of exposure and outcomes, (b) a quantitative relationship between factors and outcomes and (c) criteria are expected. Thus, there is a need for theories on the mechanisms of impairment or improvement of the condition of body structures as a reaction to external factors and personal traits. Such a concept of a relationship between external factors and personal traits could be a basis for developing a precise quantitative relationship between exposure and outcomes resulting in impairment or improvement of body structures condition.

Huang et al. (2002) reviewed literature on concepts and models of psychosocial and individual factors and their interaction, and their influence on the development of work-related MSDs. Existing concepts target occupational factors while accepting, to a limited extent, non-occupational load (Huang et al., 2002). They present an interaction of external factors leading to the development of MSDs; however, they neither consider nor discuss the beneficial effects of the same factors, which depend on variations in the exposure or time of exposure.

This paper aims to present a concept of an interaction between exposure and outcomes, which would be a basis for quantitative modeling of the relationship between external and internal factors and outcomes of harmful or beneficial effects to the human musculoskeletal system.

The concept presented here builds on an earlier approach to the interrelationship between external factors and personal traits, mostly Armstrong’s (1993). It leads in the direction of a quantitative, based on mathematical formulas, expression of the relationship between external factors, internal processes and outcomes. However, it does not present such. It does not discriminate if an external factor is occupational or non-occupational. The concept behind this model considers the interaction between the human body and the external factors. Even though this model combines external and internal factors, it focuses on the former, which impose load; however, in the context of internal phenomena.

2. The model

2.1. External factors — exposure

Biomechanical load, vibration and psychosocial factors influence development of MSDs. Therefore, the concept behind the model considers both impairment and improvement of the condition of body structures. The model embraces those positive and negative changes as associated with biomechanical load (B), vibration (V) and psychosocial factors (S). The interrelationship of parameters that define individual external factors and their combination creates exposure (E).

Biomechanical load (B) is a result of various physical activities characterized with biomechanical parameters, which define posture, force and time. The most reliable way to describe body posture is with angles in joints in three planes: sagittal, frontal and transverse. Force is described with the type of force activity (pushing, pulling, squeezing, etc.) and its values. Time describes how long a given posture and exerted force are sustained; it can also characterize the repetitiveness of tasks with respect to more and less forceful movements.
Time is important in characterizing work, e.g., it defines static and repetitive work. It is also important in considering exposure to a factor or a combination of factors. Time of exposure, understood as longitudinal exposure to a given factor repeated over weeks, months or years, like magnitude, plays an meaningful role (Lis et al., 2007). Therefore, the concept presented in this paper defines time as time characterizing the work process (t) or time of exposure (τ).

Mathematical equations that are a function of parameters describing posture, force and time expressed quantitatively can produce a biomechanical load measure. This measure may refer to a body area or the whole body. The body is commonly divided into parts in which, according to epidemiological studies, pain can occur: the neck, low back, and upper and lower limbs.

The biomechanical load can be defined according to procedures in Fig. 1 (with respect to the upper limbs, trunk and neck). The load of the neck is caused by angle in three planes; no forces are considered. When load of the upper limb as a whole is considered, or consecutive parts of upper limbs, force exerted by upper limbs must be determined. When the trunk is considered, in addition to the angles describing its posture, upper limb posture is significant, too, as is force attributed to the upper limbs. When lower limbs are considered, sitting and standing postures are analyzed (Fig. 2).

The vibration signal is characterized quantitatively by amplitude (A), acceleration (a) and frequency (f). They express quantitatively the impact that the vibration (V) has on human. The human body can be exposed to WBV or HAV in consecutive body parts. WBV refers mostly to a person sitting on a seat that is a source of vibration, i.e., a greater part of the body is exposed to vibration. HAV can cause vibration of the entire body and may negatively impact individual tissues and blood vessels.

Body parts, which are in contact with a tool or a seat, are exposed to the same magnitude of vibration as at the source. As a result of damping, other parts of the body can be exposed differently. Evidence suggests that muscles have damping properties with the damping factor given by the attenuation coefficient (Wakeling et al., 2002). The amount of vibration energy transmitted will depend on musculoskeletal stiffness and damping. This means that the dose of vibration changes as it reaches consecutive body parts. Therefore, each body region can be assigned a different dose of vibration. It can be then accepted that vibration exposure, which is a function of parameters characterizing the source of vibration, body structure properties and distance from vibration sources, can change in a continuous or discrete mode according to a mathematical formula.

Unlike biomechanical load and vibration, psychosocial factors (S) are described subjectively rather than objectively with quantitative measures. Psychosocial external factors include monotonous work, time pressure, concentration, responsibilities, workload, opportunities to take a break, clarity, control, autonomy, and support from colleagues, from a supervisor or family members. Among the various theoretical models that help to understand and to quantify job stress in relation to the work environment, Karasek’s demand—control model, later extended to include support, is the most extensively tested and validated one (Noblet et al., 2001; Pelfrene et al., 2001).

Psychosocial factors can be assessed quantitatively on a job content scale. The 4-point qualitative scale rates demand aspects of a job, from 1 (never) to 4 (always) (De Jonge and Dollard, 2000). Social support can be measured on Van Veldhoven and Sluiter (2009) 10-item scale. It should be stressed that even though assessed quantitatively, it is based on subjective assessment and the results are discrete.

Some types of work organization or job design tend to generate particular sets of physical and psychosocial factors (MacDonald et al., 2001). Workers doing such work, in addition to experiencing a physical load, tend to have relatively low levels of control; they may also experience time pressure, both of which are psychosocial factors. Therefore, exposure which influence mental system is a function of the parameters characterizing a combination of the three external factors, i.e., biomechanical load (B), vibration (V) and psychosocial factors (S). Physical factors affect the musculoskeletal system (Fig. 3). Therefore, exposure with musculoskeletal system can be well expressed with a mathematical equation as a function of the parameters that determine biomechanical load (B) and vibration (V).

### 2.2. Relationship between external factors and internal structure

Human body is modeled as a mental system and a musculoskeletal system, and results in responses leading to an improvement or impairment of the condition of the structures of the musculoskeletal system. Combining external factors that determine load with internal capacity, both of which are expressed quantitatively, and expressing that as a (mathematical) function enables obtaining responses as a function of those external factors.

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**Fig. 1.** Biomechanical load in individual body parts and biomechanical parameters defining quantitatively musculoskeletal load in the neck, trunk and upper limbs. Notes: t – time characterizing the work process sequences.

**Fig. 2.** Biomechanical load in individual body parts and biomechanical parameters defining quantitatively musculoskeletal load in lower limbs during standing (a) and sitting (b). Notes: t – time characterizing the work process sequences.
The concept of this model is based on the presumption that physical factors influence the musculoskeletal system indirectly. Psychosocial and physical factors affect the mental system; their influence results in a response that is at the same time a dose for the musculoskeletal system. Direct exposure of the musculoskeletal system comes from biomechanical load (B) and vibration (V) and a combination thereof. Thus, musculoskeletal structures are influenced by doses of direct exposure to physical factors and indirect doses that are responses of the mental system.

Evidence justifies identifying psychological influence primarily on the upper limbs (shoulder, arm, elbow, forearm and wrist) (Bongers and Kremer, 2002; Eatough et al., 2012); however, on the back, too (Eatough et al., 2012). This means that for body areas for which the relationship with psychosocial factors is not well documented, only exposure to external physical factors is considered.

The present model, dose (D) is a function of exposure (E) and it is related to each structure of the musculoskeletal system separately. Doses, dependent on external exposure, together with capacity results in responses (R). This means that response (R) is a function of both dose and capacity, which can be reduced or enhanced by previous doses and responses. The effect of the response relies on the margin between exposure and the resources reflecting a person’s capabilities.

This model divides the internal structure of the human body into a mental and a musculoskeletal system (Fig. 4). Properties of those systems depend on personal traits, which are genetically and lifestyle conditioned. Social class, education, gender and smoking and drinking habits modified by age are examples of lifestyle factors. Anthropometrical dimensions, gender and physical capacity create personal factors, which are related to the physical construction of the human body, i.e., the musculoskeletal system. Psychological system include personal traits of the individual. Personality type, psychosocial functioning, coping style and attitude towards health determine it.

In the proposed concept the human body reacts all the time. The body can adapt (change its capacity) in ways that increase or decrease its tolerance to consecutive doses. Capacity at a given moment (t) is a function of capacity and response at that moment (t - 1). Therefore, capacity (C) and capacity (t - 1) can be different. Time (τ) is treated as a discrete sample whose length can be adjusted. It can be defined as hourly, daily, monthly or yearly.

The physical and psychosocial demands of an activity and the amount of time a person is exposed to those demands plays a role in determining whether their effect will be beneficial or harmful. This leads to a conclusion that the mathematical relationship of response as a function of τ would produce an equation for predicting MSDs or beneficial effects.

The model is a concept that must be filled with specific quantitative solutions. Thus, to make the model applicable, mathematical formulas are necessary, they should express exposure as a function of parameters quantitatively describing external factors, and mathematical equations that are a function of parameters describing both external factors and internal structure parameters determining resistance or inclination to certain responses.

3. Discussion

This paper presents a concept of the interaction between exposure and internal structures resulting in responses. The model benefited from earlier concepts, especially Armstrong’s et al. (1993). Like Armstrong’s model, the concept is based on capacity, dose and response. The present model underlines the importance of the quantitative expression of the relationship between exposure, dose and response in the form of a mathematical function, which provides a basis to fill the model with data. This leads in
the direction of expressing a quantitative relationship between external factors, internal processes and outcomes. However, the model did not aim at expressing those relationships. In a further step, when a quantitative relationship between factors and outcomes and criteria is established it will provide tools for a quantitative assessment of the health outcomes and risk for the development of MSDs.

Some previous models of work-related musculoskeletal disorders include combined effect of psychosocial and physical factors (Bongers and Kremer, 2002; Melin and Lundberg, 1997; Carayon et al., 1999). Also in a conceptual model presented in (NRC, 2001) the possible pathways and processes inside human are considered. The model described in this article also takes into account the biomechanical load-tolerance relationship and the factors that may mediate it such as individual factors and adaptation. The model presented here can be complementary to previous models with respect to the problems which the other ones described to a lesser degree.

The model presented here differs from other ones with respect to the framework but also it undertakes the challenge of providing a more comprehensive framework. Since the earlier models presented more detailed diversity in biomechanical and psychosocial factors (Huang et al., 2002); this model only presented a general relationship and focused on the possible relationships and ways, which would allow a quantitative presentation. Physical and psychosocial factors are considered equally important, and the relationship is proposed to be based on scientific evidence, which takes the form of equations. It also considers the interaction among factors.

Compared to previous models, the present one is innovative in a few other aspects, too. For example, existing models either focus on occupational or distinguish occupational and non-occupational factors (Huang et al., 2002). The present model does not differentiate factors in this respect; it defines factors without labeling them as of occupational or non-occupational (including leisure time) origin. It also accepts that those factors can have both positive and negative connotations. Both impairment and improvement of the condition of body structures is of multi-factorial origin. Beneficial effects of the same factors depend on variations in the exposure or time of exposure. In areas like reference to mental and musculoskeletal systems separately or dispersion of dose into muscles, ligament and bones, this model complements the other ones.

The concept in the present model, focuses more on external exposure as a basis for quantitative solutions. There are still difficulties in precisely conceptualizing and measuring mechanisms with which external factors influence health outcomes. The biological processes that lead from the dose to the response and, as a result, to improvement or impairment, are not very well known. Therefore, at the moment a quantitative description of all the relationships is not possible. Data are necessary to produce a quantitative expression of exposure and a quantitative expression of the responses of the musculoskeletal system. That further suggests a need for investigations examining and validating proposed pathways; it also shows the necessity to follow two directions. Firstly, it is necessary to assess the relationship between exposure and response, with exposure presented as a mathematical function. The assessment would thus be based on parameters describing quantitatively external factors.

Secondly, it is necessary to gain insight into internal processes; this would make it possible to express quantitatively the relationship between the dose and the response.

It seems less challenging to produce a quantitative definition of exposure than of internal factors, although the former is still crucial. Exposure can be defined quantitatively if external factors are expressed as a mathematical equation as a function of its parameters referring to, e.g., body posture, exerted forces, vibration or to psychosocial characteristics.

In some respects, the concept of a quantitative determination of exposure is not new. There are numerous methods and procedures for assessing external load quantitatively. Biomechanical load is expressed quantitatively with measures that result from procedures that present external load as depending on posture and force in combination with the time (Moore and Garg, 1995; Roman-Liu, 2007). Those measures allow objective, quantitative assessment of external load without considering personal traits. However, the complexity of those procedures varies, so does their accuracy. Their precision is limited and they consider exposure discretely. Therefore, they can be used to establish general quantitative exposure only and should be used with caution. Studies developing more precise procedures are still in progress; once complete they might provide.

Vibration is strictly expressed with measures well described quantitatively with amplitude, acceleration and frequency, parameters that characterize vibration-emitting machines. Exposure thus characterized is present in relation to body parts that touch a machine. Body structures gradually attenuate vibration. Exposure to vibration changes depending on the body part and the distance from the source of vibration, so functions are necessary. Vibration could then be expressed as a function of parameters defining body structures and distance from the source of vibration. Established mathematical equations of exposure to vibration would depend on vibration characteristics and the distance between a body region and the source (Xu et al., 2011).

The above concludes an objective classification with quantitative mathematical equations and measures of biomechanical load and vibration exposure. Exposure to psychosocial factors is more difficult to assess objectively with quantities. Therefore, psychosocial factors are much more difficult to express with a mathematical equation. To define exposure as an equation, it is first necessary to establish an unambiguous definition and to quantify psychosocial factors and the stress exposure to them causes. De Jonge and Dollard (2000) and Van Veldhoven and Sluiter (2009) have written on systems of quantitative describing psychosocial work-related factors. However, even if psychosocial factors are assessed quantitatively, this assessment is still subjective. Measures and mathematical models are then necessary to make that subjective assessment quantitative and reliable.

It is much more difficult to express quantitatively internal factors than external ones. Internal factors that define capacity would express its value as dependent on parameters describing personal traits. However, knowledge how internal factors influence capacity and responses is still insufficient. To gain insight into internal processes, appropriate assessment procedures are necessary. Assessment with internal load procedures considers both personal traits (capacity) and external factors. Electromyography (EMG) is a method like that; it is increasingly meaningful in numerous applications. An EMG signal reflects phenomena related to muscle contraction on the junction of neurons and muscle fibers. EMG signal measures calculated in the time and frequency domains can be used to describe specific aspects of physiological phenomena. EMG can detect a number of factors, such as the proportion of fast and slow fibers in the underlying muscle (Larsson et al., 2006) and the thickness of the subcutaneous layer (Bartuzi et al., 2010). However, the level of muscle contraction, related to force exerted by the muscle, is a most influential factor that determines both time and frequency measures (Roman-Liu and Konarska, 2009; Bartuzi et al., 2007). EMG can also be used in diagnosing deterioration of muscles and nerves (Dardiotis et al., 2011).

It is possible to establish a quantitative relationship between external and internal processes with broad studies of daily physical
and/or psychosocial exposure accompanied by a medical examination of the outcomes. Epidemiological studies look for a relationship between exposure to certain factors and its effect, i.e., disorders and diseases (Hoogendoorn et al., 2002). Such studies find a relationship between the outcome and an external factor or an interaction of factors, and help to determine whether exposure is associated with manifestations of a disease. However, even though epidemiological studies are based on large populations, most rely on subjective assessment only. Personality traits can affect answers and pain assessment to such an extent that the result might not be supported by processes in musculoskeletal structures. An exposure–response relationship thus identified is biased. Therefore, the reliability of such results is limited, compared to medical diagnoses. A questionnaire shows about 50% higher prevalence of pain in various areas of the body than a physical examination (Zetterberg et al., 1997). Therefore, although many studies showed the influence of specific risk factors, it can be difficult to interpret the relative strength of statistical associations between the outcome and each external factor. Thus, it is necessary to seek a reliable quantitative relationship between external factors and internal outcomes (response).

An experimental study on internal structures is necessary. Experiments isolate the effects of individual exposure on specific outcomes and provide important information about the mechanisms of the reaction to dose, responses and recovery processes. Some studies investigated intrinsic phenomena as related to external load. Yang et al. (2011) suggests that it may be possible to use cytokines biomarkers to monitor the physiological responses of the human body to biomechanical loading. Psychophysiological mechanisms, e.g., possible effects of stress hormones on fluid retention and changes in regional blood flow would also provide data for a quantitative description of internal processes.

Computer modeling of human body functions may help in finding solutions. It would provide a basis for a mathematical quantitative expression of relation between the dose and the response. Using advanced biomechanical models may help in more effective understanding and identifying the possible sources of responses. A model for calculating internal forces related to WBV (Bazrgaria et al., 2008) and biomechanical models consisting different substrutures of the hand–arm system and the trunk subject to vibration (Adewusi et al., 2012) are examples.

It can be then stated that in order to fulfill the model with quantitative measures a proper epidemiological, experimental and mathematical modeling study is necessary. That study should conform to all relevant ethical principles and should uphold scientific standards. It should guarantee the participants’ comfort and safety and comply with all national legal and ethical requirements.

4. Concluding remarks

The model presented here is related to occupational and non-occupational factors which, together with personal traits, result in positive or negative outcomes for the musculoskeletal system. This approach addresses both physical and psychosocial factors. At this stage, the model is just a concept of a relationship between external factors and outcomes. The model is intended to be filled in with mathematical equations for the association between exposure and symptoms of improvement and impairment. In this respect, a proper epidemiological, experimental and mathematical modeling study is necessary to fill the model with values that would make it work. A quantitative verification will provide safety levels that will lead to improved work and workers protected against MSDs. Considering both occupational and non-occupational activities helps to protect the worker holistically.

Acknowledgments

This paper was prepared on the basis of the results of a research task carried out within the scope of the second stage of the National Programme “Improvement of safety and working conditions” partly supported in 2011–2013—within the scope of state services—by the Ministry of Labour and Social Policy. The Central Institute for Labour Protection — National Research Institute is the Programme’s co-ordinator. The author would like to thank Jadwiga Koznińska-Korczak for her technical help in the preparation of this paper.

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