CHAPTER 14

Work-related Musculoskeletal Disorders

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Abstract: In most industrialized countries, work-related musculoskeletal disorders (WMSDs) are a major occupational health problem resulting in productivity loss, employee absenteeism, and high workers' compensation and healthcare costs. Understanding the etiology and control of WMSDs and associated risk factors is imperative for reducing the burden of this problem. This chapter is organized by five topics on WMSDs: (1) the problem and surveillance of WMSDs; (2) the etiology of WMSDs and their risk factors; (3) risk assessment methods for job-related physical risk factors; (4) risk intervention effectiveness; and (5) ergonomic guidelines and standards for the prevention of WMSDs. The authors focus on the breadth of the scientific knowledge and literature pertaining to WMSDs for occupational safety and health professionals interested in learning about the field of ergonomics. This chapter also provides anticipated future challenges in the areas of surveillance, risk interactions, risk assessments, and intervention evaluations. The research agenda for WMSDs published by the National Occupational Research Agenda (NORA) Musculoskeletal Health Cross-Sector (MUS) Council in 2018 is recommended as supplementary reading for the future direction of WMSD research.

Keywords: Work-related musculoskeletal disorders, Ergonomics, Occupational safety and health, Surveillance, Biomechanics, Vibration, Pathomechanics, Psychosocial factors, Job risk assessment.

BACKGROUND

Work-related musculoskeletal disorders (WMSDs) constitute a heterogeneous group of disorders [1, 2] that involve the tendons, nerves, joints, muscles, and circulatory system. These disorders have been given many names over the years,

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including musculoskeletal disorders, musculoskeletal injuries, overuse injuries, repetitive strain injuries, repetitive motion injuries, cumulative trauma disorders, overuse syndrome, soft tissue disorders, and occupational overuse syndrome. All of these terms broadly describe the nature of these disorders.

Systematic reviews of the etiology and risk factors of WMSDs have suggested the importance of the workplace factors contributing to musculoskeletal disorders (MSDs) [1, 3, 4]. MSDs are characterized as work-related diseases, as opposed to occupational diseases. As described by the World Health Organization (WHO), "work-related" diseases are multifactorial, indicating the contribution of numerous risk factors toward the causation of these diseases [5]. Unlike work-related diseases, occupational diseases possess a direct cause–effect relationship between hazards and disease. The Occupational Safety and Health Administration (OSHA) defines an event or exposure in the work environment as work-related if it "either caused or contributed to the resulting condition or significantly aggravated a pre-existing injury or illness. Work-relatedness is presumed for injuries and illnesses resulting from events or exposures occurring in the work environment…"

Burden of WMSDs

In the United States, WMSDs are a frequent cause of lost workdays due to injury [6]. These disorders are the most prevalent occupational disorder, not only in the United States but globally. The World Health Organization (WHO) [7] identifies musculoskeletal conditions as the leading contributors to disability worldwide, affecting people across the life-course. Although the past decade has seen a decline in the year-to-year number of cases of WMSDs [8], the proportion of occupational injuries and illnesses remains consistent. An estimated one-third of occupational injuries and illnesses are attributable to WMSDs [9, 10]. Data from the U.S. Bureau of Labor Statistics (BLS) on non-fatal injuries and illnesses in the private industry reveal that between 2011 and 2019, the proportion of WMSDs involving days away from work (DAFW) in all industries was between 30% and 34.5% [6].

WMSDs have been associated with high costs to employers due to absenteeism, lost productivity, and increased health care, disability, and workers' compensation costs [11 - 13]. Recent data showed that workplace overexertion injuries (that is, WMSDs) cost an estimated $15.1 billion a year, accounting for about 25% of total workers' compensation costs in the United States [14]. Low back disorders (LBDs) are the largest contributors to the total workers' compensation cost. The total health care expenditures incurred by individuals with LBDs alone in the United States have reached $90.7 billion a year [15].

In addition to the high costs, WMSDs also are related to reductions in quality of life and functional status [16, 17].

WMSD Case Definitions

Although various surveillance systems all enable the quantification of WMSDs, their WMSD case definitions differ. Therefore, it is important to identify and understand the WMSD case definition of each system, including the inclusion and exclusion criteria for the worker population. This chapter defines WMSDs on the basis of both the clinical nature of the disorders themselves combined with the events or exposures that caused the injuries. Nature of injury for WMSDs includes both acute injuries caused by traumatic incidents or chronic conditions classified as illnesses. Broadly speaking, most WMSD surveillance definitions include injuries or illnesses caused by overexertion. For example, these events or exposures include strenuous or repetitive work, bodily reactions from prolonged exposure to awkward postures, and exposure to vibration. Excluded from our definition are musculoskeletal symptoms or diagnoses (such as sprains or strains) caused by slips, trips, or falls; struck-by, caught-in, or crushed-by incidents; transportation incidents; violence; and fires or explosions. Although medical treatment of injured workers for low back pain, for example, may be identical, irrespective of cause, understanding what event or exposure caused the WMSD is important for primary prevention strategies, return-to-work decisions, and work restrictions. WMSD definitions in different surveillance systems limit eligibility to the diagnosis of either soft-tissue injuries or non-traumatic, chronic diagnoses such as rotator cuff syndrome or carpal tunnel syndrome while excluding injuries likely caused by acute trauma (such as sprains). In some cases, WMSD case definitions are limited to specific body parts or body regions.

For example, within the U.S. Department of Labor, the WMSD case definition adopted by OSHA differs from the case definition used by the U.S. BLS Survey of Occupational Injuries and Illnesses. The OSHA definition reads, "Musculoskeletal disorders (MSDs) affect the muscles, nerves, blood vessels, ligaments, and tendons. Workers in many different industries and occupations can be exposed to risk factors at work, such as lifting heavy items, bending, reaching overhead, pushing and pulling heavy loads, working in awkward body postures and performing the same or similar tasks repetitively."

However, since 2011, the BLS definition has been, "Musculoskeletal disorders (MSDs) include cases where the nature of the injury or illness is pinched nerve; a herniated disc; meniscus tear; sprains, strains, tears; hernia (traumatic and nontraumatic); pain, swelling, and numbness; carpal or tarsal tunnel syndrome; Raynaud's syndrome or phenomenon; musculoskeletal system and connective tissue diseases and disorders, when the event or exposure leading to the injury or illness is overexertion and bodily reaction, unspecified; overexertion involving outside sources; repetitive motion involving microtasks; other and multiple exertions or bodily reactions; and rubbed, abraded, or jarred by vibration." [6]

Sources of WMSD Surveillance Data

The first step of WMSD prevention is typically occupational health surveillance. As adapted from the U.S. Centers for Disease Control and Prevention's (CDC) definition of public health surveillance, occupational health surveillance is the ongoing, systematic collection, analysis, and interpretation of health-related data essential to the planning, implementation, and evaluation of occupational health practice, as well as the timely dissemination of these data to those responsible for prevention and control. Surveillance data can be used for many purposes, including hypothesis generation, identifying emerging risks, prioritizing scarce prevention resources, or evaluating a program or intervention effectiveness. Alternatively, for prioritizing prevention activities within one organization, practitioners may decide to collect data from existing administrative sources (*e.g.* OSHA logs, workers' compensation records, job hazard analyses) or collect new data to better understand patterns in the distribution of relevant health data and/or exposure data across time within a group of workers, job tasks, jobs, or work processes. Quantifiable results are commonly evaluated by comparing values for counts or rates (*e.g.* per 100 full-time equivalent employees). WMSD surveillance data are available from various sources, including state, national, and non-governmental organizations.

Self-administered Surveys and Questionnaires

One of the first self-administered surveys and questionnaires used for active surveillance of WMSDs was developed by Corlett and Bishop [18]. This survey evaluated musculoskeletal discomfort by asking workers to indicate areas of pain, from worst to least, using a body diagram (body mapping). The most commonly used WMSD survey is the Standardized Nordic Questionnaire for musculoskeletal symptoms, NMQ [19]. In addition to using a body map, divided into nine anatomical regions to indicate areas of "trouble," this questionnaire also seeks additional information on symptoms of the low back, neck and shoulder. The NIOSH Symptom Survey (NSS) uses the same body-part diagram as the NMQ but evaluates severity through quantification of frequency, duration, and intensity of symptoms [20]. Researchers have assessed the reliability and validity of both the NSS and the NMQ [20 - 23].

BLS Annual Survey of Occupational Injuries and Illnesses

As part of the BLS' Injuries, Illnesses, and Fatalities (IIF) program, the annual Survey of Occupational Injuries and Illnesses (BLS SOII) tracks occupational injuries and illnesses reported by employers in private or public industry. BLS SOII is a national surveillance system for all occupational injuries and illnesses, based on an annual survey of employers. Employers submit information to the BLS on non-fatal occupational injuries and illnesses, which codes for the nature of the injury, body part, source of injury, and event or exposure. The BLS uses a hierarchical set of codes it developed, called the Occupational Injury and Illness Coding System (OIICS).

The BLS case definition for WMSDs is based on special combinations of the nature of injury and event or exposure codes. The definition includes both acute/traumatic musculoskeletal injuries and non-acute/chronic musculoskeletal illnesses. WMSD surveillance data from the BLS worker injuries and illnesses databases are available from the BLS website in the form of news releases, summary tables, customized data tables, or large, downloadable files of aggregate data. Stratified BLS data are available, sorted by employer type (private or public), industry codes and sectors using the North American Industry Classification System (NAICS) codes, and case characteristics.

Workers' Compensation Claims Data

Workers' compensation claims data is an administrative data source that provides information on occupational injuries and illnesses, including WMSDs. These data provide an effective and economical means of identifying and tracking injuries and illnesses caused by occupational exposures and quantifying their economic burden. State workers' compensation data have been used to supplement national surveillance of occupational injuries and illnesses, support epidemiologic studies, and support enactments of health and safety legislation [22].

Data available in workers' compensation claims typically include the first report of injury, job history, and case information such as diagnosis, treatments, costs, duration, outcomes, and exposures. However, adapting such data for occupational surveillance activities can be challenging [22], because various states administer their workers' compensation systems differently. These differences include WMSD case definitions (as described previously), types and accessibility of data collected, and data-validation methodologies. Researchers must understand the differences in individual states' regulations when using and interpreting surveillance data from these administrative databases. Additionally, larger employers, who tend to be self-insured, may have proprietary systems and data, limiting data sharing and availability.

These differences make it impractical to use workers' compensation data for national tracking of WMSDs.

Under-reporting of workers' injuries and illnesses in the workers' compensation system has been well documented [24 - 27]. Suggested reasons for under-reporting include the use of "light duty" to avoid losing work days; inadequate reporting by employers; employee reporting hesitancy for fear of reprisals or retaliation from employers; fear of losing wages or employment; pressure from peers or employers not to report; shifts from workers' compensation to private health insurance programs; confusion surrounding the criteria for work-relatedness; and use of sick leave or vacation days in lieu of workers' compensation [28, 29]. WMSD surveillance systems and public data are available in various formats on the Washington State Department of Labor & Industries website, the Ohio Bureau of Workers' Compensation website, and the NIOSH Center for Workers' Compensation Studies collection of workers' compensation dashboards.

Occupational Health Indicators

An additional source of WMSD surveillance data is Occupational Health Indicators (OHI). The OHI are a set of 25 indicators that rely on existing data sources to track work-related injuries, illnesses, hazardous exposures, and interventions at the state level. The OHI are managed by CSTE (The Council of State and Territorial Epidemiologists), in collaboration with NIOSH. The CSTE is a professional organization that aims to increase epidemiologic capacity at the state level through training, education, and resource development. The OHI were created in 2005, in partnership with states and NIOSH, as a mechanism for states to uniformly define, collect and report the occupational health status of the working population. The OHI primarily provides state-level data. Two of the OHI involve WMSDs. Indicator 7 uses BLS SOII data to track WMSDS of the back, upper extremities, neck, and shoulder. Indicator 8 uses state workers' compensation data to identify cases of carpal tunnel syndrome. Generally, state-level OHI WMSD data are not directly comparable to other states' or national estimates.

The OHI are collected by states throughout the year and reflect the data available at a particular point in time. Though CSTE publishes OHI data annually, there is a lag of 3 years for OHI reporting (for example, in June 2020, states reported 2017 data), with several exceptions. Washington State, for example, produces reports on a biannual basis [30] when data are available. Refer to the OHI Guidance Manual on the CSTE OHI website for a complete description of the data sources and technical information. OHI reports are also available on the NIOSH website's

State-based Occupational Health Surveillance Clearinghouse web page, including a collection of occupational health surveillance data and links to source surveillance materials.

Syndromic Surveillance

With the proliferation of electronic health records (EHR) data, syndromic surveillance has gained significance and emerged as a potential data source for WMSDs. Syndromic surveillance is a near-real-time, population-based, all-hazard surveillance system that provides information of health events, such as injuries that are not supported by case reporting or laboratory reporting [31]. From its origins as a means to detect bioterrorism-related events, syndromic surveillance is now a common component of U.S. public health departments' surveillance activities [31]. Syndromic surveillance systems have been used to identify heat-related illness, falls associated with inclement weather, suicides, and influenza [32 - 35]. These systems analyze\ medical data to detect disease or injury clusters by identifying symptoms and/or diagnoses in near-real-time. However, they are not stand-alone systems. Patient information can be acquired from a single source or from multiple existing sources, such as emergency department visits, outpatient visits, urgent care visits, and hospital admissions.

The National Syndromic Surveillance Program provides timely data for detecting and monitoring health events. Currently, it collects data from health care facilities in 49 states and the District of Columbia, including 70% of the United States emergency departments. Data are available for analysis within 24 hours of patient visits. The fundamental component of this type of surveillance is the categorization of symptoms and diagnoses into syndromes. Among EHR data are elements such as chief complaint fields, triage notes, diagnosis codes from the International Statistical Classification of Diseases and Related Health Programs (ICD codes), and patient demographic characteristics. These data can be used to create syndrome categories. However, the elements may not always be available.

Though syndromic surveillance has not been widely used to identify occupational injury and illness, efforts have begun. Key words and phrases related to work-related injuries included in the EHR chief complaint data field have been used to capture cases of non-fatal work-related injuries [36]. Advantages of syndromic surveillance include the ability to detect and monitor clusters in communities. These systems are dynamic in that data are continuously added as updates to patient records. However, because it can be difficult to determine from the chief complaint field whether an injury is work-related, some cases might not be recognized. Additionally, most systems do not collect information on industry and occupation.

Other WMSD Data Sources

Employers and labor groups may also collect surveillance data on WMSDs. Some companies collect extensive data on WMSDs, linking OSHA injury records with medical reports, workers' compensation reports, and other data to identify emerging problems and track progress. Large employers may have their own data surveillance systems. Unfortunately, those organizations that do this, oftentimes, are reluctant to provide these data for government surveillance systems. The Center for Construction Research and Training (CPWR) is a labor organization and a leading source of detailed statistics about issues in construction safety and health. It's publication, The Construction Chart Book, currently in its 6th edition [37], presents data on exposure to risks of WMSDs, such as awkward postures and vibration. Additionally, it provides data on labor force characteristics and employment

Selection of Surveillance Data Sources

As mentioned earlier in this chapter, surveillance data can be used for many purposes. Whether you decide to collect your own surveillance data or use existing sources depends on the purpose of your research. Be aware that surveillance data on worker populations will vary according to system attributes such as the time period, user interface, geographic region, industry or occupational data availability, injured worker demographic data availability, methods used to code incident causation, and denominators used for rate calculations. For example, BLS and workers' compensation surveillance data are usually not available for the current or prior year. BLS results can be stratified by detailed industry and occupation categories, but those data are missing from OHI and available from only a small number of state workers' compensation databases.

BLS and some workers' compensation systems report WMSD rates by gender and age; however, race and ethnicity data are not tracked by either system. The Construction Chartbook uses BLS WMSD data from the construction industries without including injured worker characteristics. As stated previously, workers' compensation and OHI surveillance sources in the United States are for a single state. Washington and Ohio publish the most comprehensive WMSD surveillance statistics because both state governments insure most of the working population in their respective states. In recent years, more states (such as California, Massachusetts, Michigan, and Tennessee) have been using and sharing workers' compensation surveillance data online *via* government reports or interactive data visualization dashboards. Recently, some organizations' systems have used machine learning programs to automatically code injury causation or nature, using unstructured narratives that describe how an injury occurred, combined with other sources of structured information about the incident [38, 39].

ETIOLOGY OF WMSDS

The etiologic factors involved in WMSDs were first identified in the early 18th century by an Italian physician considered the father of occupational medicine, Bernardino Ramazzini (1633–1714). Ramazzini linked the role of work to the clinical conditions he was treating. In his seminal work "De Morbis Artificum Diatriaba," Ramazzini wrote, "I ascribe to certain violent and irregular motions and unnatural postures of the body, by reason of which the natural structure of the vita machine is so impaired that serious diseases gradually develop there from."

Though the pathogenesis of WMSDs is not as clearly understood as it is for some occupational diseases, many different models and theories have been proposed in the literature. One of the earlier models developed was by Armstrong [40], who introduced four interacting factors: external exposures, internal doses, internal responses, and resistive capacity. The model of Hagberg *et al*. [2] also included four factors: workplace features (such as poor posture, workstation characteristics); generic risk factors (static loads, cognitive demands) related to work; pathophysiology (individual capacity, types of doses, short-term responses); and outcomes.

The work-style model, by Feuerstein [41], postulated changes to work-style factors (behavioral, cognitive, and physiological) from workplace psychosocial stressors, work demands, and ergonomic stressors. These work-style factors either were a way to cope with work demands or were triggered by work demands. Kumar [42] presented four different theories of WMSDs, which involve factors occurring simultaneously within an individual. The multi-variate interaction theory of musculoskeletal injury precipitation involves interactions between genetic, biomechanical, morphological, and psychosocial factors. The differential fatigue theory described differential loading on different joints and muscles, which may not be proportional to tissue capacity. Kumar's cumulative load theory involved the inability of biological tissues to self-repair in the presence of repeated or prolonged loading. A fourth theory consists of the failure of tissues from exertion, described as a function of force, duration, posture, and motion.

The National Research Council and Institute of Medicine (NRC/IOM) describes a conceptual model of possible roles and factors that may play a part in the development of WMSDs [3]. In this model (Fig. **1**), the injury mechanism results when biomechanical loading exceeds internal tissue tolerances. Personal factors such as sex, age, and body size have a direct impact on the load-tolerance relationship [42]. Workplace psychosocial factors and social context play a role in the progression of WMSDs by modifying the tissue tolerance or pain perception thresholds. The NRC/IOM model may be used to guide the study of risk factors for WMSDs.

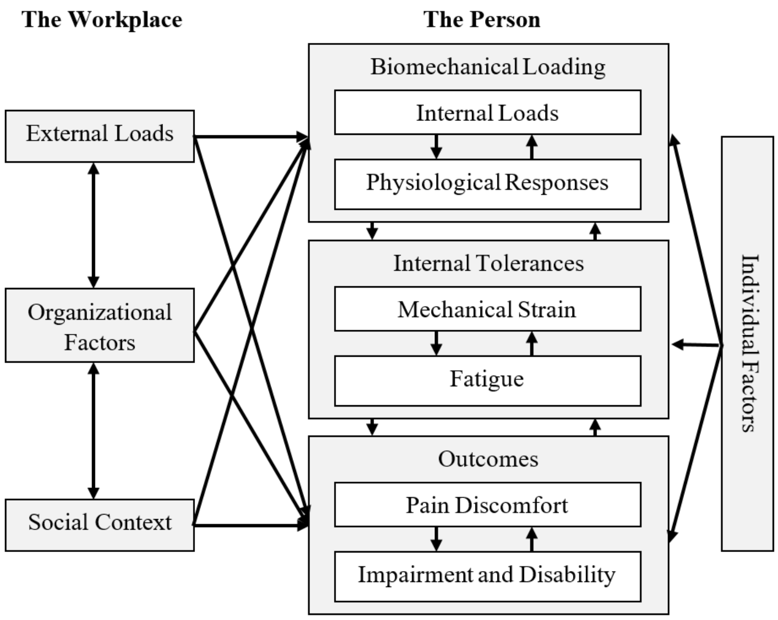

Fig. (1). The conceptual model for the development of WMSDs (adapted from NRC/IOM, 2001).

Pathomechanics

Because the load-tolerance relationship has been considered the main causal pathway for the development of WMSDs, it is important to understand the fundamentals of the pathomechanics of WMSDs. Pathomechanics is the study of the mechanisms surrounding the soft-tissue injury and/or dysfunction that results from physical loading exposures (such as external load, internal tissue tolerance, and the additional variable of the biomechanical loading envelope). Specifically, skeletal muscles are used to study loading-induced injury imparted by both static (isometric) and dynamic (lengthening, shortening, or stretch-shortenin--contraction) muscle movements on active skeletal muscle during acute and/or chronic exposure and the resulting biomechanical (strength, work) and biological (cellular, molecular) outcomes.

Skeletal muscle generates force and power during contraction(s) for movement of the limbs to generate external work, as well as absorb work. It can produce mechanical forces on adjacent tissues such as tendons, joints, and nerves. Skeletal muscle can also generate heat, which is important for thermoregulation in cold temperatures. Because skeletal muscle performs important functions necessary in everyday life, there is also a risk for injury due to these commonly experienced phenomena.

Skeletal muscle contraction studies have been valuable in advancing our understanding of how skeletal muscle injuries occur and the resolution process that follows. Historically, mechanistic investigations were aimed at isolating individual variables of the aforementioned biomechanical loading envelope (such as force, repetition number, velocity, and duty-cycle). It is important to understand and account for the multiple tissues and systems involved during the induction of loading-induced skeletal muscle injury observed with WMSDs [43]. Specifically, early studies of the mechanisms of skeletal muscle injury utilized contraction-induced skeletal muscle injury in animal models because it was useful to investigate etiology on the basis of individual factors [44 - 47].

These studies, along with others, elucidated the component of the skeletal muscle movement that was inherent in the induction of mechanical injury—the dynamic, high force generated during the lengthening or eccentric movement of the contraction [44]. The resulting injury was surmised to result from high fiber stresses in and/or near the contractile apparatus and the subsequent transmission of high forces to the contractile proteins [44, 48].

Skeletal Muscle Contraction Paradigms

In the past two decades, with advances in model methodology for pathomechanics research, more physiologically relevant contraction paradigms have emerged. These contemporary models incorporate not only active lengthening but also isometric and shortening movements [49 - 51]. The contraction paradigm is the basis of the stretch-shortening contraction (isometric–lengthening–shortening) and includes the stretch-shortening cycle [52, 53]. From an applied physiological perspective, this is the most representative movement pattern in humans [54, 55] and other mammals [49 - 51]. Thus, the use of controlled, *in vivo,* high-force skeletal muscle contractions may be the most beneficial way to study the mechanisms of skeletal muscle mechanical loading–induced injury, regeneration, and repair.

Human exposure to electrically evoked loaded skeletal muscle [56] and electrically evoked rodent dynamometer models [45, 57, 58] have shown that the cellular pathways of edema, inflammation, degeneration/necrosis, and regeneration and the accompanying histopathologic and biomechanical decrements are consistent with what is believed to occur in humans [59, 60]. This evidence is compatible with the observation that the amount of mechanical loading in injury from stretch-shortening-contraction has a graded effect with respect to increasing repetition number (that is, the number of skeletal muscle contractions). This is observed at the functional level and in the extent of resulting skeletal muscle injury *in vivo*, which are consistent with each other at both the microstructural and clinical-imaging levels [49, 61]. Indeed, skeletal muscle loading-induced injury is directly initiated by focal mechanical/physical injury [48] to microlevel structures in the skeletal muscle fibers [62]. In addition, disruption of excitation–contraction coupling [63] and surrounding interstitium [64] has been reported to be involved.

Following the initial mechanical injury, a well-coordinated biological response occurs that involve the sequential yet complementary stages of edema, inflammation, and degeneration (collectively referred to as the destruction phase or secondary injury phase). After this phase, regeneration, repair, and remodeling occur [49, 60, 65, 66]. This secondary biological response is required for the subsequent regeneration of skeletal muscle fiber and surrounding tissue and for recovery of function [45, 67, 68]. Concurrently, satellite cells (quiescent muscle stem/precursor cells) are activated, proliferate, differentiate, and finally fuse with the existing myofiber. This cell activity ensures functional restoration once the regeneration, repair, and remodeling processes are complete [69]. During this time, developmental myosin heavy chain (a molecular/cellular marker of skeletal muscle structural regeneration) is expressed in both injured and regenerating skeletal muscle fibers [70]. This expression may mark the final steps of regeneration and repair in the injured skeletal muscle tissue. Indeed, it has been shown that the muscle demonstrates a mixture of both degenerative and regenerative processes.

As regeneration and repair near completion, central nuclei appear and are present at extended time points post-injury. Eventually, these nuclei incorporate peripherally into the fully regenerated skeletal muscle fiber, indicating resolution of previous injury [71]. Thus, the use of *in vivo* animal dynamometry provides unique benefits in studying the mechanisms of skeletal muscle injury. This methodology allows for precise control of the biomechanical loading signature that comprises force, repetitions, *etc.* It also is minimally invasive in that the preparation does not compromise physiological response and allows for the study of skeletal muscle response acutely and chronically.

Risk factors of WMSDs

In the epidemiological literature, the risk factors for WMSDs are often categorized as personal, physical, and psychosocial [1, 3, 4]. Personal factors associated with WMSDs may include mental health conditions such as depression and negative mood state [72]. Because of its risk exposure characteristics, vibration is usually studied independently as a special category of physical risk factor; it is described separately in this section. The risk factors are examined in relation to different body regions, such as the neck, shoulder, upper extremities (arms, elbows, hands, and wrists), back, and lower extremities. Most published studies examined the risk factors for symptoms in the neck, upper extremities, and lower-back regions [4]. There is limited understanding of the physical risk factors for shoulder MSDs, such as upper arm elevation and repeated/sustained upper arm elevation [73 - 76]. The literature on hip or knee problems is sparse.

Personal Risk Factors

Several personal or individual factors have been linked to lower back and upper extremity disorders, such as age, sex, body mass index, muscle strength, smoking habit, history of MSDs, and psychological distress [4, 77 - 79]. Although personal factors are related to WMSDs, it is unclear whether genetic disposition plays a role [3]. There is some evidence that heredity may be a factor in up to 74% of the variability in intervertebral disc degeneration observations [80]. For carpel tunnel syndrome, a structural or genetic factor is more evident than other risk factors [81].

The effect of age on WMSDs has been examined extensively in epidemiologic studies. Several studies showed that age is associated with an increasing linear trend in the incidence or prevalence of WMSDs in the upper extremities and low back region [82 - 84]. Yang *et al*. [83, 84] used a nationally representative sample from the 2010 National Health Interview Survey to estimate the odd ratios of the neck and low back pain (LBP) reported in the previous 3 months for different age groups. They found that the age group of 41 to 64 years had a significant odds ratio of 1.8 for neck pain and 1.4 for LBP, compared with the age group of 18 to 25 years. However, this trend for LBP was not observed in a series of studies using another nationally representative sample from the Quality of Work Life Survey conducted in 2002, 2006, 2010, and 2014 [77 - 79].

A systematic review of longitudinal WMSD studies revealed that there is reasonable evidence of a positive association between age and risk of upper extremity disorders but insufficient evidence of older age as a risk factor for neck or shoulder disorders [4]. The same review study showed evidence of a relationship between younger age and LBP [4]. The mixed findings of age are likely to continue, depending on the definition of the WMSD outcome, the affected body part, the study population characteristics (such as occupation), and the confounding effects of fitness, employment length, survival bias, and other factors.

Many attributes of the human body, such as strength, anthropometric features, motor control, and perception of pain and stress, differ between sexes and also play important roles in the development of WMSDs [85, 86]. Sex and age are both correlated with strength, potentially resulting in mixed effects on the development of WMSDs. For example, although female sex is often found to be associated with higher odds for carpel tunnel syndrome, Violante *et al*. [87] reported that both men and women with taller stature and longer forearm length had 40% to 50% less risk for the syndrome than those with shorter stature and forearm length. Leg muscle strength decreases steadily in both sexes after age 30 and could decline by 20% to 50% or more in comparison with that in a healthy population of workers in their 20s [88, 89].

The required total strengths of the postural muscles for lifting tasks were found to be positively correlated with the incidence of LBP [90]. Zhang and Buhr [89] found that decreased leg strength resulted in different lifting styles. Variations in lifting styles are associated with different spinal loads, which have been considered important risk variables for LBDs. Degradation of muscular strength leads to reduction in functional capacities for manual materials handling (MMH) tasks and possibly an increase in risk for WMSDs [89].

In light of the literature on the relationship between strength and risk of musculoskeletal injuries, strength capabilities and endurance times are used for pre-placement screening in the industry. The premise is that matching workers' strengths and endurances may prevent injuries. However, a systematic review of physical capacity and future WMSDs did not support this premise [91]. The review study suggested no relationship between trunk muscle endurance and the risk of LBP. In addition, findings were inconclusive on trunk muscle strength and mobility of the lumbar spine in relation to the risk of LBP. Similarly, findings on the relationship between physical capacity measures (that is, muscle strength, endurance, and joint mobility) and neck/shoulder pain were inconclusive. More research is needed to investigate workers' strength capabilities in relation to the risk of WMSDs.

Physical Risk Factors

Physical risk factors act on the human body and may result in tissue damage. They include kinetic, kinematic, oscillatory (vibration), and thermal (temperature) factors [3, 92]. To meet the job demand, kinetic (hand force) and kinematic (body motion) factors act synergistically as physical or biomechanical loads to the body. Force can also compress the soft tissues between the external object and the contact surface of the body [92]. Compression of soft tissues by pounding or striking an object is considered contact stress. Contact stress transmits forces to the underlying anatomical structure, which may cause tissue injuries.

To control physical risk factors for WMSDs, it is important to understand different loading mechanisms associated with injury outcomes. Musculoskeletal injury resulting from a clear source of biomechanical loads that exceed the tolerances of the affected tissues may be considered a traumatic MSD. These clear mechanical factors include overexertion for singular heavy loading, sudden imbalance, the impact of force, and slip or fall [42]. If the physical demand for the job is at a sub-tolerance level but is experienced repetitively by the worker, then idiopathic MSDs may occur [42].

Idiopathic MSDs may not be associated with a singular source of risk exposure. They are possibly precipitated by cumulative physical risk factors and other confounding factors such as personal and psychosocial stressors [93, 94]. Both traumatic and idiopathic MSDs may be work related because repetitive manual exertions are often required for job performance. Regardless of the singular or cumulative exposure to physical risk factors, the required force, posture, and repetition for the job task are important factors for ergonomic job design.

Force requirements are essential knowledge for performing any work. A force requirement is often measured as a proportion of an individual's maximum voluntary effort (MVE) or strength [95]. The percentage of population-based MVE has been used for ergonomic job design to accommodate most workers' strength capabilities (for example, 75% of females or 99% of males) or those of a target working population [95]. The MVE is a function of required force, posture, repetition rate, and the total duration for repeating the task. The premise of using MVE for job design is to avoid fatigue and the subsequent risk of WMSDs. That is, ergonomic job design should aim to fit the physical job requirements to workers' strength capabilities.

This aim is typically accomplished by population strength data based on a psychophysical approach. Psychophysics follows a power exponential law between sensations and their physical stimuli [96]. For muscular effort or force, a value of 1.6 was suggested for the exponent [97, 98]. Psychophysical data for manual lifting was pioneered first by the U.S. Air Force [99], followed by Dr. Stover Snook at the Liberty Mutual Research Institute for Safety [100]. He conducted a series of studies to determine the maximum acceptable forces and weights for different manual lifting, lowering, pushing, pulling, and carrying tasks [101].

There is strong evidence that forceful exertions result in WMSDs in the neck, upper extremities, and lower back [3, 4, 73]. In contrast, for shoulder MSDs there is weaker evidence that forceful exertion is an independent risk factor [74, 76, 102, 103]. Muscular contractions for forceful exertions cause vascular obstructions leading to ischemia, fibrillar tearing, and inflammation [42]. Tissue injuries have been known to occur in maximal exertions.

Repetitiveness of the work was found to be a strong risk factor for WMSDs in the upper extremities in several cross-sectional studies [104 - 107]. A review of longitudinal studies on the risk factors for WMSDs found reasonable evidence to support repetition as a risk factor for hand/wrist disorders [4]. The interaction of force and repetition is an important consideration when assessing the risk of WMSDs. An assessment of epidemiological studies examining the interaction between force and repetition revealed that their interactions were observed as a risk factor for a wide range of WMSDs, including carpal tunnel syndrome, hand/wrist tendinitis, lateral epicondylitis, shoulder tendinitis, and low back disorders [108]. That study suggests that repetition of high-force exertions is associated with larger increases in the risk of WMSDs than repetition of low-force exertions [108]. Studies using biological materials (such as human tendons) support the evidence [109, 110].

The human musculoskeletal system bears gravitational forces and internal forces of skeletal muscle contractions in maintaining the body posture and movements [92]. As such, posture is considered a source of biomechanical loads. Poor or awkward posture has been shown in many epidemiological studies to be a risk factor for a variety of WMSDs [4, 73]. Trunk posture not only affects the spinal loads significantly but also alters the relative orientation of adjacent vertebrae, which in turn change stress distribution within the spinal joints [111]. For assessing the risk of WMSDs, the posture of a joint that deviated from the neutral position is often used, such as the neck, trunk, or wrist flexion. For assessing the risk of LBDs, trunk twisting is another commonly assessed postural load. In short, required force, posture, and repetition for the task are at the core of most practical physical risk assessment methods for WMSDs. These assessment methods are described in detail in the Physical Risk Assessment Methods section.

Examining the relationship between the tissue tolerance and external load under varying working conditions (such as different forces, postures, and task repetition rates and durations) is the essence of biomechanical research for WMSDs. Because of ethical considerations, *in vitro* experiments for describing load-tolerance relationships are rare [112]. The load-tolerance relationship is typically measured in human or animal specimens. Under different working postures, tissues have different cumulative tolerance levels for the same mechanical loads. For example, compared with neutral posture, there was a significant reduction (approximately 97%) in the number of compressive load cycles until failure for the lumbar spine, when the specimens were positioned to replicate 45º torso flexion [113].

Biomechanical modeling of the human body is a non-invasive approach to estimating internal tissue loading. It provides a good estimation of the combined effect of the force, posture, and repetition required for the task on body tissues. Biomechanical models follow the laws of Newtonian mechanics for estimating forces acting on tissues in response to the external force. Advancements in biomechanical models have been developed to improve the understanding of load-tolerance relationships as the main causal pathway of WMSDs [114 - 118]. Calculated by biomechanical models, the 3,400 N compressive spinal load for the L5/S1 intervertebral disc has been used extensively in the literature as the risk threshold for LBDs [119, 120]. Recently, 1,000 N and 700 N shear spinal loads for the L5/S1 intervertebral disc have been suggested as the risk thresholds for infrequent and frequent MMH tasks, respectively [120].

Biomechanically, an external moment (torque) is defined as the product of external force (the hand force for handling the load) and the moment arm (the distance between the external load and the body). It is used to calculate the internal moment for spinal tissues as a biomechanical risk variable for WMSDs, in particular spinal disorders. This is because the moment is proportional to the spinal loading at the lower back region (such as L5/S1) when lifting objects or exerting hand forces for manual tasks. The moment arm of the lumbar paraspinal muscles with respect to the L5/S1 intervertebral disc to counter-balance the external load is approximately 5 cm in normal adults. That is much smaller than the external moment arm, ranging from 25 to 64 cm, for lifting loads in the typical range of motion [119]. For MMH tasks in bent trunk postures (that is, the greater horizontal distance between the load and the L5/S1 joint) with heavy loads, this small moment arm of the lower spine results in large spinal moments, spinal compression, and shear forces, all of which are associated with the risk of LBDs [121, 122]. Discussion about different variables calculated by biomechanical models is beyond the scope of this book chapter. Interested readers may consult other references [94, 123].

In the absence of high force exertions, office workers performing computer work may experience musculoskeletal symptoms in the upper extremities [124, 125]. It is suggested that prolonged static posture may result in myalgia due to continuous activation of small motor units [126]. As little as 8% of a muscle's maximum contraction, if sustained, may decrease the blood flow to that muscle [127]. Static muscular load levels as low as 1% have been reported to be associated with WMSDs [128]. Therefore, the assessment of increasing biomechanical loads as the primary risk factor for WMSDs may not be predictive of certain types of WMSDs involving little tissue loading for the task [129]. To understand this paradoxical observation, the "Cinderella" hypothesis was proposed to explain the development of WMSDs associated with low-level muscular loads or tension

[130]. In this hypothesis, type 1 slow-twitch fibers are first and constantly contracted before other types of muscles are recruited for exertions. The constant contractions of the small fibers lead to energy crisis. The lack of resting of these muscles to recuperate from energy crisis may lead to trigger points or myofascial pain [131].

Vibration in the Workplace

Work-related human vibration exposures can be classified into three categories: hand-transmitted vibration (HTV), whole-body vibration (WBV), and foot-transmitted vibration (FTV). Workers operating powered hand tools such as chipping hammers, rivet guns, and nut runners or holding a vibrating workpiece are primarily exposed to HTV. Workers in seated postures while driving various vehicles such as trucks, forklifts, tractors, and agricultural and mining equipment are primarily exposed to WBV. Workers standing on vibrating platforms or equipment are primarily exposed to FTV. FTV may also be treated as WBV if its major vibration components are in the low-frequency range (<10 Hz), because they can be effectively transmitted to most parts of the human body. Prolonged and intensive exposure to vibration may cause various WMSDs.

The most unique vibration-related WMSD is called vibration-induced white finger, a vascular disorder with symptoms like those of Raynaud's disease [132, 133]. In addition to vascular disorders, HTV exposure may cause nerve and muscle disorders in the hand-arm system [134]. Repeated shocks can cause joint disorders and bone damage [135, 136]. All the disorders resulting from HTV exposure are collectively referred to as hand-arm vibration syndrome [137]. HTV exposure may also be a contributing factor for carpal tunnel syndrome [1, 138]. FTV exposure may cause vibration-induced white toe or foot [139]. The major WMSDs associated with WBV exposure include low back pain, early degeneration of the lumbar spinal system, and herniated lumbar discs [140 - 142].

Many studies of human vibration exposures and health effects have been published, forming a comprehensive body of knowledge [134, 143, 144]. It is generally understood that vibration causes health effects through two sequential processes [145]: (1) biodynamic responses such as stress, strain, and power absorption of the human body tissues to the vibration input into the body contact areas and (2) biological responses or effects that are a result of the biodynamic responses.

The biodynamic responses of the human body are similar to the dynamic responses of any engineering structure. Therefore, the methods for calculating the vibration exposure dose of the human body or segments can be identical to those used in calculating the vibration exposure dose of an engineering structure. The vibration stresses or strains are superimposed on the quasi-static stresses or strains induced by body gravity, applied hand or segment forces, and non-neutral postures of the body and/or segments. Like any engineered material, the tissues of the hand-arm system may be injured or display maladaptive changes in physiological function when the combined stresses and/or strains are beyond certain levels. This explains why vibration exposure can be considered as an additional factor contributing to the development of some WMSDs, such as low back pain and carpal tunnel syndrome.

In other cases, the vibration-induced forces or stresses and strains can be comparable or larger than the quasi-static forces [146], especially in the exposure of repeated shocks. The excessive vibration stresses and strains may play a dominant role in determining related injuries or disorders such as spine injuries, joint disorders, and bone damage, especially when such vibration exposures are combined with awkward postures [140, 141, 147]. In the cases of HTV or FTV exposure, vibration stresses and strains must play a unique role in the development of neurological and vascular disorders in the upper and lower extremities, as no one has reported that the quasi-static stresses and strains resulting from overexertion have caused VWF or vibration-induced white toe.

Different from engineered materials, the human body can repair the tissue injuries and adapt to vibration exposure through a series of complex biological responses [148]; long-term disorders or symptoms of the vibration-induced health effects occur only when the living tissues cannot fully repair the tissue injuries or fully recover normal functions. Also different from engineered materials, the human nervous system can transmit vibration information from the exposed body regions to the brain and other regions that are not directly exposed through the sympathetic nervous system [149]. These differences do not substantially change biodynamic responses of the hand-arm system to vibration or the basic formulation of the vibration exposure dose, but they make the mechanisms underlying the development of the vibration-induced health effects much different from and more complex than the mechanisms underlying the damages of engineered materials.

Furthermore, besides the four vibration exposure factors (vibration magnitude, frequency, direction, and exposure duration), the biological responses to vibration may also be influenced by environmental factors (temperature, noise, and moisture), biomechanical factors (hand forces, foot forces, and body postures), and individual factors (genetics, cigarette smoking, age, sex, hand, and arm injury history, and individual biodynamic properties) [134, 143]. As a result, the development of the vibration health effects is much more complex than the damage development of any engineered material. Partially for these reasons, no generally applicable quantitative dose-effect relationship for any vibration health effect has been established [150 - 155], despite extensive epidemiological studies on human vibration exposure and health effects [1, 142, 152, 156 - 159]. This lack is, in part, because the vibration exposures required to cause such disorders remain unknown precisely, with respect to vibration magnitude, frequency spectrum, and direction and with respect to daily and cumulative exposure duration [137, 160]. The lack may also be because the available technologies are not sufficiently reliable to measure the vibration exposure and health effects.

Significant progress has been made in recent years to enhance the understanding of vibration health effects. For example, recent biodynamic studies of the hand-arm system have helped show why the hand frequency weighting defined in the current standard [137] should not be used to assess the risk of VWF – the hallmark of hand-arm vibration syndrome [146, 161 - 166]. Some biological studies have also suggested that the frequency dependencies of vibration-induced vascular and neurological dysfunctions are associated with the frequency dependency of the biodynamic response [148, 165, 167 - 170]. Finger biodynamic weightings suggest that the use of the standard hand frequency weighting is likely to overestimate low-frequency vibration effects but underestimate high-frequency vibration effects. This is consistent with the findings of several epidemiological studies [150, 171 - 176]. An important step has been made toward resolving this issue. An ISO Technical Report [177] has defined an alternative finger frequency weighting to assess the VWF, similar to the proposed biodynamic frequency weighting of the fingers [145].

Workplace psychosocial risk factors

Workplace psychosocial factors may be described as the result of interactions between work organization factors and workers' capacities, needs, and experiences [178]. Stress resulting from workplace psychosocial factors has been linked to many adverse health outcomes such as cardiovascular disease, depressive symptoms, and insomnia, in addition to WMSDs [179 - 184]. In particular, poor supervisory support and/or co-worker support, high job demands, low job control, and low job satisfaction have been shown to be work-related psychosocial risk factors for WMSDs [82, 180, 181, 185 - 188].

In a systematic review of longitudinal studies that investigated the effects of workplace psychosocial factors on neck and shoulder disorders, Kraatz *et al.* [180] found strong evidence of the incremental effects of high job demands, low job control, low co-worker support, and high job strain on the occurrences of these disorders. In addition to the above-mentioned psychosocial factors, an analysis of data extracted from the 2010 National Health Interview Survey core and supplementary occupational health questions showed significant associations between the low back or neck pain and several emerging psychosocial factors, including work-family imbalance, exposure to hostile work, and job insecurity [83, 84].

The linkage of workplace psychosocial factors to WMSDs has briefly mentioned in the NRC/IOM conceptual model described previously. The NRC/IOM model integrated the pathways of an earlier ecological model proposed by Sauter and Swanson [189], which represents the roles of biomechanical, psychosocial, and cognitive factors in the development of upper extremity disorders. The proposed pathways of psychosocial stressors include an increased biomechanical load in the tissues in response to a psychosocial stressor and an increase in the somatic interpretation of musculoskeletal symptoms during stress [189]. Under this ecological model, the psychological stressors play moderating roles and may interact with physical risk factors to increase muscular or psychological strain [190, 191]. Similar to the moderating effects of psychosocial stressors on increased tissue loading in upper extremity disorders, they may also result in increased spinal loads for MMH tasks [192].

Marras *et al*. [192] found not only that stress resulted in increased spinal loads for lifting but also that the personality style of the lifter was predictive of increased spinal loading. As compared with extraverted subjects, introverted subjects exhibited increased spinal loads while performing the same lifting tasks. The personality style was incorporated into a stress theory proposed by Smith and Sanfort [193]. In their balance theory of job design and stress, three domains of the human stress response are specified: biophysiological, behavioral, and psychological/cognitive. In that theory, working conditions impose both physiological and psychological loads on the worker. Selected personality characteristics, past experiences, and social situations may influence the perception of the workloads [193].

Psychosocial factors are typically measured by the constructs of a psychosocial model. The job demands-control (DC) model [194, 195] and the effort-reward imbalance (ERI) model [196] are frequently used for assessing workplace psychosocial stressors. The DC model primarily measures job-induced psychological demands and decision latitude (that is, job control), while the ERI model deals with the balance between the extrinsic work environment and intrinsic personal nature. Compared with the DC model, the ERI model is thought to cover a wider range of psychological aspects, such as job satisfaction, promotion, and work stability [196]. The ratio of job demands *vs.* control was used as job strain in many previous studies and was explored as the main stress variable in association with adverse health outcomes [197], including WMSDs

[198 - 204]. Moreover, using constructing scales of the models, a number of studies have shown that stressors such as low social support, high job demands, low job control, and over-commitment were linked to sickness absenteeism due to WMSDs [187, 205 - 207].

The physiological response to psychosocial stressors may be considered as a potential causal pathway. The physiological response of stress is associated with the sympathetic-adrenal-medullary (SAM) and hypothalamic-pituitary-adrenal cortical (HPA) systems. The SAM system influences blood pressure, heart rate, and secretion of catecholamines, while the HPA system affects the secretion of cortisol, which is often considered a stress hormone [130]. The stress response to adverse psychosocial factors many continue after work in the form of muscle tension sustained by the secretion of stress hormones such as adrenaline and cortisol [190]. The delayed recovery from sustained muscle tension poses an additional risk for MSDs [208, 209]. Hagg [210] suggested a model to include a new explanatory factor for WMSDs, related to unwinding and sustained adrenaline and cortisol secretion after work. His model indicates that unwinding after work is an important mechanism in the interaction between workplace psychosocial stressors, physical loads, and WMSDs.

If workers learn how to handle or control workplace psychosocial stressors, then the activation of stress hormones and related muscular tension may be reduced [191]. To test this hypothesis, salivary cortisol was used as a potential biomarker for measuring stress. A study has shown that job strain (high job demands and low job control) was associated with elevated salivary cortisol levels in 105 schoolteachers [211]. Another study investigating 383 workers' cortisol level parameters in relation to work stress found that high awakening cortisol response and low cortisol decline were associated with lower perceived job control and high job demands, respectively [212]. Maina *et al*. [213] found that the awakening cortisol response in a sample of 104 workers was positively associated with job strain but negatively associated with higher ERI. The two stress models' different associations with the secretion of cortisol may be explained by the different theoretical bases of their psychosocial constructs [213]. Therefore, combining two models for determining adverse psychosocial work environments was suggested [213]. Yu *et al*. [181] evaluated the associations between various combinations of the psychosocial scales of the two stress models and sickness absence due to low back symptoms among 2,737 blue collar workers. The ERI model appeared to be more predictive of sickness absence due to low back symptoms than the DC model in that study population. However, no advantage of using combined stress models for predicting sickness absence due to low back symptoms was evident [181].

Environmental factors

Environmental stressors and hazards present in a working environment can have various adverse effects on workers. These environmental stressors and hazards can include chemicals (such as arsenic phosphates) and physical agents (such as low and high temperatures humidity). They may directly affect or uniquely interact with the complexity of work, leading to WMSDs. Specifically, factors such as ambient temperature and humidity have been associated with WMSDs [92, 214 - 218]. Exposure to cold temperature may lead to decrements in musculoskeletal functions, such as decreased dexterity, tactility, and strength [92]. However, understanding of cold exposure as a causative factor for WMSDs is incomplete [219]. There is a lack of controlled studies, in particular population based prospective studies, to examine the effect of cold temperature. To date, the only prospective study on this topic showed a slightly increased risk (odds ratio: 1.15) of having any pain in one of the six examined anatomical regions and no significantly increased risk of severe pain in multiple body regions [220]. That study, however, used imprecise measurements of exposure to a cold working environment (self-reported exposure time > 25% of work time) without controlling for many other risk factors, such as physical and psychosocial risk factors.

The detrimental effects of heat on workers are likely to worsen over time, with average and extreme temperatures increasing in many parts of the world [221]. Furthermore, investigations have revealed that with ongoing or prolonged exposure, heat stressors are associated with other WMSD factors, specifically with respect to varying ambient temperature(s), personal behavior(s), unsafe work practices, and personal work injury history. The development of WMSDs that may manifest during and/or following exposure to heat stressors is likely to be multifactorial, incorporating physical, metabolic, and cognitive as well as psychomotor function domains [222].

ERGONOMIC ASSESSMENT METHODS FOR PHYSICAL RISK FACTORS

Identifying and mitigating workplace factors for the prevention of WMSDs fall within the scope of the ergonomics discipline. Ergonomics seeks to eliminate or reduce exposures to work factors ascribed to WMSDs through the proactive identification of physical risk factors (force, posture, repetition, vibration, contact stress).

The concept of ergonomics, from the Greek *ergon* (work) and *nomos* (natural law), was derived by the Polish scholar Wojciech Jastrzebowski (1799–1882). In the late 19th and early 20th centuries, research primarily emphasizing improvement of worker productivity through minimization of process inefficiencies and maximization of motion economy, led by pioneers such as Frederick Taylor and Frank and Lillian Gilbreth, resulted in early ergonomic benefits. During and after WW II, with the development of more complex machinery and equipment, focus was placed on the interaction between humans and machines to reduce operator error and thus improve performance.

Following WWII, ergonomic principles were extended to newer, evolving technologies, placing greater emphasis on worker safety and health, with greater recognition of the cumulative effects of work on the musculoskeletal system. The International Ergonomics Association (IEA) now defines ergonomics as "the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design in order to optimize human well-being and overall system performance [223].

As part of the ergonomic process, jobs and work methods can be screened for the basic identification of risk factors with the use of simple checklists. Checklists are generally easily interpreted screening tools to identify problematic job tasks that expose workers to risk factors for WMSDs. Checklists generally identify the presence of risk factors so that those areas of concern can be followed up with a more rigorous assessment. Examples of commonly used checklists include those of Keyserling *et al*. [224]; Washington State Department of Labor & Industries Caution and Hazard Zones; Quick Exposure Checklist [225] and the Ontario Ministry of Labor and the Canadian CRE-MSD. As an example, the Washington State Caution Zone checklist has 14 items addressing the presence of awkward posture (upper arm, neck/back, squatting/kneeling); high hand force (pinching and gripping); highly repetitive motion (including keyboarding); repeated impacts with the hand; hand/arm vibration; and heavy, frequent, or awkward lifting. The Hazard Zone checklist is slightly more detailed (19 items) and is intended to be applied to jobs/tasks identified in the "caution zone." It includes a calculator for analyzing lifting operations and estimating hand-arm vibration exposure.

Identification of jobs or tasks as problematic should be followed up with more detailed assessments that use direct reading and/or continuous reading measurements of risk factors or that use a semi-quantitative observational-based approach to characterizing risk. Both approaches are briefly described below.

Direct reading methods include those in which a physical measurement device is used to objectively measure one or more aspects of exposure. Examples include a digital force gauge that can record peak or average force; more advanced continuous time-recording and data-logging instrumentation, such as a surface electromyograph for active muscle groups or an electrogoniometer; or other sensors for measuring joint angle(s)/position(s) over time. An electrogoniometer is an electrical device used to assess the range of motion of a joint. It follows angular positions through distinctive planes of motion *via* topical body attachments for monitoring voltage signals in response to movements. Two main types of electrogoniometers include potentiometers and strain gauges, devices for measuring the axial rotation of a joint to provide biofeedback on the range of motion. These methods do not rely on visual estimation or judgement of risk factor levels by an observer/analyst.

A recent large-scale survey of professionals certified in ergonomics practice in the United States, Canada, United Kingdom, and Australia [226] indicated the most commonly used direct reading equipment, as shown in Fig. (**2**). Grip dynamometers had the highest prevalence of use; 64.9% of ergonomists have used them. They also are used more frequently than other methods, although only 31% of ergonomists using them do so once per year or less. By contrast, wrist electrogoniometers have been used by only 12% of ergonomists, and over 60% use them once per year or less.

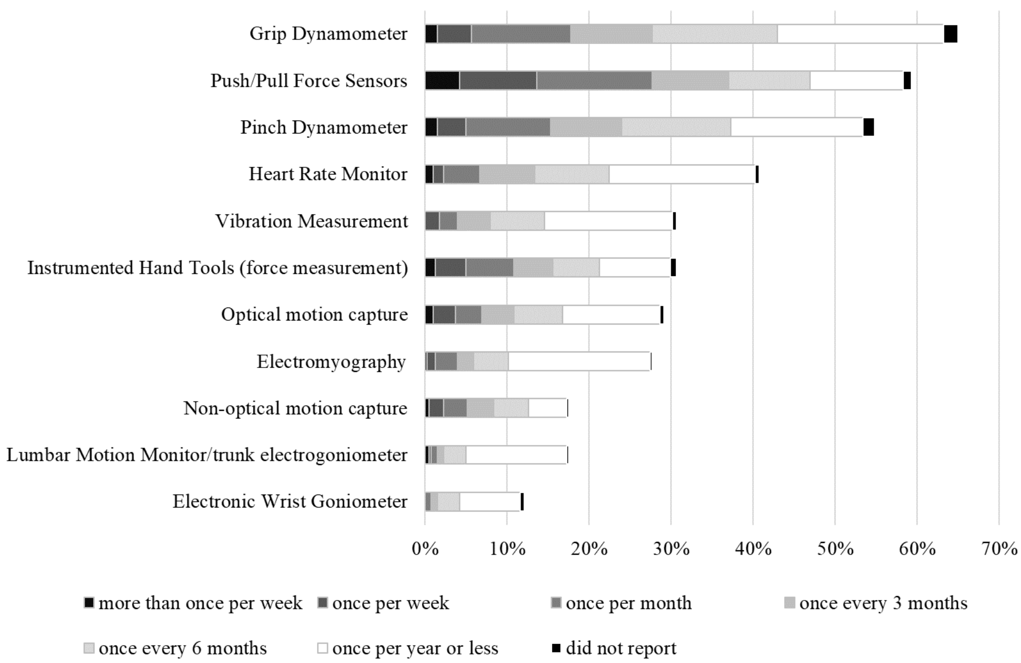

Fig. (2). Direct reading methods for assessing musculoskeletal risk factors: frequency of use by professional ergonomists (percentages are of survey respondents [$n = 405$]).

Numerous observation-based methods have been developed and widely used for ergonomic risk assessment [227]. Table **1** contains a description of such methods commonly used by practicing U.S. ergonomists [226, 228]. A comprehensive description of the application and interpretation of all available methods is beyond the scope of this chapter, and the reader is referred to the AIHA Ergonomic Assessment Toolkit [229].

Table 1. Commonly used ergonomic assessment methods [226, 228].

Method	Description
Whole Body Assessment	
OWAS: Ovako Working Posture Analysis System [230]	OWAS is based on visual documentation of basic descriptive postures and time duration (estimated with the use of work sampling techniques) in these non-neutral postures. Trunk (back) posture can be described as "straight," "bent," or "twisted"; upper limbs as "below or above shoulder level," lower limbs as "both loaded and bent," "one loaded and bent," "kneeling," or "body is moved by the limbs." The duration of work time spent in the non-neutral categories can be compared before and after a process improvement method is implemented to reduce postural stress.
RULA: Rapid Upper Limb Assessment [231]	RULA is a widely used method intended to quickly assess the combination of posture and load (force). Posture is categorized by upper arm elevation; elbow flexion; wrist flexion/extension; neck flexion, lateral bending, or twisting; and trunk flexion, twisting, or lateral bending as follows: upper arm elevation greater than 20, 45, or 90 degrees; elbow flexion; wrist flexion/extension greater than 15 degrees; neck flexion 10 degrees, 20 degrees, or lateral bend or twist; trunk flexion greater than 20 or 60 degrees or twisting or lateral bending. Points accumulate as posture deviates from the neutral position. Points are also given to resistance or load is classified: 2–20 kg (intermittent) is assigned one point, 2–10 kg static load is assigned 2 points, and 10 kg or more is assigned 3 points. Points accumulate to a total of 7 and result in four levels to define the need for corrective action through process or workstation redesign. RULA does not include lower extremity posture/load.
PLIBEL [232]	The PLIBEL method is a questionnaire-based framework with posture-, repetition-, and force/loading-related considerations as relevant to each of the following body regions depicted visually: neck-shoulders and upper back; low back; elbows, forearms, hands; hips and knees; and feet. While the method resembles a checklist approach with dichotomous response options, these dichotomies were grouped according to the scaling of the well-referenced AET procedure (German ergonomics job analysis procedure, published in German).
PATH: Posture, Activity, Tools, and Handling [233]	PATH is a system for real-time tracking of postures at fixed intervals, including observations of trunk flexion beyond 20 and 45 degrees and lateral bending; neck flexion of 30 degrees or twisting of 45 degrees; elbow(s) below or above shoulder height; and leg bending, squatting, kneeling, sitting, or crawling. Fixed-interval sampling of posture and activity is recommended at 45- to 60-second intervals. PATH was developed for characterizing stresses in non-repetitive work, such as construction.

(Table 1) cont.....

Method	Description
REBA: Rapid Entire Body Assessment [234]	Similar to RULA, this is a posture-based assessment for the trunk (20 or 60 degrees flexion, 20 degrees extension, or lateral bend or twist); neck (20 degrees flexion/extension or lateral bend or twist); upper arms (20, 45, or 90 degrees flexion, abduction, or rotation); lower arms (elbow flexion exceeding 60 or 100 degrees); and wrists (15 degrees flexion/extension and/or deviation/rotation). Loads handled are scaled as <5 kg, 5–10 kg, or >10 kg. Quality of the coupling of the body with the load is considered in four categories (good, fair, poor, unacceptable).
Rodgers Muscle Fatigue Analysis [235]	Developed by Dr. Suzanne Rodgers, this is a practical method for evaluating the exertion of muscle effort and associated fatigue. Effort intensity levels are determined for each body part as a low, medium, or high (1, 2, 3). Duration and frequency of efforts are similarly rated on the three-level scale. Effort duration categories are <6, 6–20, and >20 seconds. Effort frequency categories are <1, 1–5, and 5–15 per minute. For each body part, a "priority for change" score is based on the combination of scores for these three variables. Process changes are assessed on the effect they would have on the priority-for-change score for each body part.
Manual Handling Assessment	
Liberty Mutual MMH Tables ("Snook" tables) [100, 236]	For continuous manual lifting, pushing/pulling, and carrying; psychophysical data were compiled from research participants to determine the self-selected acceptable loads as determined by males and females. The loads could be increased or decreased by participants to represent the conditions in which they were willing to perform for up to 8 hours. Some of the load limits have been linked in epidemiological studies to a dose-response relationship with musculoskeletal outcomes. The tables were developed by Dr. Stover Snook and his colleagues at the Liberty Mutual Research Institute for Safety and are often referred to as the "Snook tables".
Revised NIOSH Lifting Equation (RNLE) [119]	A lifting index (LI) is calculated on the basis of the load handled and six lifting task variables (horizontal location of hands to the body, vertical location of hands to the ground, frequency of lifting, asymmetry angle of the torso relative to the center of two ankles, and quality of hand grip) to measure the physical demands in relation to the recommended weight limit (RWL). The LI is used as a metric for assessing the risk of LBDs associated with a particular lifting task. A composite lifting index (CLI) is calculated for multiple lifting tasks as the overall risk metric for the job. NIOSH recommends an LI or CLI ≤1.0 as the risk threshold for most workers (99% male and 75% female).
ACGIH® Threshold Limit Value® (TLV®) for Lifting [237]	Various RWLs are calculated for lifting tasks starting in 12 lifting zones, defined by the vertical distance (between the load and the floor) and horizontal distance (between the load and the body). The RWL values are modified by the lifting frequency and are designed for repeated exposure to manual lifting, day after day, without the development of work-related low back and shoulder disorders.
Washington State (WISHA) Lifting Calculator [238]	The Washington State lifting calculator is part of the Hazard Zone Checklist, developed by the Department of Labor and Industries (described above). Similar to the ACGIH TLV for lifting, it considers the weight of the load, the vertical height and horizontal distance from the body at the beginning of the lift, as well as frequency of the lift and body, twisting angle during the lift. Using these dimensions, a weight limit for lifting is calculated. A web version and an app version are available from Oregon OSHA.

(Table 1) cont.....

Method	Description
Ohio Bureau of Workers Compensation (BWC) Lifting Guidelines [239]	The online lifting guide asks the user a series of task- related questions, including the vertical lift height (floor, knee, weight, or shoulder level), the horizontal reach for the task, and the trunk asymmetry angle for the task. The calculator will provide the RWL for the particular lifting condition.
Lifting Fatigue Failure Tool (LiFFT) [240]	This tool estimates the daily dose of cumulative loading on the low back, using fatigue failure principles. Three input variables (the weight of the load, the maximum horizontal distance from the spine to the load, and the number of repetitions for tasks performed during the workday) are needed to derive the cumulative load for a lifting task. The probability of tissue damage resulting from the cumulative load is calculated as the risk information.
Health Safety Executive (HSE) Manual handling assessment charts (MAC) [241]	Manual lifting, pushing, and pulling tasks are included in the assessment charts comprising two axes (X: frequency of task; Y: RWL). The RWL values for each MMH are marked in green, yellow, and red to represent low, medium, and high risks for WMSDs. The document for using MAC also describes various ergonomic principles for job design.
Upper Extremity Assessment	
Muscle fatigue equations [242, 243]	Studies dating back to the 1950's and 1960's reported experimentally-derived equations for localized muscular fatigue. Endurance time limits are known to be a function of the relative level of force exertion and the rest allowance. The actual observed exertion time in the task can be compared to the exertion time capability predicted by the equations. These equations are used by ergonomists for evaluating the acceptability of manual force exertion.
Strain Index [244]	The index is based on five categorical scales with five levels for the intensity of force exertion, hand/wrist posture, efforts per minute, duration per day, and speed of work. Multipliers are used to scale these levels and determine a Strain Index Score. Extensive literature has related overall Strain Index Scores to distal upper limb disorder outcomes.
ACGIH TLV for Hand Activity [237]	This is based on the combination of hand activity and the amount of required force exertion. Hand activity is either assessed through an observer rating using a 10-point scale with verbal descriptors or else is derived from the combination of a measured duty cycle/force duration. The normalized peak force is calculated from the maximum required force (estimated or measured), as a percentage of maximum force capability for the individual. The combination of hand activity and normalized peak force defines a TLV.
OCRA: Occupational Repetitive Actions [245]	OCRA is structured similarly to RNLE and is based on an equation relating a count of "technical actions" performed in a work shift to a recommended count limit of technical actions. The recommended limit is determined by multipliers for the upper limb force exertion, posture (discount factor for postures deviating from neutral), recovery time, and task duration. According to a recent survey, the OCRA method is not widely used by U.S., Canadian, U.K., or Australian practitioners [226].

(Table 1) cont.....

Method	Description
Psychophysical Upper Extremity Data (*e.g.* "Snook and Ciriello Tables") [246]	Developed through studies conducted at the Liberty Mutual Research Institute for Safety, these data for the upper extremity (hand/wrist) complement the psychophysical data for manual load handling. The studies established maximum acceptable force and torque exertions of the hand/wrist for combinations of power grip and pinch grip with the wrist in postures of flexion/extension and radial/ulnar deviation. These are presented at repetition rates of 15–25 per minute. The limits reported are those that research participants were willing to perform for 7 hours per day, representing maximum acceptable psychophysical limits.
TLV for Upper Limb Localized Fatigue (ACGIH) [237]	This TLV establishes a recommended limit for repetitive exertion of force to prevent excessive or persistent upper limb musculoskeletal fatigue in healthy workers. It is based on two inputs: the percentage of maximum voluntary contraction (%MVC) of the force exertion and the force duty cycle (percentage of exertion time to the total time). The guideline presents a logarithmic equation and the associated threshold curve in graphical format.
The Distal Upper Extremity Tool (DUET) [247]	The DUET score is based on two factors: the rated intensity of the exertion for the task and the number of repetitions of the task during the workday. Exertion intensity can be obtained with use of the OMNI-RES scale or other methods. The cumulative damage of the task is calculated with the DUET approach but does not consider working posture or how repetitions of the task are distributed over the course of the work day.
Health Safety Executive (HSE) Assessment of Repetitive Tasks (ART tool) [248]	The U.K. ART tool is intended for use with tasks that repeat frequently and occur for at least 1–2 hours per shift—typical of assembly, production, processing, packaging, packing, and sorting. Risk factors are categorized as "green" (low), "amber" (medium), and "red" (high) levels. Includes frequency/repetition of arm movements (green, amber, red); four levels of force exertion; and presence of awkward head/neck, back, arm, and wrist postures ("no" = green, "part of the time" = amber, "more than half of the time" = red).

The advantages and disadvantages of direct-measurement and observation-based assessment methods have been described in the literature [249 - 251]. In brief, observation-based approaches may sacrifice some validity in comparison with direct methods such as using motion capture systems, force sensors, or electrogoniometers. However, observation-based methods typically have lower equipment costs, are more accessible, require less data-processing expertise, and are generally easier to implement for the practitioner in the field. The time and costs associated with highly detailed, manual video-based analyses can be high, depending on the objectives and the nature of the jobs and risk factors assessed.

For observational assessment methods, sufficient sampling of observed work activity is an important consideration, as the sampling period must be representative of the exposure profile that is associated with health effects. Observation-based assessment methods, particularly for exposures to the upper limbs, are more suited to relatively mono-task work of a cyclical nature, in which similar or identical task elements (motions/exertions) are performed repeatedly.

Jobs that are highly variable in terms of physical demands, without a cyclical pattern of task elements, are difficult to assess because of the sampling required to adequately represent the exposure profile.

In 2017, among professional ergonomists surveyed in English-speaking countries, 86.9% reported using the RNLE [226]. This was the highest percentage for any ergonomic assessment method. RULA was the second most prevalent in terms of use, at 80%, followed by REBA at 68.9%. Findings from the same survey conducted in 2005 and 2017 suggest no increased use of traditional direct-measurement instrumentation for WMSD risk factors in the intervening 12 years [226]. Most ergonomists often resort to pencil and paper to record WMSD risk factors [226]. With the recent advancements in efficient computer algorithms equipped with Edge and cloud computing for estimating ergonomic risk factors, many of the ergonomic risk assessment methods listed in Table **1** may be completely or partially automated with reasonable accuracy and reliability.

Advances in lower-cost inertial measurement unit (IMU) sensors and toward simpler, easy to use, commercially available wearable sensors and small cameras for motion and posture measurement may make integration of measurement devices commonplace in an ergonomics assessment. An IMU device combines information obtained from multiple electromechanical sensors (such as accelerometers, gyroscopes, and magnetometers) to estimate the dynamic human body motions [252]. The application of IMUs for tracking human motion as a part of ergonomic assessments is becoming popular because the collection of human body motion does not greatly interfere with workers' job performance [253, 254]. A brief literature review of the application of IMUs revealed that the majority of studies explored the use of IMUs for estimating whole body joint kinematics; few studies were conducted to automate ergonomic assessments [255].

A recent survey of 952 safety and health professionals in the United States showed that over one half of respondents considered using IMU sensors to track workplace risk factors [256]. In that study, many implementation barriers were also identified, including privacy concerns, the durability of sensors, return on investment, and lack of best practices [256]. Surveys of ergonomics professionals show that direct measurement equipment continued to be less commonly used than other observation-based approaches [226, 228]. Once the barriers to implementing wearable sensors are overcome, the adoption of IMU sensors for ergonomic assessments may increase.

Another rapidly advancing technologic approach to ergonomic assessment is the application of computer vision algorithms to replace the human analyst in conducting assessments of lifting parameters or repetitive motion from video analysis. Proof of concept has been demonstrated for assessing the horizontal and vertical distance of the load [38, 257], as well as trunk angles and kinematics [258]. To date, these have been established in controlled environments with invariant objects being handled (lifted/lowered). Computer vision using machine learning algorithms has been reported; it employs feature extraction to differentiate facial expressions, which has been proposed as an indicator for estimating hand grip force exertion [259]. As the accuracy of computer vision and IMU sensor technologies for estimating body posture and motion improves, they will become the backbone of automated observation-based ergonomics assessments.

Another approach to evaluating biomechanical loads on the musculoskeletal system related to working posture and forces, both static and dynamic, is through digital human modelling (DHM) with computer software. DHM platforms continue to advance as the underlying biomechanical models incorporated in the software improvements in the validity of predicting the risk of musculoskeletal injury. As of this writing (early 2021), there are several commercial and open source development platforms available for digital human models that include evaluations of risk levels. Readers are referred to several reviews of DHM tools and their incorporation of biomechanical models and ergonomic risk assessment capabilities [260, 261]. Although the validity of the biomechanical models underlying these methods continues to improve, varying degrees of specialized expertise are required to use these tools. Software products more commonly used by ergonomics practitioners are capable of only static force analyses and require simpler static postural inputs. More complex dynamic modelling platforms require inputs of kinematics by way of motion capture recording and are generally limited, at present, to laboratory-based tasks and research applications. Two thirds of ergonomics practitioners in the 2018 survey of ergonomists reported having used some form of biomechanical/or digital human modelling software for ergonomic assessment purposes [226]. It is believed that simpler, static based analyses may currently comprise the majority of these uses.

ERGONOMIC INTERVENTIONS

The reduction of WMSDs is accomplished through the control of worker exposure to WMSD risk. NIOSH and other health/safety standards development organizations, such as ANSI/American Society of Safety Professionals (Occupational Safety and Health Management Standard Z10-2012, R2017), promote the hierarchy of controls (Fig. **3**) as the foundation on which worker protection from workplace hazards is based. The hierarchy of controls can be applied to the prevention of workplace risks for WMSDs.

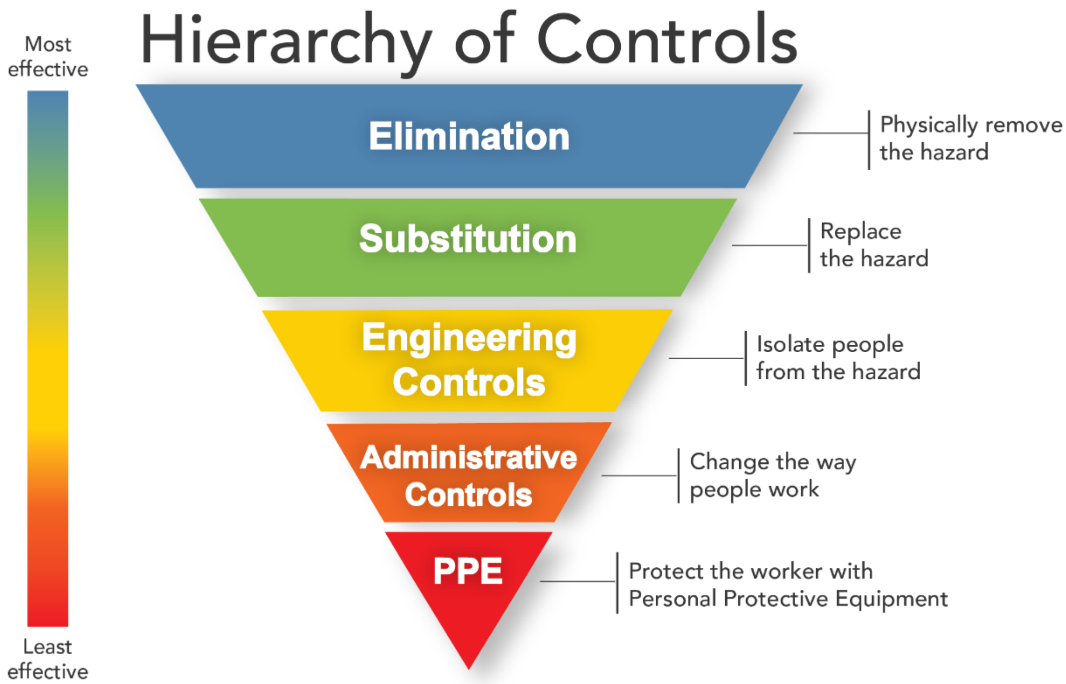

Fig. (3). The hierarchy of controls (NIOSH graphic).

Elimination

MMH can be eliminated with the use of equipment for load handling of materials as a means of avoiding worker exposure to associated lifting, carrying, and pushing/pulling risk factors. Other forms of automation are beneficial in eliminating high force/high repetition elements from work or reducing force/repetition characteristics of jobs. Ergonomic interventions that eliminate exposures have been shown to be more effective, in terms of reducing associated workers' compensation costs, than those that reduce the level of exposure or reduce exposure time [262].

Substitution

For processes in which materials must be handled manually, substitution with lighter and/or differently sized or shaped materials can be considered as a way to reduce workers' cumulative risk factor exposure. A concrete example of this (literally and figuratively!) is an alternative to a traditional masonry block that is lighter in weight and that allows the block to be placed between vertically oriented rebar reinforcement rods rather than manually raised and lowered down over the top of the rebar. These alternative designs reduce the load on the shoulder

[263]. Another example is the substitution of lighter bags of cement mortar and other construction materials, which has been shown to reduce compressive forces on the lumbar spine [264].

Engineering Controls

Engineering controls can be developed in the form of improved tooling and/or workstation modifications to improve working posture, reduce manual forces, and improve resulting biomechanical stresses. For example, raising surfaces from which objects are lifted (lift origin) and moving the objects closer to the torso reduce the moment about the lumbar spine. Lift tables, self-leveling pallet carousels, and other lift aids are examples [265 - 267]. Although the object may still require manual handling, the design of the workstation and tools can be altered to reduce biomechanical loading.

Administrative Controls

Administrative controls include organizational practices such as providing rest breaks, job rotation (having employees rotate periodically between tasks that have lower and higher levels of risk factors), matching employee capabilities to physical job demands, training, and other approaches that rely on behavioral changes. These approaches often require that workers follow additional practices in the absence of other methods of controlling the hazard and are generally considered to be less effective for this reason.

Personal Protective Equipment

Many practical solutions have been documented in established industries to address WMSD hazards at their source, and examples of resources are described below. With creative thinking and input from the workers, who understand the work process best, risk factors can often be eliminated, reduced, or otherwise "designed out" in a cost-effective manner. For some work processes, it is not feasible to completely mitigate risks through the design of the work process.

Personal protective equipment (PPE) has not traditionally been considered as a means of mitigating such residual risks for musculoskeletal disorders. In the traditional hierarchy of controls, PPE serves as a last line of defense when the hazard cannot be mitigated by other control approaches. There has been a recent upsurge in the development of industrial exoskeletons and exosuits (that is, exosystems) as forms of human physical augmentation, with the goal of reducing muscular exertion and reducing fatigue in workplace activities. Some perspectives suggest that these devices are simply a form of enhanced tooling (an engineering control) to reduce risk factors. However, the wearable nature of the devices, requiring considerable fitting and being more individualized and nuanced with respect to user comfort, makes them similar to PPE. Some organizations have begun to require the use of exosystems in tasks that exceed an established musculoskeletal risk threshold, for which no other control measure is feasible and for which a safety risk assessment indicates the device introduces no other risks. The military has been exploring the use of human augmentation technologies since the early 2000s, but the developments toward industrial workplace application and injury prevention have been limited to a few proof-of-concept cases [268].

In 2017, ASTM Committee F48 was formed to develop standards on exoskeletons and exosuits (https://www.astm.org/COMMITTEE/F48.htm). The scientific literature and industry case studies on this topic have since proliferated, and peer-reviewed literature on occupational use of exoskeletons has increased rapidly [269]. Early adoption in manufacturing industries reveals promise, particularly for overhead assembly applications [270, 271]. These applications are maturing, and preliminary studies in the laboratory and production environments have shown specific reductions in electromyographically assessed shoulder muscle activation for arm/tool support tasks [272 - 274] and the perceived effort [273, 275].

More research is needed to understand the potential for, and effects of, transferences of internal tissue loads, such as increased spine loading with non-anthropomorphic support arms [276] and how different exoskeleton configurations and tasks affect these transferences and their tradeoffs relative to specific tissue tolerances. No studies to date have shown long-term benefits in musculoskeletal outcomes, such as reduction in lost work time, associated lost work time or medical costs, and employee turnover. The growing adoption of these technologies has shown promise in some specific industrial and military logistics applications. Additional risk assessment considerations may be warranted for specific tasks in which the devices are implemented.

Resources for Ergonomic Interventions

Many studies of ergonomic interventions and controls have evaluated the effect of the equipment or workplace practice on WMSD risk factors through cross-sectional designs and case studies. A number of occupational health and safety organizations maintain resources documenting interventions that have addressed WMSD risk factors, in peer-reviewed cross-sectional studies, ecological/observational exposure assessment studies, and other industry case studies from reliable sources. The U.S. NORA MUS Council, through the International Ergonomics Association (IEA), maintains a database of ergonomic interventions or solutions for a variety of industries (https://iea.cc/member/

musculoskeletal-disorders/). Another resource is the Solutions Database maintained by CPWR specific to the control of hazards in construction work (http://www.cpwrconstructionsolutions.org/). Many of these solutions address risk factors for WMSDs. Several U.S. state and Canadian province programs have resources on interventions to address WMSD risk factors:

- Federal (U.S.) OSHA (https://www.osha.gov/ergonomics/control-hazards#industry-specific)
- Ohio Bureau of Workers Compensation Safety Intervention Grant program
- Occupational Health & Safety Council of Ontario (https://www.whsc.on.ca/Resources/Publications/Ergonomic-Resources)
- Washington State Department of Labor and Industries (https://lni.wa.gov/safety-health/preventing-injuries-illnesses/sprains-strains/).

Although many organizations have developed industry-specific resources on solutions (interventions) to address WMSD risk factors, there are significant gaps in this knowledge, and some industries/occupations still lack solutions to WMSDs. Growing industry sectors such as healthcare delivery are in need of effective interventions, and the structure of the modern workplace is changing in ways that challenge the practice of workplace safety and health. Many of the successful examples of interventions are in traditional, controlled workplace environments such as manufacturing, warehousing, and construction sectors and are not transferrable to high-risk jobs in the service economy. For example, home health care delivery is particularly problematic, especially in light of an aging population and the increasing prevalence of obesity. Additionally, the growth of so-called “gig” or informal economies erodes traditional employer-employee relationships and the associated employer responsibilities for workplace/labor protections. When responsibilities for mitigating workplace risk factors that would normally fall on the employer (General Duty Clause of the 1970 U.S. Occupational Safety and Health Act) no longer exist, this may create a greater need to raise workers’ awareness of interventions and understand their barriers to adoption.

Intervention Effectiveness—Systematic Reviews/Cochrane Reviews

Demonstrating the effectiveness of interventions toward improving musculoskeletal health outcomes requires more robust prospective experimental study designs. Systematic reviews of interventions for WMSD-related outcomes, such as low back pain or upper limb symptoms and pain, have identified relatively few interventions where evidence of effectiveness has been shown through robust study designs. Workplace intervention studies that meet the most rigorous study design criteria are difficult to conduct.

Systematic reviews have shown some evidence of the effectiveness of arm supports and computer input devices as equipment interventions. Two systematic reviews yielded moderate- or inconsistent- quality evidence that arm support with an alternative computer mouse reduced the incidence of neck or shoulder MSDs [277, 278]. Van Eerd *et al*. [277] found modest evidence that mouse use feedback and forearm supports prevent upper-extremity musculoskeletal disorders (UEMSDs) or symptoms among computer users. In the same review, Van Eerd *et al*. [277] reported moderate evidence of no benefit of EMG biofeedback, job stress management training, and office workstation adjustment for UEMSDs and symptoms. A Cochrane collaboration review by Hoe *et al*. [278] reported inconsistent evidence for arm supports and alternative computer mouse designs preventing upper limb and neck WMSDs among office workers.

There is some systematic review evidence of the effectiveness of lift assist equipment in reducing overall injuries associated with patient handling tasks in health care facilities. Teeple *et al*. [279] reviewed studies of safe patient handling programs and reported injury rate ratios in a meta-analysis. They concluded that overall the programs were effective in reducing injury rates, but it was challenging to discern effects attributable specifically to the equipment interventions in the multi-component programs from those attributable to policy changes (such as requiring team lifts or weight lift limits) introduced in conjunction with new equipment. Furthermore, when outcomes are limited specifically to back pain prevention, a previous Cochrane review showed moderate evidence that equipment interventions combined with training had no effect [280]. Hignett [281] reported a moderate level of evidence supporting the single-factor interventions that included use of hoist equipment to prevent patient-handling-related injury. As a basis of comparison, that same review concluded that providing only lift technique training had no effect on working practices or injury rates associated with patient handling.

Recent systematic reviews have concluded that a resistance exercise is an intervention approach with quality evidence demonstrating effectiveness in improving WMSD outcomes. Lowry *et al*. [282] concluded that there is low-grade evidence that a workplace exercise program may reduce the intensity of shoulder pain. A systematic review [277] of studies from 2008–2013 concluded that there is strong evidence that resistance training helped prevent and manage UEMSD and symptoms, and there is moderate evidence to that effect for stretching programs. Van Eerd *et al*. [277] recommended: "…implementing a workplace-based resistance training exercise program to help prevent and manage UEMSD symptoms and disorders." It is worth noting that only seven studies met the study design quality criteria established in that review; five of those seven studies were conducted in Denmark, one in Finland of office workers [283], and one in Italy of nursery school teachers [284].

The studies from Denmark are predominantly of strength training protocols requiring kettlebells [285] or dumbbells [286 - 288]. Programs requiring this equipment may be difficult to conduct in an employee group setting during work hours. Compliance with these programs outside of work hours relies on individual employee motivation and exercise readiness, and it is reasonable to question the transferability of these findings to diverse worker populations and industries in the United States and North America.

A review of the literature specific to effects of exercise on shoulder and neck pain that included a broader set of studies not meeting the most stringent randomized control trial (RCT) design criteria (as above) was conducted by Lowe and Dick [289]. They found that the studies were heterogeneous with respect to many parameters of the exercise program, including exercise modality (specific resistance training, endurance training, general fitness training, stretching, *etc.*), environment (home or recreational facility *versus* workplace), exercise dose (intensity, frequency/duration, and the number of sessions and program duration). Most studies were of shorter duration, and longer-duration studies tended toward null effects, suggesting that shorter-term relief of symptoms may not be predictive of longer-term outcomes.

Program compliance and participant motivation/incentives are often difficult to discern in workplace studies, and employee compliance is a known barrier with workplace exercise programs. Thus, although exercise can have benefits toward managing and perhaps preventing musculoskeletal pain, there are many considerations in the design of exercise programs as workplace interventions. Administering such programs in practice brings additional challenges. Workplace exercise relies heavily on employee behavior for participatory action, and in the context of the hierarchy of controls, it is believed to be less effective than engineering approaches to controlling risk factors.

In light of these considerations, it is recognized that of all the exercises that may be used for the prevention and/or intervention of chronic dysfunction along the lifetime of the worker, resistance training appears to be the most accessible, effective, and multifactorial modality known to improve health and treat chronic disease [286, 290]. Increasing compliance, adherence and implementation of exercise and/or wellness programs is of major interest to ameliorating WMSDs. The interest in exercise as a means for prevention and/or intervention is not a new concept; however, more recently, interest in its efficacy and evidence of its pluripotency have led to the now global initiative known as Exercise is

Medicine® (EIM). This is an initiative of leading agencies, associations, and centers such as the American College of Sports Medicine, the American Medical Association, and the Centers for Disease Control and Prevention that is supported by the Surgeon General of the United States. The initiative aims to translate evidence-based, scientifically proven health benefits of exercise into the current and future healthcare system [290].

ERGONOMICS GUIDELINES AND STANDARDS

Globally, a variety of national bodies and professional organizations have issued regulations, standards, or guidelines related to worker health that involve worker protection from WMSDs. For example, legislation in many countries addresses problems related to MMH, such as limits on the amount of weight that can be handled by workers in the course of their jobs [291]. This section focuses on the ISO and European standards on WMSDs because of their global influence on WMSD standards activities, and it covers a selection of key standards developed and issued by states.

To date, there is no national ergonomic standard in the United States to protect workers from work-related ergonomic hazards. In other words, permissible exposure limits (PELs) have not been established for WMSD risk factors for enforcement by the Occupational Safety and Health Administration (OSHA). However, under Section 5(a) (1) of the Occupational Safety and Health Act (known as the General Duty Clause), employers are responsible for furnishing, to all employees, a place of employment "…free from recognized hazards that are causing or are likely to cause death or serious physical harm...." For preventing WMSDs, OSHA compliance officers may use the general duty clause to cite violations for ergonomic hazards.

In 1997, California was the first state in the United States to adopt an ergonomic standard. In 2000, a federal ergonomic standard in the United States was passed and signed into law, but it was repealed in 2001. In the same year, the state of Washington passed an ergonomic standard. Similar to the federal ergonomic standard, the Washington State ergonomic standard was revoked in 2003. In lieu of a state standard for MMH, California OSHA and NIOSH co-published the ergonomic guidelines for MMH [292]. Other states, such as Washington and Ohio, have adopted voluntary ergonomic guidelines for MMH. These guidelines are available online:

- Washington State Department of Labor & Industries, https://lni.wa.gov/safety-health/preventing-injuries-illnesses/sprains-strains/get-help-with-ergonomics
- Ohio State Bureau of Workers Compensation, https://info.bwc.ohio.gov/wps/

portal/gov/bwc/for-employers/safety-and-training/safety-education/ergonmic-resources
- California Department of Industrial Relations/CAL OSHA, https://www.dir.ca.gov/dosh/puborder.asp#IIPP.

Because WMSDs are prevalent in healthcare work, some ergonomic standards are addressed in state-enacted safe patient handling and mobility (SPHM) legislation. Texas was the first state to introduce SPHM legislation in 2005. California, Illinois, Maryland, Minnesota, Missouri, New Jersey, New York, Ohio, Rhode Island, Texas, Washington, and Hawaii followed suit to promulgate SPHM regulations. These laws require healthcare facilities to establish policy and guidance for appropriate patient handling equipment, personnel training, and injury prevention evaluation. The American Nurses Association (ANA) partnered with the NORA Healthcare and Social Assistance Sector Council on developing SPHM national standards. In 2013, ANA released the guidance document entitled "Safe Patient Handling and Mobility: Interprofessional National Standards."

International (ISO) and European Standards

Both the International Organization for Standardization (ISO) and European Nations (EN) have developed standards that address risk factors associated with MMH. Individual European countries and the European Union (EU) have published standards related to WMSD prevention. Focusing on the EU standards, the European Committee for Standardization (CEN), under Technical Committee (TC) 122, published the Machinery Directive 2006/42/EC [293]. This document pulls together a large number of European standards (EN) on machinery and workplace design, safety, and ergonomics. In particular, the EN 1005 series of standards are directed toward ergonomics and assessment of risk factors for WMSDs.

Whereas the ISO and EN standards described below address similar subjects and provide in many cases similar approaches and data, the ISO standards are directed primarily to practitioners who may be assessing existing jobs, and the EN 1005 series of standards are addressed to the designers of machinery. The EN standards listed apply to machine operation, including set-up, operation, maintenance, or process changes. They can also be applied to the decommissioning and dismantling of machinery. It should be noted that the data and guidelines presented in these standards are based on European populations. In addition to developing standards, the ISO process allows for Technical Reports (TRs) that are not intended for adoption as standards for compliance purposes but present useful information to users or designers in a particular technical area.

The following ISO and EN standards are relevant to the prevention of WMSDs.

Working Postures

ISO 11226:2000/Cor 1:2006 Ergonomics—Evaluation of static working postures

This standard [294] establishes ergonomic recommendations for different work tasks. It provides information to those involved in the design or redesign of work, jobs, and products and who are familiar with the basic concepts of ergonomics. It specifies the recommended limits for static working postures with no or only minimal external force exertion while taking into account body angles and time aspects. It is designed to provide guidance on the assessment of several task variables, allowing the health risks for the working population to be evaluated. It applies to the adult working population. The recommendations will give reasonable protection for nearly all healthy adults. The recommendations concerning health risks and protection are mainly based on experimental studies regarding the musculoskeletal load, discomfort/pain, and endurance/fatigue related to static working postures. These limits are based loosely upon the Muscle Fatigue Equations described in Table **1** [242, 243].

EN 1005-4:2005+A1:2008 Safety of Machinery—Human physical performance— Part 4: Evaluation of working postures and movements in relation to machinery

This standard [295] addresses operator working postures and motions during machine operation. This standard was originally the basis for ISO 11226, although with different content.

Manual Handling

Lifting and carrying

ISO 11228-1:2003 Ergonomics—Manual handling—Part 1: Lifting and carrying

This standard [296] specifies recommended limits for manual lifting and carrying while taking into account the intensity, frequency, and duration of the task. ISO 11228:2003 is designed to provide guidance on the assessment of several task variables, allowing the health risks for the working population to be evaluated. This standard applies to manual handling of objects with a mass of 3 kg or more. It assumes moderate walking speed, that is, 0.5 m/s to 1.0 m/sec on a horizontal level surface, and does not include the holding of objects (without walking), pushing or pulling of objects, lifting with one hand, manual handling while seated, and lifting by two or more people.

ISO 11228-1:2003 is based on an 8-hour working day. The manual lifting limits it presents are based on the RNLE, with the addition of different reference mass limits for different populations and a suggested strategy for interpretation [297]. The manual carry limits are based upon Liberty Mutual and European data on carrying. Cumulative mass limits for repetitive lifting and carrying and risk reduction methods are also presented. ISO 11228-1 has undergone extensive revision to include the composite lift index, the sequential and variable lift indices, and suggested approaches for longer than 8-hour workdays and also for one-handed lifting. The content on carrying has also been updated, and an annex on the suggested interpretation of the outcome metrics of the Revised NIOSH Lift Equation has been included. The revision was published in 2021.

Pushing and pulling

ISO 11228-2:2007 Ergonomics—Manual handling—Part 2: Pushing and pulling

This standard [298] gives the recommended limits for whole-body pushing and pulling. It provides guidance on the assessment of risk factors considered important to manual pushing and pulling, allowing the health risks for the working population to be evaluated. The recommendations apply to the healthy adult working population and provide reasonable protection to the majority of this population.

These guidelines are based on experimental studies of push-pull tasks and associated levels of musculoskeletal loading, discomfort/pain, and endurance/fatigue. Pushing and pulling, as defined in ISO 11228-2:2007, is restricted to whole-body force exertions (that is, while standing/walking); actions performed by one person; forces applied by two hands; forces used to move or restrain an object; forces applied in a smooth and controlled way; forces applied without the use of external support(s); forces applied on objects located in front of the operator; and forces applied in an upright position (not sitting). ISO 11228-2:2007 is intended to provide information for designers, employers, employees, and others involved in the design or redesign of work, tasks, products, and work for organization. It incorporates abbreviated Mital, Nicholson, and Ayoub push/pull psychophysical data from their publication [291] as “Method 1” for assessment of whole-body push-pull tasks. “Method 2” presents a detailed biomechanical-based model utilizing strength and back compressive force to assess limits for whole-body push/pull tasks that do not fit the assumptions of the Mital, Nicholson, and Ayoub data. An addendum to this standard will be published in 2022 that clarifies and expands the method used to measure whole-body push or pull forces with hand-held gauges.

Manual handling of low loads at high frequency

ISO 11228-3:2007 Ergonomics—Manual handling—Part 3: Handling of low loads at high frequency

This standard [299] establishes ergonomic recommendations for repetitive work tasks involving the manual handling of low loads at high frequency. It provides guidance on the identification and assessment of risk factors commonly associated with handling low loads at high frequency, thereby allowing evaluation of the related health risks to the working population. The recommendations apply to the adult working population and are intended to give reasonable protection for nearly all healthy adults. Those recommendations concerning health risks and control measures are mainly based on experimental studies regarding musculoskeletal loading, discomfort/pain, and endurance/fatigue related to methods of working. ISO 11228-3:2006 is intended to provide information for all those involved in the design or redesign of work, jobs, and products and provides considerable detail on the OCRA method [300] as the primary assessment tool. Screening and detailed versions of OCRA are presented, and additional screening and assessment tools are listed and briefly discussed.

Manual handling of machinery and component parts of machinery

EN 1005-2:2003+A1:2008 Safety of Machinery—Human physical performance— Part 2: Manual handling of machinery and component parts of machinery

This standard [301] applies to the manual handling of machinery, component parts of machinery, and objects processed by the machine (input/output) that weigh 3 kg or more and for minimal carrying (<2 m). The standard provides data for ergonomic design and risk assessment concerning lifting, lowering, and carrying in relation to machine operation. This standard was originally the basis for ISO 11228-1 on lifting and carrying, although the later revision of ISO-1122--2 has greatly expanded content.

Manual handling of people (health care)

ISO/TR 12296: 2012 Ergonomics – Manual handling of people in the health care sector

This is a technical report [302] that provides guidance for assessing the problems and risks associated with manual patient handling in the health care sector and for identifying and applying ergonomic strategies and solutions to those problems and risks. Its recommendations are primarily applicable to the movement of people (adults and children) in the provision of health care services in purposely built or adapted buildings and environments. Some recommendations can also be applied to wider areas such as home care, emergency care, voluntary caregivers, and cadaver handling.

Its main goals are to improve caregivers' working conditions by decreasing the risk of biomechanical overload and to reduce work-related illness and injury, costs, and absenteeism of care providers. It should also improve patients' quality of care, safety, dignity, and privacy with regards to their needs, including specific personal care and hygiene. The recommendations for patient handling take into consideration work organization, type and number of patients to be handled, handling aids, and spaces where patients are handled, as well as caregivers' education and awkward postures. It does not apply to object movement, transfer, pushing and pulling, or animal handling.

Force Limits

EN 1005-3:2002+A1:2008 Safety of Machinery—Human physical performance—Part 3: Recommended force limits for machinery operation

This standard [303] specifies recommended push and pull force limits for operator actions during machinery operation. EN 1005-3 provides data for professional use by the adult working population (healthy and with ordinary physical capacity) and concerning machinery for domestic use operated by the whole population, including youth and older adults. This standard was originally the basis for ISO 11228- 2, although the ISO standard has significantly expanded content.

Human Physical Performance

EN 1005-1:2001+A1:2008: Safety of machinery. Human physical performance. Terms and definitions

This standard [304] provides information, terms, and definitions related to equipment safety, occupational safety, ergonomics, physiological effects, definitions, and symbols for machinery designers that are used throughout the EN 1005 series.

Human Vibration Exposures

ISO 5349-1, 2001; ISO 2631-1, 2001; ISO 2631-5, 2018 [137, 160, 305]

These ISO standards have been established for the measurement and assessment of work-related vibration exposures and WMSDs [137, 160, 305]. Although the

ISO standards do not specify the exposure limit, many countries have developed corresponding national standards and set up the exposure action value and exposure limit for controlling HTV and WBV exposures [237, 306, 307]. A few series of ISO standards have also been established for the detection and diagnosis of HTV health effects [308 - 312] and for the testing and evaluation of vibrating tools [313], vibration-reducing seats [309, 314], and anti-vibration gloves [315], which can be used to help in their selection for controlling the vibration exposures. The Society of Automotive Engineers (SAE) International has also developed a standard for helping select powered hand tools [316].

Other Standards and Guidelines on WMSDs Produced by Scientific/ Professional Organizations

The Human Factors and Ergonomics Society (HFES)

Since the early 1980s, HFES has participated in the development of American national standards and has worked to establish U.S. positions for international standards. The American National Standard Institute (ANSI), as the premier U.S. standards-making body, has delegated to HFES the responsibility of managing U.S. involvement in ISO TTC159 and its sub-committees. As such, HFES administers the Technical Advisory Groups (TAGs), appoints TAG chairpersons, funds travel and other expenses related to sustaining U.S. experts in TC159. HFES can develop standards related to ergonomics and human factors and publish them as ANSI/HFES through the ANSI process (https://www.hfes.org/ Publications/Technical-Standards#ANSI) and include standards on the human factors and ergonomics of computer workplaces. The ANSI Technical Report [317] for Machine-Ergonomics Guidelines for Design, Installation, and Use offers ergonomics references for a variety of physical risk factors, including force exertions, posture, temperature, vibration, noise, and illumination. The Liberty Mutual MMH Tables are included in Annex 1 of the technical report.

International Ergonomics Association (IEA) Published Guidelines

In 2010, IEA, in partnership with the International Commission on Occupational Health (ICOH), published a document entitled "Ergonomics Guidelines for Occupational Health Practice in Industrially Developing Countries" [318]. Unlike ergonomic guidance documents for developed countries, this IEA/ICOH document employs a framework of physical, mental, and psychosocial factors influencing workers' health (ICOH 2010). Checklists are included for hazard identification, risk assessment, risk control, and evaluation of controls. Two hundred ergonomics principles are described as high-level guidance.

In addition to the ergonomic interventions/solutions, the IEA document lists ergonomics guidelines from the United States, Canada, Europe, and Australia. It includes a variety of guidance documents listed by occupation, industry, and job task. The objective of this list is to guide the user on finding potential ergonomic guidelines/solutions by these variables.

CONCLUDING REMARKS

This chapter has provided a foundational perspective on progress to date and anticipated future challenges in addressing the burden of WMSDs. The economic burden and societal impact of WMSDs in the United States and other developed countries continue to be substantial problems. As we have demonstrated, the prevention of WMSDs requires a comprehensive approach to mitigating personal and work-related physical and psychosocial risk factors. The complex, unclear interaction between these risk factors continues to challenge researchers and occupational safety practitioners in their risk prevention efforts. Few results of systematic reviews on the effectiveness of ergonomic interventions are conclusive. High-quality research is needed to further evaluate the effectiveness of intervention strategies while recognizing the multi-factorial nature of WMSDs and the difficulty in conducting highly controlled workplace studies. However, occupational safety and health practitioners can continue to make progress in preventing WMSDs on the basis of our existing knowledge of work-related risk factors, risk assessment tools, and interventions according to existing ergonomic guidelines and standards.

As changes occur in the nature of work, the workplace, and the workforce in developed countries, the occupational safety and health community is adapting approaches to WMSD surveillance and exposure assessment and the development and delivery of interventions to prevent and control WMSDs. Relevant consensus standards and recommendations for exposure limits are emerging. Revisions to the current standards for exposure to multiple or variable risk factors are needed to address the deficiencies. Popular notions of the fourth and fifth industrial revolutions suggest that the proliferation of wearable technologies and exploitation of "big data" will open opportunities; however, it is important to balance these opportunities and advancements with ethical concerns in studying how humans interact with and are affected by their work environment.

Demographic trends indicate shifts towards an older, more heterogeneous working population. The growth in e-commerce and associated fulfillment centers has an impact on working conditions. Macro-economic trends show growth in the informal, so-called "gig" economies and in human capital outside of traditional employment structures (that is, alternative, contingent, app-based, platforms).

These changes in the future of work may impact access to and adoption of technologies, equipment, and work organizational practices that affect musculoskeletal health. New challenges are arising as many of the challenges of preventing WMSDs in long-established industries and occupations persist.

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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