Risk Assessment of Work-Related Musculoskeletal Disorders in Construction: State-of-the-Art Review

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Abstract: Work-related musculoskeletal disorders (WMSDs) have long been a primary cause of non-fatal injuries in construction. They involve sudden or continuous stresses on a worker's musculoskeletal system (e.g., muscles, tendons, ligaments, bones) and may impair the ability of the worker to perform his or her job, or even cause permanent disability. Although assessing exposure to risk factors of WMSDs has proven to be feasible to alleviate the incidence rate of this injury, the field remains underdeveloped because of a lack of knowledge among construction professionals regarding the enabling techniques and their performance and limits. This paper reviews the available techniques for WMSD risk assessments, summarizes their benefits and limitations, and identifies areas in which further studies are still needed. Current techniques are categorized into self-report, observation, direct measurement, and remote sensing assessment. Particular interests are revealed in the wearable-sensor and vision-based techniques within the construction community. This review helps the industry to better understand the severity of WMSDs and the related risks in construction. This review also provides the construction research community with a holistic view on available techniques, their limitations, and the need for research in achieving automatic assessments on construction sites. **DOI: 10.1061/(ASCE)CO.1943-7862.0000979.**

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Introduction

Work-related musculoskeletal disorders (WMSDs) are a serious problem, accounting for 33% of all occupational injuries and illnesses that require days away from work in the United States [Bureau of Labor Statistics (BLS) 2013e]. In the construction industry, highly physically demanding tasks expose construction workers to a number of well-recognized WMSD risk factors such as repetitive motion, high force exertion, awkward body posture, vibration, and contact force. Tremendous loss may occur to the injured workers and their employers (i.e., contractors). In addition, the workers' compensation is partially shared by the society. It is necessary to find ways to effectively identify and assess WMSD risks, which is the key to alleviating this problem.

Thus far, a plethora of methods have been developed to discover the risk factors of WMSDs in ergonomic and epidemical studies. Among them, self-report and observational methods are typically used. However, these methods can only detect easily identifiable risk factors such as repetition and awkward posture, leaving other risk factors (e.g., high force exertion and vibration) unsolved in the workplace. With advances in sensors and sensing, marker-based and remote-sensing methods have been proposed to collect human movements. Biomechanical models are associated with these techniques to help estimate tissue loadings for assessment of WMSD risks.

Until now, reviews contributing to the understanding of WMSD risk assessments include Li and Buckle (1999) and David (2005) in ergonomics, and Inyang et al. (2012) in construction. Li and Buckle (1999) reviewed existing posture-based observational, direct, and self-report methods used in the assessment of physical workload and associated exposure to WMSD risks. This review pointed out that most of the existing methods developed for assessing exposure to potential WMSD risks were research-oriented and thus not suitable for use in many real work situations. David (2005) provided a general overview of the advantages and disadvantages of the self-report, observational, and direct-measurement methods from the perspective of occupational safety and health practitioners. His review concluded that the observation-based assessments appeared to be best matched to the needs of occupational safety and health practitioners who have limited time and resources. In a recent review conducted by Inyang et al. (2012), the severity of WMSDs in construction was examined using the statistical data in Canada. This review also discussed the resultant economic loss (cash and productivity) of WMSDs along with a brief introduction to the main assessment techniques. In summary, these reviews set forth the discussion of existing methods and needs for musculoskeletal disorders (MSD) assessments. However, there is still room for researchers and practitioners to better understand WMSD issues and their assessment techniques in construction: (1) In ergonomic and epidemical studies, cost-effectiveness has not been factored into the design and selection of assessment methods; however, it is important in construction. (2) Many existing methods analyze the MSD risks with high-incidence rate by mimicking and assessing the human behavior in laboratories. However, preventive measures to enable assessments in real workplaces have prevailed. To this end, remote-sensing techniques and biomechanical models are two important research thrusts, which have not been discussed.

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(3) Current ergonomics practice for the U.S. construction industry has not been summarized, and the applicability and practical issues of existing assessment methods for use on construction sites have not been analyzed.

This review identifies the risk factors of WMSDs in the construction industry and provides a holistic overview of existing assessment methods with respect to their advantages, limitations, applicability, efficiency, cost, and labor requirements. In addition, the severity of WMSDs on construction sites is revealed, and the research achievements within the construction community are summarized. This paper helps to bridge the gap between studies in ergonomics and epidemiology and the requirements of on-site construction, non-fatal-injury assessments.

In the following section, the symptoms and causes of WMSDs are introduced, followed by an examination regarding the severity and risk factors of WMSDs in the construction industry.

Work-Related Musculoskeletal Disorders

Musculoskeletal disorders (MSDs) are a group of painful disorders of soft tissues (i.e., muscles, tendons, nerves, joints, cartilage, and ligaments) [Canadian Centre for Occupational Health, and Safety (CCOHS) 2013]. They are also known as cumulative trauma disorders, repetitive strain injuries, repetitive motion disorders, and overuse syndrome. Most WMSDs develop over time and are caused either by the work itself or by the employees' working environment. Based on the cause of injury, WMSDs can be categorized into sprains, strains, and cumulative trauma disorders (Inyang et al. 2012). Sprains and strains are injuries in the joints or muscular tears caused by high levels of force that take place during a single event of lifting, lowering, pushing, pulling, or carrying. In such an event, the physical forces exerted are beyond one's physiological capability. The other type of WMSDs is cumulative trauma disorders that result from performing a task repetitively, even if the load is relatively small (i.e., repetitive motions such as bricklaying), or from a worker's body being in an uncomfortable position (i.e., awkward body postures such as tying rebar) [Health and Safety Executive (HSE) 2014]. The most common WMSDs among construction workers are carpal tunnel syndrome, tendonitis, tennis elbow, trigger finger, sciatica, herniated discs, and low back pains [Albers and Estill 2007; Connecticut Department of Public Health (CDPH) 2014]. Symptoms of these disorders include pain, aching, discomfort, numbness, tingling, and swelling that normally occur in the back, shoulders, neck, legs, wrists, fingers, elbows, and arms. At a construction site, the typical tasks associated with WMSDs include, but are not limited to, lifting and carrying heavy objects, laying blocks, handling pipework, paving slabs and curbs, installing plasterboards, installing mechanical and electrical (M&E) equipment, and working at height (Albers and Estill 2007).

Severity of WMSDs in the Construction Workplace

Incidence rates are used widely in WMSD studies to denote the number of injuries and illnesses per 10,000 full-time workers during the calendar year (BLS 2013e). They are calculated as $(N/\mathrm{EH}) \times 20{,}000{,}000$, where N = number of injuries and illnesses, EH = total hours worked by all employees during the calendar year, and 20,000,000 = base for 10,000 equivalent full-time workers (working 40 hours per week, 50 weeks per year) (BLS 2013e). A high-incidence rate (i.e., 43.7 cases of 10,000 full-time workers in 2012) of WMSDs has been reported among workers in the construction industry (BLS 2013e). In West Virginia, this incident rate is even higher, accounting for 55.6 cases occurring per 10,000 full-time workers in 2012 (BLS 2013c). These WMSD statistics are publicly documented and are therefore conservative; they do not include unreported cases and incidents not resulting in loss of working days. A recent one-year follow-up study, in which 750 bricklayers were randomly selected and surveyed, revealed that 67% of the surveyed workers reported some symptoms of WMSDs (Boschman et al. 2012). Tremendous personal and economic losses can occur to injured workers, contractors, and society. The cost of workers' compensation insurance for construction contractors is normally higher than most other industries (WCRC 2012). One insurer reported that 29% of the insured contractors' workers' compensation claims were the result of WMSDs (Albers et al. 2006). In addition to these direct costs, contractors may incur a variety of indirect costs, including but not limited to, wages paid to injured workers for absence, cost related to time lost as a result of work stoppage, and employee training and replacement cost (OSHA 2012). Considering that the construction industry employs a population of 5.5 million, which accounts for 4% of the entire U.S. workforce (BLS 2013a), construction workers' WMSDs can cause problems that affect the regional or national economy. Based on a recent study (Leigh 2011), the U.S. workers' compensation for occupational injuries and illnesses covers less than 25% of their total cost; the rest is therefore shared by society. This problem may cascade further because of the aging construction workforce, caused by the shortage of skilled construction workers in the ensuing 3 to 5 years (MHC 2012).

Fig. 1 shows that a number of construction tasks are associated with high WMSD incidence rates (highest: flooring), and the risk of residential projects is higher than that of nonresidential projects. Fig. 2 shows that concluding from statistics of all private industries in the state of West Virginia, the incidence rate of pain in the trunk (mostly in the back) is much higher than that in other body parts (i.e., five times that of the second—shoulder) (BLS 2013d). Median days away from work is the measure used to summarize the time loss resulting from injuries, and it is another key indicator of the severity of injuries and illnesses (BLS 2013e). The days away from work as a result of back injuries from construction work are third only to that of transportation and retail among all private industries (CPWR 2013b). Back injuries account for half of WMSDs in all body parts that result in days away from work [Center for Construction Research and Training (CPWR) 2013a]. Therefore, WMSDs in the back are the most common injury in the construction field. In addition, the research conducted in Texas on WMSDs among residential carpenters revealed that approximately 40% of WMSD injuries are claimed by low back pain, which accounts for 44.5% of the total medical and insurance cost of all body parts (Simonton 2007). Construction workers who suffer from WMSDs can have reduced work ability, and the symptoms are likely to recur if not treated properly (Inyang et al. 2012). In even more serious cases, WMSDs can result in permanent disability (Albers and Estill 2007).

Risk Factors in the Construction Workplace

Construction workers tend to adapt themselves to harsh work environments and productivity requirements at a sacrifice to their own health (Lloyd and Besier 2003). Thus, WMSD risk factors in construction workplaces are not easily revealed until a large WMSD incidence rate is witnessed (Nunes and Bush 2012). In this study, the WMSD risk factors are factors in the workplace that increase WMSD risks (Jaffar et al. 2011). They can be divided into three types: physical (biomechanical) exposures, psychosocial stressors, and individual factors.

Physical exposures, which are also referred to as physical risk factors, are hazardous operations or conditions that expose workers to WMSD risks. They involve repetitive motions, high force

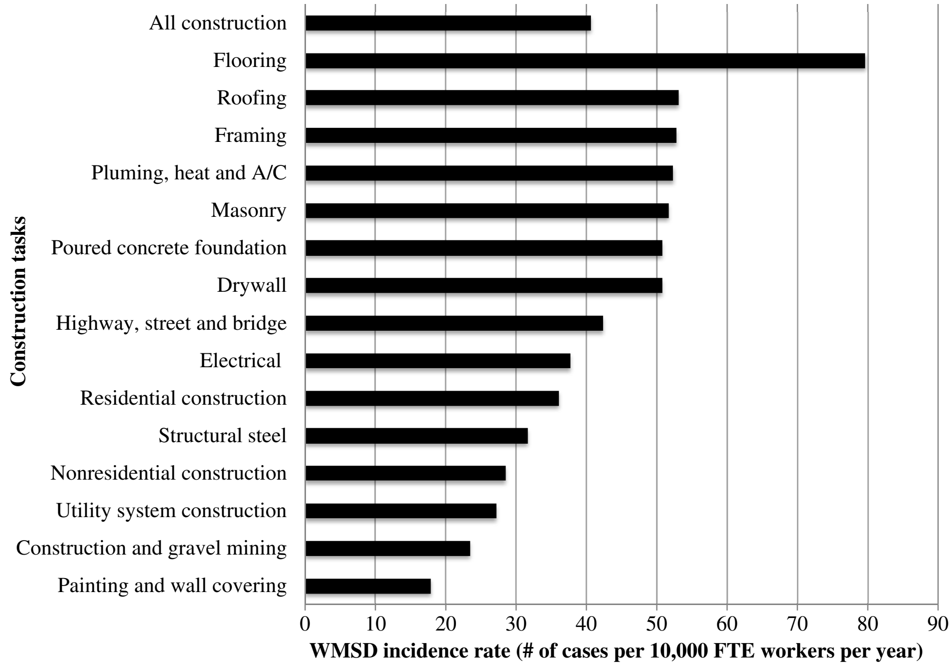

Fig. 1. WMSD incidence rates of typical construction tasks, 2011 forward (data from BLS 2014)

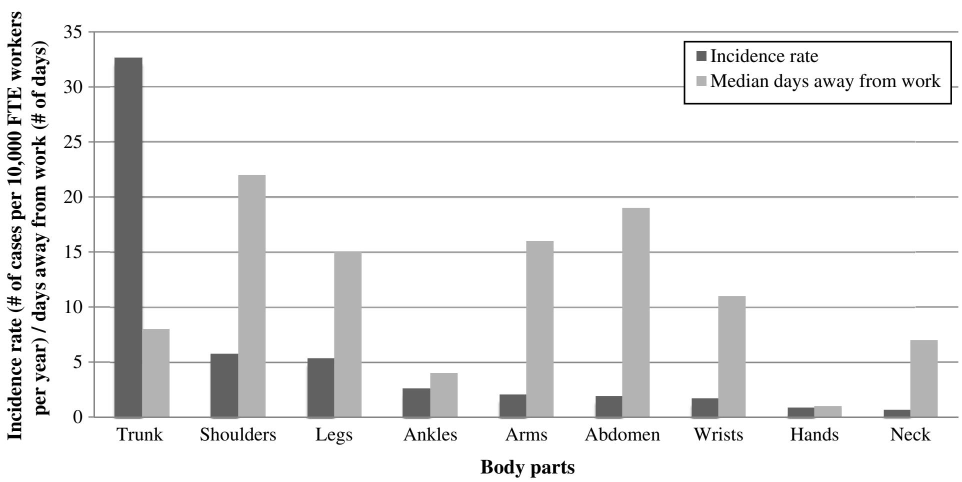

Fig. 2. Distribution of WMSD incidence rates and days away from work by body parts in private industry, West Virginia, 2012 (data from BLS 2013c)

exertions, awkward postures, and poor working conditions such as extreme temperature and high vibration (Devereux et al. 2002). Table 1 lists the most common physical risk factors, their symptoms, and construction task examples. In many cases, multiple physical risk factors may function together to expose the workers to a WMSD risk. Of these factors, handling heavy objects and repetitive tasks are the most common causes for WMSDs in construction (HSE 2014).

So far, research conducted on physical work factors has demonstrated a strong correlation between physical factors and WMSD risks in specific body parts (Table 2). A study conducted on over 2 million WMSD cases found that, among injuries resulting from overexertion in lifting or handling objects, over half affected the back; among injuries resulting from repetitive motion, 55% affected the wrist, whereas 6% affected the back (Putz-Anderson et al. 1997). These statistics indicate a potential correlation between overexertion and WMSDs in the back, and a correlation between repetition and WMSDs in the wrist. The correlation corresponds with the fact that construction workers are exposed to a higher risk of low back injuries than assembly and health workers (CPWR 2013a).

In addition to physical exposures, psychosocial stressors and individual factors can also increase WMSD risks. Psychosocial stressors can come from social issues such as family problems, safety worries, and time pressure. Individual factors can vary among individuals in many aspects and they include gender, age, poor physical/mental health conditions, or bad habits (Jaffar et al. 2011). It has been reported that the risk of human body injuries can be measured by the total amount of physical and psychosocial exposures over the body endurance (i.e., individual factors) (Gatchel and Schultz 2012). However, so far no studies have researched how psychosocial and individual factors contribute to the development of construction WMSD risks. It is also unknown what role the gender plays in attribution of WMSDs because very

Table 1. Common Physical Risk Factors of MSDs in the Construction Industry (Adapted from Jaffar et al. 2011)

Factor	Definition	Damage and symptoms	Correlated tasks
Repetition	Using the same muscles all the time without rest	Strains in tendon and muscle groups involved in direct repetition motions and positioning and stabilizing the extremity in space	Masonry work, assembly, roofing
Force	The physical effort required to perform a task or to maintain control of tools	Stress on the muscles, tendons and joints, and is associated with risk of injury at the shoulder, neck, low back, forearm, wrist, and hand	Lifting wall sections, material, trusses, and sheeted end gables
Awkward posture	Any joint of the body bends or twists excessively or any muscles stretch over, beyond a comfortable range of motion	Sprains and strains in wrist, shoulder, neck, and low back	Installing deck, roofing
Vibration	Any movement that a body makes about a fixed point	Damage caused to body organs buffeted by relatively low frequency and breakdown of body tissues resulting from continued resonance or absorption of high energy vibration	Sitting or standing on a vibrating surface: Roofing, plumbing
Contact stress	Impingement or injury by hard, sharp objects when grasping, balancing, or manipulating	Nerves and tissues beneath the skin of wrist, palm, or fingers injured by pressure when a hard or sharp object comes in contact with the skin	Carpenter, masonry
Extreme temperature	Extremely cold and extremely hot	Cold-caused shivering, clouded consciousness, extremity pain, dilated pupils, and ventricular fibrillation; heat-caused heat exhaustion, heat cramps, or even heat stroke	Outdoor roofing

Table 2. Evidence for Causal Relationship between Physical Work Factors and MSDs (Adapted from Putz-Anderson et al. 1997)

Evidence	Repetition	Force	Posture	Vibration	Combination
Neck and neck/shoulder	++	++	+++	+	N/A
Shoulder	++	+	++	+	
Elbow	+	++	+		+++
Hand/wrist					
Carpal tunnel syndrome	++	++	+	++	+++
Tendinitis	++	++	++	N/A	+++
Hand-arm vibration syndrome	N/A	N/A	N/A	+++	N/A
Back	N/A	+++	+	+++	++

Note: +++ = strong; + = insufficient.

little data exist. Because the percent of women in construction is low, there is not much interest in analyzing this factor. However, studies are still needed to obtain a comprehensive understanding of the effects of the psychosocial and individual factors on the development of construction WMSDs.

Construction Ergonomics Practice

Ergonomics study the human physical and cognitive abilities, limitations, and characteristics in the workplace to enable the design of safe, comfortable, and effective tools, machinery, systems, tasks, jobs, and work environments [UMass Lowell Hardhat Ergonomics (UMLHE) 2000]. Construction ergonomics practice normally involves enforcing federal and state regulations, and establishing numerous programs and guidelines from safety and health organizations.

Legislation

In the United States, the first ergonomics regulation (i.e., CA Labor Code Section 6357 and 8 CCR Section 5110) was established in California. This regulation was created by the state Occupational Safety and Health Standards Board as the result of a 1997 legislative mandate. Its aim was to minimize repetitive motion injuries in the workplace. Although this standard was challenged, a state appeals court upheld it [Occupational Safety and Health Administration (OSHA) 1998]. The other significant ergonomics legislation was L&Is (the Washington State Department of Labor & Industries) ergonomics rule [Washington State Department of Labor and Industries (WSDLI) 2003], which required a critical review of the ergonomics risk factors in the workplace before starting a project. In addition, ergonomics caution zones and hazard risk-factor levels, such as bending flexion angle, lifting loads and repetitive frequency, were intended to be set as a legal restriction. This rule, however, was repealed by Washington voters on December 4, 2003 (WSDLI 2003), partially because of the high cost and the lack of training in ergonomics practice.

Practical Solutions

Construction ergonomics practice is also promoted by safety and health organizations (e.g., OSHA, HSE, and NIOSH), both in the United States and European countries. Numerous programs exist for revealing and eliminating risk factors in different specific occupations. Thus far, efforts on construction WMSD risk management have been primarily categorized into engineering controls (e.g., redesign of work methods and tools), administrative and workplace controls (e.g., work breaks, job rotation), and personal protective equipment for self-protection [Albers and Estill 2007; Ohio Bureau of Workers' Compensation (OBWC) 2014; North Carolina Department of Labor (NCDOL) 2014; Hoe et al. 2012; OSHA 2012]. For example, NIOSH (National Institute for Occupational Safety and Health) has published a booklet to suggest simple

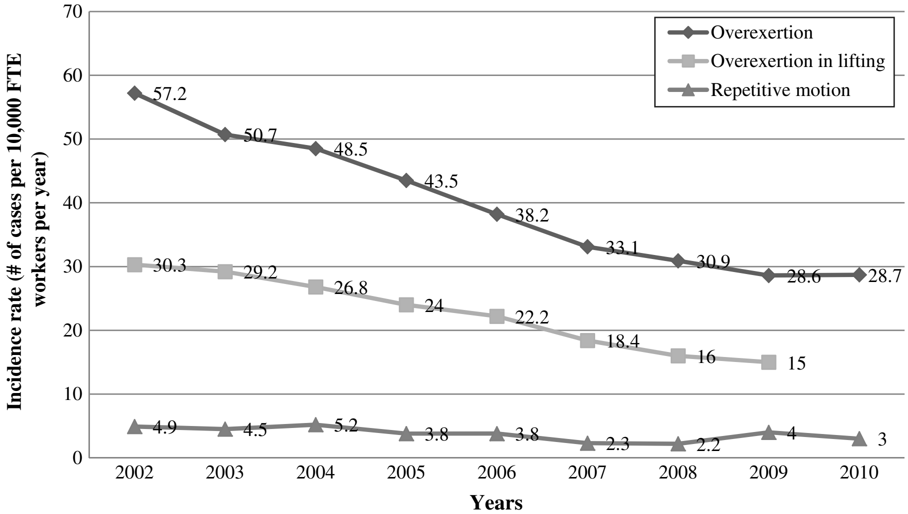

Fig. 3. WMSD incidence rates by exposure in construction, 2002–2010 (data from BLS 2013b)

and inexpensive ways to aid in the prevention of injuries on construction sites (Albers and Estill 2007). OSHA (Occupational Safety and Health Administration) has offered training courses and programs to help workers recognize, avoid, and prevent of safety and health hazards in their workplaces (OSHA 2012). In addition, OSHA and NIOSH have provided detailed guidelines for WMSD prevention in typical workplaces such as retail grocery stores, foundries, nursing homes, shipyards, and other workplaces involved with manual material handling. However, to date, there are still no guidelines specifically for construction; therefore, it is the contractors' obligation under the General Duty Clause to keep their workplaces free from recognized serious hazards, including ergonomic hazards (OSHA 2014).

Effective practice of construction WMSD hazard control should be able to eliminate or reduce the effect of risk factors as much as technically and practically feasible until health and job surveys indicate that the problem is under control (Albers and Estill 2007; Albers et al. 2006). Based on this criterion, some promoted guidelines and measures still lack practicality: (1) most guidelines are written briefly and generically, which cannot guide on-site WMSD risk assessments without the experts' explication (CCOHS 2013); (2) the practice mostly relies on the experts' experience or precedent medical records, leaving those that are not easily identifiable untouched, such as vibration and contact force; and (3) customization is required to make the guidelines fit a specific construction task. For example, almost all guidelines state that adding additional workers will reduce WMSD risks. However, a recent study found that the ergonomic influence of an additional worker is task-dependent and position-dependent (Kim and Nussbaum 2013). In other words, an additional worker standing at a certain location for lifting may increase WMSD risks (Kim and Nussbaum 2013). Therefore, the existing guidelines can be misleading for contractors.

Although investments in ergonomic practices have been increasing annually, limited effects have been achieved. Fig. 3 provides a statistical view of the WMSD incidence rates in construction from 2002 to 2010 (BLS 2013b). Fig. 3 shows that the WMSD incidence rate resulting from overexertion has reduced to a considerable extent, but has come to a standstill recently; the incidence rate of WMSDs resulting from repetitive motion has almost remained unchanged over the past years. These facts indicate that there would be a bottleneck that exists in current practice and advanced risk-assessment methods are needed.

Risk Assessment Methods of Work-Related Musculoskeletal Disorders

There have been a plethora of efforts from employee representatives, regulating authorities, and researchers in measuring exposure to known risk factors as the basis for risk detection and reduction. In the fields of ergonomics, medical care, and information technology, researchers have been working on WMSD prevention and mitigation for decades, primarily focusing on risk assessment in relation to awkward posture, repetitive motion, and high force exertion as the main factors. Intervention has been developed for providing new instrumentation or enabling redesign to change the way a high-risk task is carried out. In general, risk-assessment methods to WMSDs can be categorized into (1) self-report, (2) expert observation, (3) direct measurement, and (4) remote-sensing method. Biomechanical models are associated with these methods to measure internal exposures.

Table 3 summarizes and compares the main risk-assessment methods with respect to focused risks, tasks, assessment accuracy, advantages, limitations, lab/field applicability, cost, labor, and time requirement. Although a large number of existing methods in survey, observation, and direct measurement and their accuracies, focused body parts, advantages, and limitations may vary. Therefore, we have summarized the characteristics that are most in common for each type.

Self-Report

Self-report was developed initially to assess the WMSD problems and is used widely in epidemic and ergonomic studies (Spielholz et al. 2001; Dane et al. 2002; David 2005; CDPH 2014; Inyang et al. 2012). Self-report takes time for workers to finish and interrupts ongoing work. It sometimes is a face-to-face interview between the workers and an investigator. Historically, a number of questionnaires have been developed to assess musculoskeletal symptoms in occupational settings such as the Nordic Musculoskeletal Questionnaire (Kuorinka et al. 1987; Aarås et al. 1998; Kucera et al. 2009; Reme et al. 2012), Borg Scale (Borg 1970; Vieira et al. 2006; Jones and Kumar 2010; Li and Yu 2011), and Job Requirements and Physical Demands Survey (JRPDS) (Dane et al. 2002). In the construction industry, Task Analysis (Silverstein 1985) was used to develop surveys to quantify the perceived injury risk of various site tasks such as painting and hammering nails (Killough

Table 3. Comparison of Main WMSD Risk Assessment Methods

Assessment methods	Example techniques	Focused risks	Applicable tasks	Reported accuracy	Advantages	Limitations	Lab versus field	Instrument cost	Time/labor
Self-report	Questionnaire (Spielholz et al. 2001); interview (Dane et al. 2002); body map (UWO 2011)	Injured body part report	General construction tasks	Moderate; self-reported symptom description (pain and postural discomfort, and/or levels of subjective exertion)	Perceived injury report; suitable for large survey population; easy to use; high applicability	Imprecise perceptions; personal implications; inter-rater difference (interviewees); low repeatability	Lab/field	Instrument free; available online	Time for interview; sufficient subjects required
Observation	OWAS/PATH (Buchholz et al. 1996); RULA (McAtamney and Corlett 1993); REBA (Hignett and McAtamney 2000)	Whole-body or upper-limb posture-oriented risk assessment	Typical construction tasks: masonry, drywall, framing, electrical, plumbing, painting, utility system construction, lifting, and handling	High; mostly for static posture or lesser repetitive movement; approximate flexion angle detection (error: ∼10–20°)	Inexpensive and practical for use in workplaces; minimum work disturbance	Partial risk analysis (mostly postures); low inter-rater reliability (experts); unable to detect slight movement: vibration, typing; large observed sample population (min: ∼15–25)	Lab/field	Expert employment; toolkit available online	Site visit; trained ergonomist required
Direct measurement	(Wireless) EMG (Lloyd and Besier 2003)	Whole-body risk-assessment, analysis and prevention	Short and repetitive movements: bend, squat, stoop	Very high; accurate muscle signal detection for repetitive motion	Accurate and various exposure data collection; automatic	Makers attached directly and tightly on the skin; extensive technical support; time/cost-consuming	Indoor/outdoor	Equip. approx. $2,000	Time for experiments; sufficient subjects and experiments required
	Vicon (Richards 1999)	Whole-body awkward posture detection	Whole-body movement: bend, squat, stoop, lift, and handle; typical construction tasks: flooring, roofing, framing	Very high; skeleton joint location: 0.1 mm	Accurate data collection; automatic	Markers attached directly on human body; discomfort and interruption of work; extensive technical support; time/cost-consuming	Lab only	Equip. approx. $96,000–$120,000	Time for experiments; research practitioners required
Remote-sensing measurement	Kinect (Han et al. 2013)	Awkward posture detection of shoulders, back, and legs	Basic whole-body movement: bend, squat, stoop, lift, handle, and ladder climbing	Moderate; skeleton joint location: 0.2-0.3 mm	Automatic, cost-effective, real work environment deployment	Short range for detection (0.8–4 m); sensitive to illumination and occlusion	Indoor	Equip. approx. $150–$250	Time for algorithm development and testing; research investigators required
	Stereo camera system (Han et al. 2012)	Awkward posture detection of shoulders, back, and legs	Unsafe actions detection: reach, bend, squat, stoop, lift, and handle	Depends on the motion image processing	Automatic; cost-effective; real work environment deployment	Challenged post-data processing; sensitive to illumination, viewpoints, noises; extensive technical support	Indoor/outdoor	Equip. approx. $1,500–$2,500	Time for algorithm development and testing; research investigators required
Biomechanical models	OpenSim (Delp et al. 2007)	Whole-body joint loading and force estimation	Basic static and dynamic movement analysis	Accurate estimate of human motion (e.g., elbow flexion, extension) during static and low-velocity range-of-motion tasks	User-interface friendly, visualization, risky movement simulation and analysis	Motion data required; based on rigid human models	Computer-based	Open source	Time for modeling and analysis; research investigators required

and Crumpton 1996). Recently, Internet surveys, recorded videos, and video conferences were also used as a means to help improve the efficiency and accuracy of the self-report approach (HSE 2014). For example, the investigator prepares his or her questionnaire in advance, and the workers provide their feedback through video recording or video conferencing. Similar to paper-based questionnaires and face-to-face interviews, videos can also serve as an instrument by which the investigator collects feedback from workers in an efficient manner.

Musculoskeletal injuries are often difficult to detect through simple surveys, and it is difficult for construction workers who have no medical background to name the WMSDs in their body parts. To achieve an effective and accurate symptom description, the body map that has the body parts graph was used to help the workers point out the exact parts where the WMSD affects. For example, the University of Western Ontario WMSD Prevention Program (UWO 2011) has applied a self-report method in its research, containing a body map with a set of questions regarding WMSD risk factors (e.g., frequency, symptom) in a workplace for each body part [for details on the questionnaire, readers may refer to the "Worker Discomfort Survey—Form 1B" of the WMSD guidelines in UWO (2011)].

The advantage of self-report is that a large number of workers can report issues and problems that are difficult to observe (e.g., pain and perceived workload), and this method is cost-effective and applicable to a wide range of occupations. The downside, however, is that the results are based on subjective assessments and thus can vary significantly among individuals. In addition, the survey responses can be biased because of personal implications, undermining the reliability of this method in comparison to other methods such as direct measurement and advanced sensing techniques (Spielholz et al. 2001; Jones and Kumar 2010).

Observation

Observation is a systematic recording of postures in a workplace (i.e., region, frequency, severity, duration) (David 2005). An experienced observer is required, and evaluation forms are usually used by experts to measure the WMSD risks for potential redesign of a task or work environment. A number of observational tools have been developed (Armstrong 1985; van der Beek et al. 1992), allowing experts to record and evaluate on a set of structured variables (e.g., a checklist with questions for different body regions) in relation to an evaluation of risk factors. One early observation tool was the Ovako Working Posture Analyzing System (OWAS), which was first introduced by a steel company in Finland in 1973 (Karhu et al. 1977). The OWAS evaluated the WMSD risk level of different body segments (back, arms, and legs) by assessing postures of workers during their task performance. Based on OWAS, Buchholz et al. (1996) developed an enhanced tool named PATH (Posture, Activity, Tools, and Handling) and used it in the work risk assessment of highway construction workers. In comparison to OWAS, PATH not only evaluated the working postures, but also included descriptions of workers' activity, tool use, load handling, and types of grasp in the evaluation. The Rapid Upper Limb Assessment (RULA) was another observational tool that was developed to assess the risk of work-related upper-limb disorders (McAtamney and Corlett 1993). RULA was also used to investigate the corresponding ergonomic designs. Recently, a whole-body postural analysis tool called Rapid Entire Body Assessment (REBA) was developed to primarily analyze unpredictable working postures detected in the healthcare and service industries (Hignett and McAtamney 2000).

These observational tools are used widely in field studies and are advantageous in (1) minimal disturbance to worker task performance, allowing for assessments of tasks in real settings, and (2) experts' visits with minimal instrumentation, leading to cost effectiveness for field investigations. However, expert observational tools have to rely on experts' visits and their subjective evaluations. The assessment cannot be performed continuously and only a limited number of jobs can be assessed during experts' visits. In addition, the inter-rater differences may result in disagreement among the results of different experts' evaluations.

Direct Measurement

To increase the accuracy of risk assessment, direct measurement is often used to assist or replace expert observation. When conducting direct measurement, apparatus such as goniometers, force sensors, and accelerometers are used. Often in a laboratory, but occasionally in a real setting, markers or sensors are directly attached to the human body (skin or clothes) to record human parameters such as three-dimensional (3D) motion of joints and body segments. Compared to self-report and expert observation, direct measurement is objective. Typical direct measurements include electromyography (EMG), optical markers, goniometers, inclinometers, optical scanners, and sonic sensors, which are frequently used as key instrumentation in analyzing biomechanics and tissue and joint loading (CPWR 2013b). Among them, EMG is used primarily in studying muscle exertions by attaching a group of sensors on the skin over the sampling muscles (Ning and Mirka 2010; Ning et al. 2014; Marras and Granata 1997b), as shown in Fig. 4. It features synchronous recording of muscle tension and computerized analysis of myoelectric signals, and is widely used to evaluate muscle fatigue (Ning 2011; Nimbarte et al. 2014; David 2005).

Various optical marker–based direct-measurement methods are commercially available, such as Vicon, APAS, CODA, Motion Analysis, and Qualisys. Three-dimensional coordinates of markers on the body can be recorded with dedicated algorithms to track the position and angular movement of different body segments in real time (Li and Buckle 1999). These kinematics data are then combined with muscle EMG measurements to estimate muscle and joint loadings with the aid of biomechanical models (Lloyd and Besier 2003). One of the prevailing 3D-motion capture systems is Vicon, which involves retroreflective makers placed on the human body and multiple infrared cameras surrounding the capture volume used to track human motion (Richards 1999). Another system was the lumbar motion monitor (LMM) that was developed by Marras et al. (1992) for the purpose of assessing workers' risk of low back injury in the workplace. This system was equipped with a triaxial electronic goniometer and was capable of recording a worker's 3D thoracolumbar spine motion during the performance of different manual material-handling jobs. The same group also investigated the characteristics of trunk motion during the performance of repetitive manual material handling with the aid of LMM (Marras and Granata 1997a).

Being applicable to conditions such as different illumination, temperature, indoor and outdoor, wearable measurement systems such as inertial motion capture (IMC) were also used to track human motion for ergonomic analysis (Kim and Nussbaum 2013). For example, the Xsens MVN (Enschede, Netherlands) is a full-body, cameraless inertial motion-capture system. It involves up to 20 micro-electro-mechanical system (MEMS) inertial sensors attached to a whole body-wearing Lycra suit with embedded cabling. Among these sensors, the inertial measurement unit (IMU) conducts the computational fusion of the accelerometer, gyroscope, and magnetometer data. According to Kim and Nussbaum (2013),

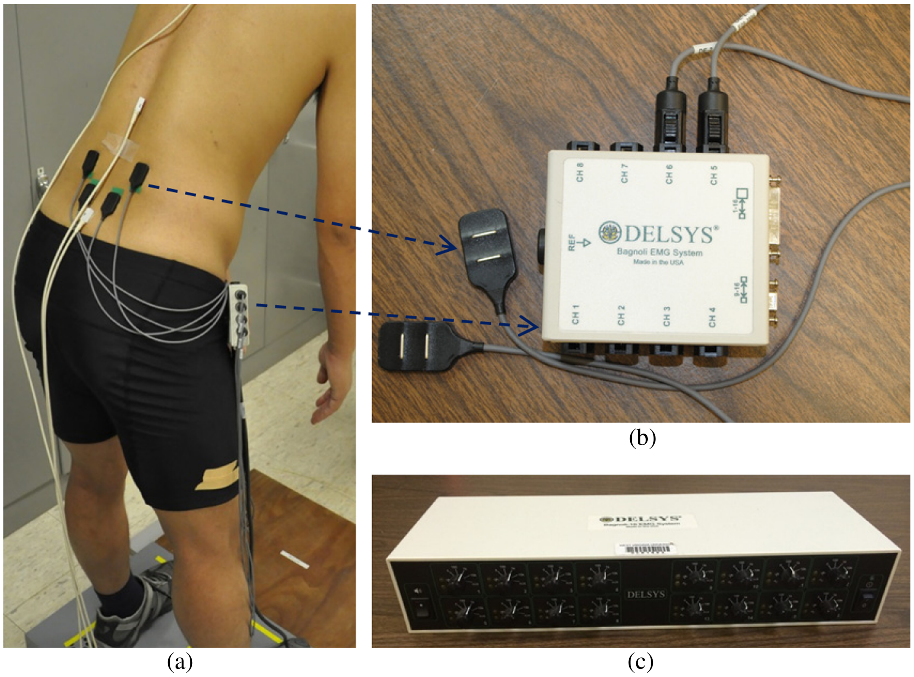

Fig. 4. (a) Electromyography (EMG) sensors placed on the back; primary components of a desktop EMG system including (b) sensors and input module; and (c) main amplifier

this system has the potential for physical exposure detection of handling jobs and is applicable to both indoor and outdoor settings. However, it suffers from joint-estimation errors at the extremity of joint movements. Another example is the physical status monitor, which is used to monitor the physiological parameters (e.g., heart rate) of construction workers (Gatti et al. 2010). Combined with environmental conditions such as temperature and humidity, this system was applied to estimate the physical strains of site crew.

Other methods such as the use of exoskeletons and electromagnetic sensors are not used as frequently because of the high cost or restrictive-use environments. Moreover, a stretchable carbon nanotube strain sensor made from stretchable electronic materials has been developed to track the stretching or strains of fingers and joints of upper and lower limbs (Yamada et al. 2011).

Direct-measurement methods provide detailed information, but the equipment cost, data storage, and time needed for data analysis preclude their use on a large number of subjects or for long-term data collection windows. In general, the accuracy of applying direct measurement is high, and the post-processing of data collected by the instrument is relatively simple (Moeslund et al. 2006). However, most direct-measurement systems require sophisticated instrumentation and laboratory (indoor) environments to collect body motion and muscle activity data (McGill and Norman 1986; Marras et al. 1992; Kingma et al. 1996; Marras and Granata 1997b; Ning et al. 2012; Hu et al. 2013). The body-attached markers may also interfere with the workers' behavior and undermine the performance of regular activities on sites. In addition, direct measurement requires considerable initial investment on equipment, and the resources needed to maintain and employ highly trained and skilled technical staff to ensure their effective operation are expensive (David 2005). Overall, direct measurement is suitable for lab assessment, in observation of the characteristics of risky postures, motions, investigating injury causes, and understanding how injury develops. For continuous assessment and monitoring of on-site WMSD risks, direct measurement is bound to its constraints of functioning properly.

Remote-Sensing Techniques

Advanced remote-sensing techniques concern markerless sensor-based biomechanics, in which range or image/video sensors are used to capture human movements. The collected motion or kinematics data can serve as the input not only for existing observational risk-assessment tools to determine the risk levels on site, but also for biomechanical models to compute the joint or tissue loading that is highly associated with WMSD risks. These techniques do not need human subjects to be directly attached with markers or signal receivers (Chang et al. 2003; Coenen et al. 2011); thus, they are viable to use for assessments in real work settings. To analyze complex and dynamic human motions, 3D-sensing technologies have been developed using range sensors such as Microsoft Kinect (Redmond, Washington) (Warade et al. 2012; Wang et al. 2012) to collect the depth of each image pixel inside the device to its corresponding location in the scene. Based on the depth values, the human skeleton can be extracted by coding the 20-joint human model through the development of the software development kit (SDK) (Diego-Mas and Alcaide-Marzal 2014). Fig. 5 provides an example of the coded 20-joint human model, based on which human body segments and joints can be subsequently detected and tracked.

Many studies have also been working on the feasibility of applying video streams to perform WMSD-related assessments. Initially, studies focused on two-dimensional (2D) images for recording human motion and obtaining kinematic data (e.g., joint angle, body segment acceleration) by manually identifying the location of human joint centers from each frame (Chang et al. 2003; Solomonow et al. 2003; Coenen et al. 2011). Although the optical sensors are suitable for both indoor and outdoor environments, the procedure involved in processing the video data is not considered fully automatic because it still relies on manual input in determining the posture and joint angles for joint loading estimation. In addition to computing joint loadings, researchers have also attempted to apply training models of motions as a benchmark to compare with human skeleton models extracted from videos (Han and

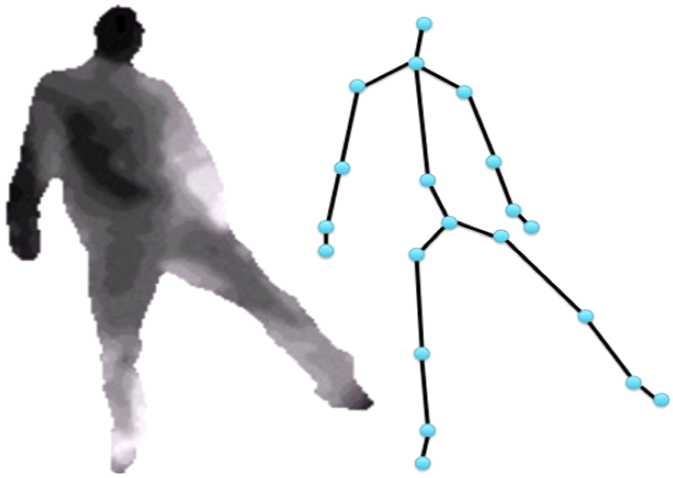

Fig. 5. (a) Kinect depth map; (b) 20-joint human skeletal model

Lee 2013) for analyzing site workers' safety behaviors in a statistical way. For this method, the accuracy of analysis results not only relies on the extracted geometric skeleton model, but the training model and comparison scheme also affects the analysis performance.

In summary, for outdoor construction MSD risk assessments, remote-sensing techniques are promising. However, there is much to be desired. Post-processing the data contained in the videos from the unstructured format to informative knowledge is still challenging.

Biomechanical Models

Sensing-based techniques have advantages over self-report and observation methods because they are able to capture accurate and objective human motion data that can be used to estimate joint loadings. To assess WMSD risks, joint loadings may need to be determined. The joint loading refers to the force or moment put on a weight-bearing or load-bearing joint during activity. According to existing literature (Norman et al. 1998; Neumann et al. 1999; Kerr et al. 2001; Bakker et al. 2007), joint and tissue loading is highly associated with WMSD risks. Therefore, biomechanical models are introduced to analyze human movements and estimate joint loadings. The goals of most biomechanical models are to accurately estimate tissue and joint loadings. There are published tissue and joint-loading threshold values from in-vitro studies that demonstrate the limits of loadings that joints and tissues can withstand (Waters et al. 1993; Gallagher and Marras 2012). In general, the higher loading indicates the higher risk. However, unlike uniformly designed mechanical systems, the human biomechanical system varies among individuals. Therefore, specific dose-response relationships are not defined.

Based on the assumption that the human body is a series of rigid links, the very early models were constructed with limited numbers of rigid links in two dimensions for external loading analysis (Kroemer and Sheridan 1988). These models assumed handling and lifting slowly enough and thus ignored their velocity or acceleration (Chaffin 1967; Chaffin and Baker 1970). With the development of high-speed photography techniques, modeling in 3D was attempted (Garg and Chaffin 1975; Schultz and Andersson 1981). The rapid development of multiple-segment dynamics also enabled the internal-loading calculation associated with external exposures.

To estimate internal tissue loading, electromyography-assisted biomechanical models have been developed (Nussbaum and Chaffin 1996; Marras and Granata 1997a, b; Nussbaum and Chaffin 1998). These models require the collection of instantaneous EMG signals to estimate muscle force; therefore, sensors must be attached to the designated muscle sites. For remote-sensing approaches, only anthropometric data and body kinematics can be obtained. Therefore, to estimate spinal loading, optimization models may be used to estimate tissue loadings with objective functions and constraints. For example, a double-objective function optimization model was established to estimate lumbar tissue forces and the associated lumbosacral joint compression and shear force (Bean et al. 1988). In addition, Waters et al. (1993) identified the maximum acceptable spinal compressive force of 3,400 N, which can be used as a threshold in finding highly risky tasks that could cause acute back injuries. With these models, both acute and cumulative (long-term) low back disorder risks can be revealed and measured.

The development of biomechanical models to the back has made it possible to assess spine loading using the remote-sensing method (Ning and Guo 2013). However, the human head-neck-trunk complex is a severe challenge for biomechanical modeling in that the complex consists of approximately 57 articular bones and numerous muscles (Lee et al. 2009); thus, further efforts are expected.

Nowadays, biomechanical models are usually applied for the post-processing of human-motion data collected by direct measurement or remote sensing. For instance, the ariel performance analysis system (APAS) is a passive marker optical system that has built-in biomechanical models to conduct post-processing and biomechanical analysis. The vision-based motion track system acquires linear and angular velocity of human joints and links. For the biomechanical analysis process, the estimation of internal loads requires computations with 3D whole-body biomechanical models (APAS 2014). Currently, several computerized software packages such as Three-Dimensional Static Strength Prediction Program (*3DSSPP*; Chaffin et al. 2006), *OpenSim* (Delp et al. 2007), *Visual 3D* (C-Motion 2013), and *AnyBody* (Damsgaard et al. 2006) are available to estimate joint loadings and are proven to have the potential of processing motion data captured by remote sensing (Han et al. 2013).

Overall, biomechanical models have strengths in that they can be used not only as post-analysis tools for vision-based systems, but can also be applied independently to human movement analysis. However, biomechanical models have limitations on the amount of data that they require and the error induced by the deviation of the joint locations within the biomechanical models and motion-capture systems. Specifically, since skeletal models are rigidly set, a large amount of external data may be required, which may include individual data (e.g., gender, age, weight) and motion data associated with all the joints defined in the model. This may significantly increase the cost and time for data collection and analysis. Moreover, the definition of joint locations in a motion capture system may vary from that in biomechanical skeleton models. The configuration of the biomechanical skeleton model with the motion data from the nearest joints may lead to errors.

Research Achievements in Construction Ergonomics

Just like the rapid development and extensive applications of motion capture technology, in the past few years, advances in WMSD assessments have been made in the construction research field, especially on the posture-oriented assessment. Among them, studies on vision-based methods and wearable sensor systems are

Table 4. Assessment of WMSDs in the Construction Research Field

Sensors	Focused risks	Sensing data processing	Risk evaluation	Publications
Kinect (depth sensor)	Posture-oriented WMSD risk	Input: Depth map Output: Unsafe action classification; joint 3D coordinates and angles; human skeletal model	Action classification and unsafe posture detection (ground truth: Vicon)	Han et al. (2012), Ray and Teizer (2012), Han et al. (2013), Ning and Guo (2013)
Stereo camera systems	Posture-oriented WMSD risk	Input: 2D images and video Output: Joint 3D coordinates and angles; human skeletal model	Action classification and unsafe posture detection (ground truth: video observation)	Han and Lee (2013)
RTLS, PSM	WMSDs in the torso	Input: Heart rate; location; torso bending degree Output: Frequency of unsafe bending; real-time localization	Risk threshold of heartbeat and torso bending degree (ground truth: video observation)	Cheng et al. (2013a, b)
AMR and optical encoder	WMSDs in hinge-like joints: e.g., shoulders, knees	Input: Joint angle, time duration Output: Temporal stress on shoulders, knees	Risk threshold of joint flexion (ground truth: Vicon)	Alwasel et al. (2011, 2012, 2013)
Accelerometer	WMSDs in the trunk	Input: Acceleration in three dimensions Output: Masonry action detection	Simple action classification (ground truth: video observation)	Joshua and Varghese (2010, 2011)

two main ongoing streams. Table 4 provides a state-of-the-art overview in the achievements of a variety of works in construction in terms of sensors, focused risks, and data processing.

Vision-Based Methods

As a markerless-based assessment method, the vision-based method relies on depth sensors or multiple cameras to perform 3D reconstruction of objects. Computer vision methods are applied for skeleton extraction and motion tracking. In terms of evaluation of performance of the vision-based methods, the accuracy of captured motion data (e.g., rotation angles, joint angles, position vector, and movement direction) is used as a metric, which is fundamental to the body part tracking and post motion analysis.

Kinect

As an emerging vision-based motion capture tool, Microsoft Kinect has been applied to collect 3D information of the human body since it was first introduced in 2010 (Ning and Guo 2013; Goetsch and Goetsch 2003; Ray and Teizer 2012; Han et al. 2013). Significant research efforts have been led in site-unsafe action detection using Kinect (Han et al. 2012; Ray and Teizer 2012; Han et al. 2013; Han and Lee 2013). For analysis, the classification algorithm was developed based on spatial-temporal similarity, and motion data types (e.g., rotation angles, joint angles, position vector, movement direction) were selected as features for classification (Han et al. 2013). Through data-set training and testing, action patterns were then modeled and recognized. To the authors' knowledge, the method has been applied to relatively simple indoor construction ergonomic analysis, such as ladder climbing (Han et al. 2013) and simple posture classification (i.e, stand, sit, stoop, crawl) (Ray and Teizer 2012).

Kinect outperforms the traditional optical-marker-based systems such as Vicon in its cost-effectiveness and high precision. Performance of Kinect in construction safety monitoring was tested in a ladder climbing experiment of 25 trials of ascending and descending by a subject, and the error of motion data fell in a range compared with the ground truth collected using Vicon (Han et al. 2013). Through correspondence and synchronization, the Kinect and Vicon data were mapped into the same coordinate system and a discrepancy of up to 10.7 cm in joint location and 16.7° in rotation angle was detected. The performance of Kinect data for motion analysis and action recognition (i.e., ascending and descending) was also evaluated, and only one case of an ascending action was detected incorrectly (i.e., accuracies of 98% and 100% for ascending and descending actions, respectively). Kinect has proven to have potential in daily risk assessment on construction sites (Han et al. 2012), but it has the downside of short-range applicability (i.e., less than 4 m). In addition, the post-processing classification and recognition at the current phase are only applied to relatively simple postures and motions in a restricted range. Occlusion by objects and the high illumination may also severely reduce the accuracy of the classification. These limits solicit future extension, which are needed to build an automated vision-based risk assessment system with robust classification.

Stereo Camera System

A computer vision-based method using stereo cameras to collect 3D human postures was proposed by Han and Lee (2013). This method applied computer vision to extract features from 2D images and estimate correspondences on images taken from two viewpoints. This way, depth values of the joints were generated for reconstruction of human skeleton in 3D space. Relevant motion templates were used and site videos of safe and unsafe actions were collected as the training data for motion recognition. This method was tested using a case study of reaching far to a side on the ladder. In the test, 22 out of 25 trails were correctly detected, which indicated a detection precision of 88%. Nevertheless, the effects of occlusion and viewpoints of the cameras were not validated, and the robustness of the vision-based method was not tested on real construction sites.

Wearable Sensor System

A plethora of trials of applying wearable sensor systems to assess WMSDs were also undertaken. The sensors used consisted of anisotropic magneto-resistive sensors (AMR), ultra-wide bands (UWB), real-time locating systems (RTLS), physiological status monitoring (PSM), and accelerometers.

Joint Angle Measurement System

To address shoulder-related WMSDs among construction workers, a wearable musculoskeletal joint angle sensor system was developed by Alwasel et al. (2011, 2012). This system had an array of AMR sensors placed at the center of joint rotation on an exoskeleton that would be worn by the worker to track the upper-arm motion. As the relative angle between a moving-arm frame and a reference-torso frame was measured, the predefined awkward shoulder postures could be detected. A microcontroller was deployed in this system to store the data on a secure digital (SD) card. Furthermore, to achieve real-time measurements of the joint angle of the human body such as shoulder, elbow, and knee joints, the AMR sensors were replaced with an optical rotary encoder (Alwasel et al. 2013). Nevertheless, these systems suffer from a lack of degree of freedom for parallel measurements and are restricted to assessments of limited joints (e.g., knees, elbows). Therefore, it is not applicable to heavy construction activities. In addition, it may be restricted in battery durability and interference with ongoing work.

Real-Time Locating System and Physiological Status Monitoring Sensors

In addition, Cheng et al. (2013a, b) proposed the fusion of a real-time locating system and a physiological status-monitoring sensor for construction-site risk analysis. In this study, a PSM sensor was used to monitor the heartbeat rate and the upper torso angle to detect unsafe actions; an ultra-wideband or global positioning system (GPS) was applied to real-time localization. Through the fusion and analysis of the two groups of data, unsafe behaviors (i.e., torso bending over 25°, heartbeat over 106, in working zone, with load) was detected and localized at the same time. Meanwhile, video observation analysis was conducted as the benchmark. This system focuses on the prevention of WMSDs in the trunk. It is only capable of detecting preset postures in bending, and the bending threshold in a dynamic situation is hard to determine.

Accelerometer

An accelerometer also shows the potential of detecting unsafe construction actions. It returns the position and acceleration in three dimensions. Because high acceleration is commonly associated with larger range of motions and increased joint loadings, accelerometers would potentially be used to assess repetitive arm and trunk motions and the associated shoulder and back injury risks. In the experiments led by Joshua and Varghese (2010, 2011), the accelerometer was attached at the waist to track the movement of the trunk, and the data were transmitted to a host personal computer for action recognition. Based on the sensor data collected during masonry activity, three different classifiers (i.e., Naïve Bayes, decision trees, multilayer perceptron) were applied to the classification of different masonry actions (e.g., etching and spreading mortar, fetching and laying bricks, filling joints). In the experiments, masonry activities were videotaped to label the activities and provide input for classifier training and testing. The performance of a classifier with difference sensor positions was evaluated, and it was found that the best performance of 79.83% was obtained with sensors attached to both sides of the waist, in which 79.83% of the masonry actions were correctly detected in comparison to the benchmark video record. As wearable sensors, accelerometers show potential in construction applications because of the low cost, high accuracy of position tracking, and low power consumption. However, this technique has proven efficient only in fixed or repetitive motion analysis. It requires a task dealing with only a limited number of actions to train the classifier and relies heavily on the selection of features. Evidence shows that the selection of the location of accelerometers has a significant influence on the accuracy of assessing results.

Section Summary

This section provides an overview of the efforts led by construction investigators on the assessment of WMSD risks, which focus primarily on the vision-based motion capture and wearable sensor methods. Because of the limits of available technologies, both main research streams are restricted in detecting simple or preset construction actions.

Specifically, wearable sensors are restricted in degrees of freedom and may cause inevitable inconvenience during heavy construction activities and have a negative effect on productivity. The battery life and portability could also be issues. Nevertheless, it is advantageous over optical cameras in that it can collect accurate data regardless of the illumination condition.

In contrast, vision-based methods may suffer from the issues when applied to assess ergonomic risks under real conditions. Normally, camera sensors are sensitive to illumination changes, viewpoints and occlusions, and may not be as reliable as wearable sensor systems. Postprocessing of the image/video data is still challenging (e.g., time-consuming) for the camera sensors. In terms of the limited range sensors (e.g., Kinect), the data-collection ability only within a short range is a big issue when applied in large construction sites. However, the capability of vision-based methods in capturing 3D information of body joints has shown great potential for daily construction ergonomic analysis (i.e., objective, less interference).

Recently, in the construction research field, a trend has arisen for inertial measurement units (IMUs) to be applied in injury risk assessments, including fall incidents, lifting, and carrying (Chen et al. 2014; Jebelli et al. 2014; Yang et al. 2014; Aria et al. 2014). To address the limits (i.e., sensitiveness to occlusion, illumination, and limited detection range) of vision-based methods such as Kinect, IMUs were used to collect acceleration and angular velocity to help reconstruct human postures and track human motions for injury risk assessment of lifting and carrying (Chen et al. 2014). In addition, IMUs were applied to detect fatal injury risk (i.e., slips, trips, and falls from height) (Jebelli et al. 2014). Yang et al. (2014) and Aria et al. (2014) conducted a preliminary study using IMUs to collect data on ironworkers' typical movements, in which supervised classification algorithms were developed for training and testing on the near-miss fall data.

Discussion

This discussion focuses on the current assessment techniques, and through this review, gaps still remain between current techniques and what construction site assessment requires. Both technical (data collection) and methodological limitations still exist for use of existing methods in ergonomic evaluation in construction. Data collection on real construction sites may face hurdles as a result of limited applicable tasks, high instrument cost, instrument importability, interference with ongoing work, and time/training/labor requirement. For example, some marker-based methods like EMG require sensors tightly attached to the human skin. However, at real construction sites, the sensors may affect the productivity and are highly likely to become loose as a result of active body movements, leading to incomplete and inaccurate measurements. Similarly, the infrared vision–based methods such as Vicon and

Kinect are sensitive to illumination and occlusion and therefore may not be used in outdoor environments. Productivity and cost-effectiveness are commonly not considered in existing ergonomic studies. In addition, most existing ergonomic field assessment tools are subjective and compromised in accuracy. Therefore, many ergonomic studies focus on the identification and assessment of risk factors in controlled lab environments. A need exists for proactive prevention of WMSDs during real job performance before an injury occurs. Moreover, in comparison to acute injury risks, the assessment of cumulative injury risk is much more complex as the exact pathology of many existing WMSDs is still not clear, and the occurrence of WMSDs can be affected by multiple factors.

The construction industry is a labor-intensive industry. It is very difficult to replace labor with robots and machines. Construction workers are exposed to high WMSD risks, and suffer from a high incidence rate of WMSDs, especially low back disorders. A series of ergonomics practices and risk-assessment methods have been proposed. However, construction managers should be aware of the limitations and applicability of these methods before applying them at real sites. Although self-reported survey and expert observational tools are easy and inexpensive to implement, the data collected with these tools are subjective, inter-rater unreliable, and the results can be error-prone. Direct measurement can provide more objective results; however, this technique requires sensors or markers to be attached directly on human subjects. The commercial systems such as Vicon require a significant amount of investment and are restricted to lab uses. Therefore, they are not suitable for use at real construction sites. Vision-based human-motion capture technologies require a much lower budget, yet they are still involved with manual procedures and bottlenecked by constraints. Biomechanical models have proven to have the potential to convert joint moments to force and torque, and can be used for the post-processing of human-movement data (APAS 2014). In addition, research has been conducted in an attempt to link the human motion capture methods (e.g., Kinect) with biomechanical models (e.g., SPSS, OpenSim) through conversion of data formats (Seo et al. 2014a, b, c).

This review reveals a trend that researchers tend to resort to remote-sensing technologies for development of new WMSD assessment methods in construction. However, a significant amount of work is still needed to build an automated real-time on-site WMSD risk monitoring system with reasonable cost. Undertakings in other fields may help enhance the applicability of these technologies in the construction industry. For example, Kinect was designed to be embedded into the electric skateboard as the next generation urban transport. Three components of voice analyzer, motor controller, and sensor classifier were designed and integrated to capture and recognize human gestures and voice (Aziz et al. 2012). In sociology studies, an accelerometer was applied in the physical activity research of teenagers or seniors. In manufacturing, to enhance job rotation efficiency and eliminate work injuries, Red, Green, Blue, Depth (RGB-D) camera technologies have been developed to capture the human depth map and assist in anthropometric measurements. Based on risk evaluation functions, work discomfort levels and risks could then be measured (Huang and Pan 2014).

Based on the current progress in human motion capture and biomechanical models, it is possible to accurately capture human motion and extract the loading and force. However, the paper identifies that there are still gaps to be bridged. First, the computer vision-based motion capture methods focus primarily on posture-based risk factors, but are not capable of identifying other risk factors such as vibration and contact force. Second, vision-based methods that lead to the output of joint loadings and estimate the loadings on soft tissues still needs investigations to reduce the environmental interference (e.g., poor illumination, occlusion). Third, vision-based methods use the postures as a single indicator to measure the risk, ignoring, e.g., muscle signal and force. The analysis of the output can be further improved with an emergence of a better injury indicator or a combination of different existing indicators, which should be tied with ergonomic or epidemical study findings. Fourth, the design of a WSMD risk-assessment method should start with a specific construction task and/or a real site problem. The existing wearable sensor systems and vision-based methods in construction research aim to discover a generic solution to WSMDs, and performance evaluation primarily focuses on a few simplified actions. Fifth, a combination of different methods may generate better results than a single method when considering the resource cost (i.e., instrument, labor, and training), accuracy, and time limitation. Some existing studies have demonstrated this point. For example, Vicon and EMG measurements were combined when Vicon was used as a motion capture system and the resulting kinematic data were combined with the muscle data collected by EMG to estimate muscle and joint loadings using biomechanical models (Lloyd and Besier 2003). Real-time locating and physiological status monitoring were integrated to collect and fuse the heartbeat rate, upper torso angle, and working location to detect unsafe behaviors of site workers (Cheng et al. 2013a, b). Another example is Xsens MVN, a wearable system prevailing in the market that is capable of providing real-time motion capture and visualization through the computational fusion of data resulting from accelerometers, gyroscopes, and magnetometers. At present, a combination of cost-effective sensors (e.g., IMU, RTLS, Kinect) is promising in on-site applications (Chen et al. 2014).

Conclusion

This paper reviewed the WMSD risk factors in the construction industry and summarized the current risk-assessment methods, along with a discussion of their applicability and limitations at the construction site. Risk assessment of WMSDs in construction is difficult because of the complexity of construction tasks.

It is suggested that after the risk or risk factors are detected for a specific construction task, based on the severity and effects of the factor, a minor or a major redesign of the work may be required, either in the environment setting, tools, equipment, or procedure of the operations. Moreover, for a selected operation, there could be alternative postures or different actions that the workers could take to finish. A comparison study that is designed for a specific construction operation would be beneficial so that safer actions could be detected and guidelines could be provided.

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