Data Fusion of Real-time Location Sensing (RTLS) and Physiological Status Monitoring (PSM) for Ergonomics Analysis of Construction Workers

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Abstract

Previous research and applications in construction resource optimization have focused on tracking the location of material and equipment. There is a lack of studies on remote monitoring for improving safety and health of the construction workforce. This paper presents a new approach for monitoring ergonomically safe and unsafe behavior of construction workers. The study relies on a methodology that utilizes fusion of data from continuous remote monitoring of construction workers' location and physiological status. To monitor construction workers activities, the authors deployed non-intrusive real-time worker location sensing (RTLS) and physiological status monitoring (PSM) technology. This paper presents the background and need for a data fusion approach, the framework, the test bed environment, and results to some case studies that were used to automatically identify unhealthy work behavior. Results of this study suggest a new approach for automating remote monitoring of construction workers safety performance by fusing data on their location and physical strain.

Keywords: construction worker behavior, ergonomics, physiological status monitoring, remote location sensing, workforce safety and health.

1. Introduction

The construction industry is continuously trying to improve work site conditions. However, in 2008, 28,340 nonfatal occupational injuries resulted in musculoskeletal disorders (BLS 2008)

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and 3,020 workers suffered from lower back pain. Among various well-known reasons, construction activities are typically characterized as physically demanding tasks that are often performed in harsh environments (Hartmann and Fleischer 2005; Schneider and Susi 1994). As a result of the continuous and repetitive exposure to physically demanding work, strains and sprains are the most common type of work-related, nonfatal injuries. Furthermore, the continuous exposure to an excessive level of physical strain can lead to physical fatigue, which may result in decreased productivity and motivation, inattentiveness, poor judgment, poor quality work, job dissatisfaction (Abdelhamid and Everett 2002), and increase in the risk of developing worker-related musculoskeletal injuries (MSIs) or cardiovascular disorders (Mathiassen 1993).

Previous research found that lower back injuries are among the most common MSIs (Hootman et al. 2002). These occur when the demand of work exceeds the capacity of a worker's body, or the worker repetitively performs heavy activities. MSIs can also be found in other parts of the body, such as the shoulders, wrists, andknees. MSIs are usually caused by overexertion, which is a leading cause of time-loss injury for construction workers (BLS 2008). An overexertion occurs when either the demand of work exceeds the capacity of a worker's body or the worker repetitively performs heavy activities. Statistics shows that more than one quarter (25.7%) of the overall disabling workplace injuries are due to overexertion (Zaidman 2008). Overexertion is not only the most common event category, but also the most expensive, resulting in $12.4 billion in direct costs to businesses. In addition, substantial indirect costs are caused through overexertion, such as (temporary) replacement of personnel and the human cost in terms of pain and/or (long-term) disability (Liberty Mutual Research Institute for Safety 2008).

Examples of injuries caused by overexertion include those related to inappropriate execution of manual material handling (MMH) tasks, such as lifting, pushing, pulling, holding, carrying, and throwing. The complex interaction of factors that determine physical load or exposure intensity makes it challenging to assess the performance of MMH activities in the construction environment (Paquet et al. 1999). The dynamic nature of construction work also makes it a challenge to measure ergonomic exposures and MMH factors systematically (Tak et al. 2011). Moreover, the Occupational Safety and Health Administration (OSHA) does not provide ergonomic standards. Instead, it utilizes a lifting guide issued by the National Institute for Occupational Safety and Health (NIOSH) (Water et al. 1994).

Since heavy load lifting frequently leads to MSI, the identification and localization of repetitive material handling activities is crucial to better understand MSI ergonomics. Previous studies suggest that ergonomic- and physiology-related attributes, such as posture, body acceleration, and heart rate can be measured using remote sensing technology. One example is Physiological Status Monitoring (PSM) technology. Commercially-available PSM devices have shown to provide reliable information during dynamic construction activities (Gatti et al. 2011). The problem with PSM is, however, that is does not record nor relate the location of a test subject wearing the PSM technology to the location where unsafe lifting events occur.

Other technology, such as real-time location sensing (RTLS) devices, exist that can deliver such location data. An example of such location sensing is the commercially-existing Global Positioning System (GPS) or Ultra Wideband (UWB) technology. Recent research in construction has shown that sufficient accuracy is provided to track construction personnel with these technologies (Cheng et al. 2011).

This paper aims at fusing data of PSM and RTLS to match physiological and location information of construction workers. The objective is to detect the workers' physical characteristic in a spatio-temporal relationship, demonstrate the capability of identifying MSI hazards automatically, map such unsafe acts to the work environment, and finally recommend changes to work site set up. The authors have conducted multiple experiments where workers were instructed to perform specific manual material handling tasks of heavy load lifting. By using a data fusion approach, the authors have synchronized and analyzed the data streams from (1) Physiological Status Monitoring (PSM) (that continuously monitors activity factors of construction workers) and (2) Ultra Wideband (UWB) technology (that records real-time worker location). This study is limited to fusing information from two specific sensing technologies (UWB and PSM). All tests were performed in a controlled study environment. Working activities that were recorded with UWB, PSM, and video camera technology occurred indoors and on the same elevation level. This study focuses only on activities associated to the construction personnel, especially, heavy load lifting. Social, legal, or behavioral impacts on workers using UWB and/or PSM technologies were not part of the scope of this study.

2. Methodology

Data fusion of real-time location tracking data and worker physical information has not been tested in construction. To fill this gap, this study evaluates the performance of a data fusion approach for UWB and PSM data. The researchers designed a novel testbed to measure and analyze the ergonomic and positioning factors of repeated material handling activities. Results to an experimental approach are presented. Opportunities and barriers using UWB and PSM data recording are discussed.

The components of the experimental test bed are illustrated in Figure 1. For later control measurement, all activities were taped with video cameras. The data analysis process is shown in the flowchart in Figure 2. Data analysis consists of four major components: work sampling, data synchronization, activity identification, and localization. An empirical approach was selected (explained later) for identifying ergonomically unsafe worker motions, for example, lifting heavy loads without bending the knees.

Since the study environment was indoors and little obstructions were present, a commercially-available UWB localization system was selected to track the real-time location of test persons participating in the test cases. UWB tags were placed on the helmets of the test persons, and on relevant static locations in the test scenery (e.g., to identify material bay, rest, and water supply areas). The UWB system itself consists of a central processing hub, which triangulates the position of the incoming radio frequency signal from multiple UWB receivers based on the Time-Distance-of-Arrival (TDoA) principle. These antennas were distributed systematically around the work environment and outside of any of the participating test person's travel paths. The UWB receivers were connected to the hub via shielded CAT5e cables and a static tag functioning as a reference location was placed in the center of the monitored area.

A variety of commercially-available PSM systems exist. PSMs can be described as non-invasive ambulatory wireless telemetry systems. They can autonomously and remotely monitor workers' physiological status without hindering or interrupting their routine activities for several hours. The system utilized in the experiment was composed by a chest belt that hosts conductive fabric sensors and module with a mobile transmitter. The selected device had the ability to perform live data transmission wirelessly through a USB radio receiver, which was connected to a data logging PC. As an alternative to real-time transmission, PSMs allow for local data logging. The selected PSM system monitored and recorded physiological and motion data using wearable electrocardiograph (ECG) sensor, respiration sensor, and a 3-axial accelerometer. It transmitted the data in real-time to the receiver via a radio frequency signal. Among various parameters, PSM measured the heart rate and the thoracic bending angle. Heart rates were deducted from ECG data. The three-axial (vertical, lateral and sagittal) accelerometer was used to generate the subject's default activity data measured in Vector Magnitude Unit (VMU). VMU was measured as a portion of the gravity acceleration (g). The system built-in module used the VMU values to derive the subject's thoracic bending angles from the 3-axis gravity compensated value calculated over the previous 1.008 second epoch. The angle was derived as a scalar with positive and negative values, where zero degree represented the vertical right-up posture.

Meanwhile, a network camera was utilized to visually record the experiments. The timeline of the video was regarded as a metric, which means the temporal information from both sensors had to be synchronized to the video time. Visual analysis of the video recording was implemented to establish a ground truth validating the result of the inappropriate posture identification.

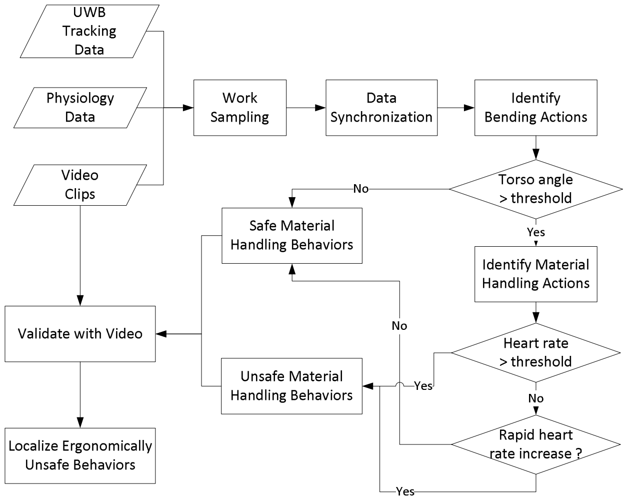

Figure 1: Testbed for experiments ***Figure 2: Locate ergonomically unsafe acts***

3. Experiment

Three experimental settings were designed to simulate construction tasks. To avoid potential interference of ambient influences, all experiments were conducted in a controlled indoor technology testbed environment. Written informed consent was obtained and the subjects were instructed about the experiment by a trained lab technician. The training covered three main topics. First, subjects were trained on how to properly wear and operate UWB and PSM. Secondly, correct material handling techniques and PPE (i.e., gloves, foot guards, knee pads, hard hat, and goggles) utilization were explained. Third, working areas and construction tasks were described. The three simulated construction tasks consisted of: (a) Experiment No. 1: Building a wall: one test subject builds a wall using 23-lb concrete blocks. One installation and one material area is available; (b) Experiment No. 2: Assembling a raised deck: one subject assembles a deck using plastic supports and 16-lb concrete tiles. One installation area and two material storage areas exist; (c) Experiment No. 3: Assembling and disassembling a raised deck: one subject disassembles a deck and stores material in a material laydown area, the other subject uses the material from the laydown area to assemble a raised deck in a second work area. Assembly and disassembly are spatio-temporal dependent activities. The subjects share two storage areas, but have their own installation area available.

4. Results and Discussions

4.1 Sampling UWB Data

The tracking data collected from UWB was sampled by the traveling speed, which was implemented to identify several zones where the subjects were (more or less) static. According to the experimental tasks, the subject had to stop when he was operating in the installation, deinstallation, material bay, rehydration, and rest areas. Hence, it was assumed that ergonomically unsafe behavior, especially bending with heavy loads, only occurs when the subject was standing or moving with very low speeds. Since the UWB tag was mounted on the subject's helmet, head motions such as nodding and shaking may result in many small to zero movements of the UWB tags (which may lead future research to install location tracking devices on the worker's clothing, preferably the belt). Moreover, subjects moved slowly within the work zone to complete the work task. A speed threshold based on statistical analysis was implemented to determine the subject's walking and staying status.

4.2 Event-Based Data Synchronization

Sensing data from multiple sensors were synchronized with the video time, where the time clock of the video was considered as the ground truth. The general principle to synchronize timelines among sensors was to compare the time clock of manually set time flags, e.g. when a recognizable event occurred in the UWB data, it should also appear at the corresponding moment in the PSM data set. Examples are entry or exit in a work zone, rapid velocity changes, and/or rapid posture changes such as bending motions.

4.3 Automatic Identification and Mapping of Ergonomically Unsafe Behaviors

Since musculoskeletal disorders were accounted for the first reason of nonfatal occupational injuries in construction, a particular emphasis was placed on identifying the ergonomically unsafe behaviors among the dynamic construction activities. Specifically in these experiments, one of the goals was to identify the working behaviors such when the subject was bending (or lifting) with heavy loads. To demonstrate how multiple sensing technologies can assist the evaluation process of ergonomic behavior, synchronized tracking and physiological data were fused. An analysis of the signal propagation pattern between heart rates and posture angles provides additional reasoning into the subject's behavior.

Safety guidelines for manual material handling state "to reduce the strain on the back, a subject should maintain a posture of the upper body as vertical as possible when lifting or placing heavy loads" (Water et al. 1994). No further official statement has been made on what constitutes a safe bending angle (most likely since a detailed determination depends upon a variety of factors, including work environment and a subject's physical characteristics). In this experiment, the subject's material handling activities are classified into two categories: safe and unsafe (see Figure 3). The individual in this figure was not a subject in the study.

Figure 3: Safe and unsafe work task

While a subject is conducting physically demanding activities such as lifting and placing loads her/his heart rate is higher than normally. According to rules set by NIOSH (2007), material handling with up-right body posture is safe. Histograms of the subject's heart rate while the bending angle exceeded 25 degrees were developed. Two Gaussian distributions were differentiated. One has the mean at 91 bpm (beats per minute) and the other at 106 bpm. The higher the heart rate value is, the more oxygen a subject consumes. High heart rates in this experiment were directly associated with a subject carrying a load. The two Gaussians connected at 99 bpm, which implies the transition between bending with and without load. The threshold was set slightly higher to 106 bpm to differentiate safe from unsafe lifting/placing motions.

Defining and applying only a heart rate threshold probably would not account for other factors that influence the heart rate, for example, subject fatigue or very fast transitions between work activities. Therefore, a pattern analysis for heart rate changes was performed. Several changes in the heart rate pattern can be noticed that correspond to the subject's posture angle: (1) the posture angles were found to be lower than the threshold value when high heart rates were observed (time span from 1,000 sec. to 1,100 sec; the subject might have already been tired due to the rapidly changing motions); (2) both the heart rates and posture angles were found at a low level or less than the threshold value (time span from 1,030 sec. to 1,050 sec.; which implies the subject's torso was in vertical up-right position and recovering to the normal situation); (3) the heart rate maintained at a high level while the posture angle increases and exceeds the threshold value (time span from 1,100 sec. to 1,125 sec.; which indicates bending motions with loads; the heart rate maintained at a high level because the body was not recovered from the previous motion); and finally (4) rapid increments were observed on both heart rate and posture angle (associated with several seconds delay: time span from 1,045 sec. to 1,052 sec.; and simultaneously, time span from 1,105 sec. to 1,110 sec.; these also demonstrate bending motions with loads). The first two patterns have heart rate and posture performance values indicating safe behavior. The last two patterns relate to unsafe work behavior.

An additional consideration to analyze PSM data might be the analysis of the slope change of heart rate values. The changing rate (slope) of the heart pulse when the subject bended more than 25 degrees consists of three isolated peaks: the first one is at 0 bmp/min, the other two peaks were at 1.2 and -1.1 bmp/min. The first peak implies that the subject's heart rate is maintaining, which indicates no physical action or idle status. The other non-zero peaks are symmetrically around the first peak representing the transitional period of the subject's heart rate from the idle status to physical active status or the other way around. Since this research focuses on unsafe behavior related to workers bending with heavy loads, the positive peak (1.2 bpm/min) on the changing rate is utilized to differentiate a physically demanding bending from normal activities.

4.4 Localization of Unsafe Behaviors

Fusing the heart rate data and the posture data from PSM provides the capability of differentiating safe from unsafe material handling activities. As one of the objectives of this research was to map unsafe acts to a work setting to assist future decision makers in designing better (ergonomically safe and healthy) work environments, the next step was to fuse the spatio-temporal data collected by UWB and physiological data. Trajectory and PSM information of one subject performing a concrete wall installation for Experiment No.1 are shown in Figure 4. The weight of each concrete block was 23 lbs. The distance between assemble and disassemble of wall was about 12 meters. The blue color in Figure 4 represents the walking paths of the subject between the installation and de-installation areas, and to/from the rehydration area. The location where the subject squatted safely is show in green. The red color denotes unsafe bends with a heavy load.

During the 62 minute long experiment, 105 ergonomically safe and 93 unsafe motions were automatically identified and mapped. Figure 5 shows the analysis of all unsafe bends over the observation time. The unsafe lifts indicated in red color relate to labor (install a concrete wall) that is physically very demanding and leads to exhausting. Manual video analysis confirmed that the subject followed more frequently safe bending practices at the beginning of the work shift. The guidelines were followed when handling heavy materials during the first 8 minutes of the experiment. Although the observation time was too short to find statistically significant results for an increase in unsafe acts over time, the number of unsafe lifts slightly increased towards the end of the work shift. Fatigue may have played a role leading to more unsafe lifts at the end of the shift.

As a general practice, work site layout could be improved. Since the worker carried the material by hand from the deinstallation to the installation area, a change to the work environment is suggested. Providing the worker with a wheel barrow or a flat cart eventually would have simplified the task and made it safer/healthier to perform. As of additional note, the subject should take frequent breaks. As the algorithm automatically found, the subject rehydrated only once at the 59 minutes into the experiment, and since the work task had already been completed, spent the remainder of the observation time at the rehydration station. The subject did not take any other break(s).

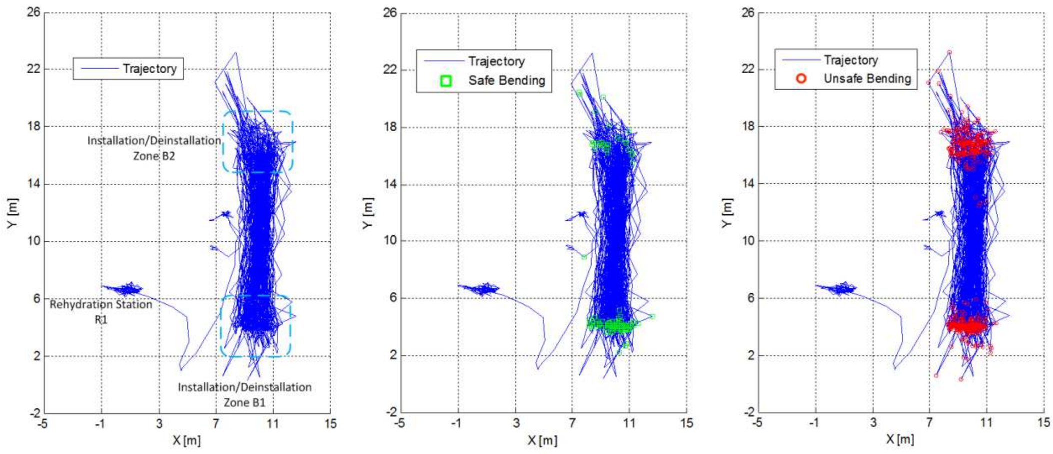

Figure 4: Localization of trajectory, and safe unsafe materials handling motions

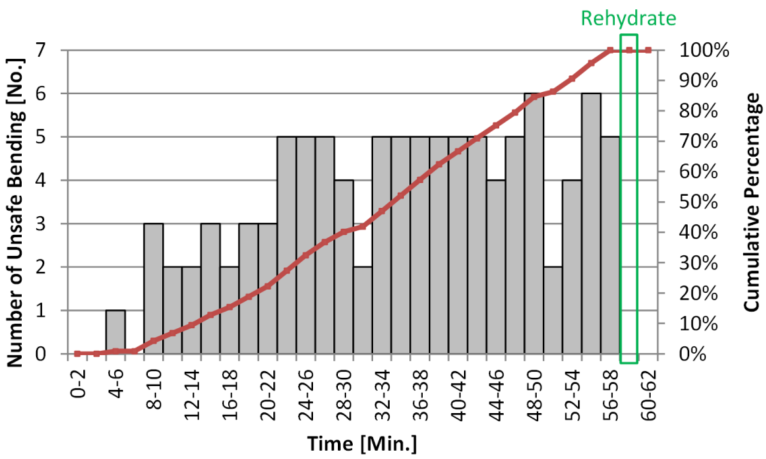

Figure 5: Unsafe bending over time

4.5 Validation of UWB/PSM Data Fusion Approach with a Video Camera

The detecting of unsafe/unhealthy material handling activities was validated through a manual analysis of the video data that was recorded for all three experiments. The analysis of work activities using video served as ground truth. The results from the video were also divided into two categories: safe and unsafe bending. Results from video and UWB/PSM data were compared against each other to conclude on the error rate of the developed automatic ergonomics algorithm. On average the data fusion approach of UWB and PSM performed accurate detection of unsafe bending with an average success rate of more than 90%.

False positive cases were due to rapidly changing postures. The utilized PSM technology yet has to be adapted to construction environment and may not have always reported a subject’s heart rate precisely. A typical example for such an event is when a subject performs several unsafe bending acts in a very short sequence of time (basically one after the other, also called rework or adjustment work to the same concrete block). As the subject does not carry a load during the second time of bending, but the heart rate is still elevated (the body has not recovered yet), the developed algorithm interprets the PSM signal as another unsafe bend. The false negative cases are another type of error, representing situations where the algorithm considers an unsafe lift as a safe motion. This error occurs because the PSM recordings of a subject are always slightly delayed (up to one second) during physically very demanding activities. A typical example is when a subject bends and lifts a heavy load, then very rapidly stands up, and walks away. As the subject's torso angle is high at the moment of the lift, the heart rate might still be slow. The developed algorithm assumes wrongly identifies a safe lift.

These two types of errors can be reduced by calibrating the physiological factors such as heart rate for each individual. Usefulness of the developed approach may also depend on improvements in technology, for example, existing PSM technology has not been configured to suit construction industry applications. Measurement error can also be solved by increasing the data collection frequency and adding a physiological response function to compensate for signal delays. Since a subject's physiology response mechanism depends very much on the individual, it will be a future research task to develop a uniform model that fits most users in the construction industry. Further study is necessary on the developed rules, such as the relationship of bending angle and heart rate, thresholds, and their interactions to precisely identify ergonomic hazards.

5. Conclusion

Rapid technological advances such as UWB and PSM technology have facilitated the monitoring of the position and physiological status of construction workers. Traditionally, data from these sources have been independently used and eventually analyzed to infer about the status of entities being observed. Using a set of experiments conducted in an indoor facility, this paper demonstrated that UWB and PSM data can be fused to automatically identify and localize the ergonomic related unsafe working behaviors. The results show that current technology is satisfactorily reliable in autonomously and remotely monitoring subjects during simulated construction activities. Partially validated through video analysis, these results suggest that data from these sources can be successfully fused to augment real-time knowledge of construction workers’ status. Nevertheless, the selected monitoring technologies show limitations that have to be addressed to fully validate the proposed algorithm. For example, the bending threshold utilized to differentiate the squat from normal posture is ambiguous because of constraints in the existing technology. Therefore, the connection between the bending threshold and the performance of the PSM in dynamic situation requires further study. Whereas this study focused on identifying occurrence and location of unsafe worker behavior, the analysis of the locations where repetitive unsafe behaviors occur could lead to identifying underlying ergonomic issues with work the environment. To evaluate this potential, the authors have planned to repeat apply the research results on a field study. In summary, the present work showed that potential construction applications of some technologies lie in the integration of various technology-specific data sources.

References

Abdelhamid, T. S., and Everett, G. J. (1999). “Physiological Demands of Concrete Slab Placing and Finishing Work.” *Journal of Construction Engineering and Management*, 125(1), 47-53.

Abdelhamid, T. S., and Everett, G. J. (2002). “Physiological Demands During Construction Work.” *Journal of Construction Engineering and Management*, 128(5), 427-438.

Astrand, P., Rodahl, K., Dahl, H. A., and Stromme, S. B. (2003). *Textbook of work physiology*, Human Kinetics, Champaign, IL.

Bureau of Labor Statistics (BLS) (2008). Case and Demographic Characteristics for Work-related Injuries and Illnesses Involving Days Away From Work, U.S. Department of Labor, Washington, DC.

Cheng, T., Venugopal, M., Teizer, J., and Vela, P.A. (2011) “Performance Evaluation of Ultra Wideband Technology for Construction Resource Location Tracking in Harsh Environments.” *Automation in Construction*, in press.

Gatti, U.C., Migliaccio, G.C., and Schneider, S. (2011). “Wearable Physiological Status Monitors for Measuring and Evaluating Worker’s Physical Strain.” *Proc., 2011 ASCE Workshop of Computing in Civil Engineering*, ASCE, Miami, FL.

Hartmann, B., and Fleischer, A. G. (2005). “Physical Load Exposure at Construction Sites.” *Scandinavian Journal of Work Environment and Health*, 31(2), 88-95.

Hess, J. A., Hecker, S., Weinstein, M., and Lunger, M. (2004). “A Participatory Ergonomics Intervention to Reduce Risk Factors for Low-back Disorders in Concrete Laborers.” *Applied Ergonomics*, 35(5), 427-41.

Hootman, J.M., Macera, C.A., Ainsworth, B.E., Addy, C.L., Martin, M., and Blair, S.N. (2002). “Epidemiology of Musculoskeletal Injuries among Sedentary and Physically Active Adults.” *Medicine and Science in Sports and Exercise*, 34(5), 838-844

Liberty Mutual Research Institute for Safety (2008). “Liberty Mutual Workplace Safety Index.” <http://www.libertymutualgroup.com/researchinstitute> (Mar. 2,2011).

Mathiassen, S. E., Winkel, J., Sahlin, K., and Melin, E, (1993). “Biochemical Indicator of Hazardous Shoulder-neck Loads in Light Industry.” *Journal of Occupational and Environmental Medicine*, 35(4), 404-413.

National Institute for Occupational Safety and Health (NIOSH), (2007). *Ergonomic Guidelines for Manual Material Handling*, National Institute of Occupational Safety and Health, Atlanta, GA.

Paquet, V., Punnett, L., and Buchholz, B. (1999). “An Evaluation of Manual Materials Handling in Highway Construction Work.” *International Journal of Industrial Ergonomics*, 24(4), 431-444.

Schneider, S., and Susi, P. (1994). “Ergonomics and Construction: A Review of Potential Hazards in New Construction.” *American Industrial Hygiene Association Journal*, 55(7), 635-649.

Tak, S.W., Buchholz, B., Punnett, L., Moir, S., and Paquet, V. (2011). “Physical ergonomics hazards in highway tunnel construction: overview from the construction occupational health program.” *Applied Ergonomics*,42(5), 665-671.

Water, T.R., Anderson, V.P., and Garg, A. (1994). *Applications Manual for the Revised NOISH Lifting Equation*, U.S. Dep. of Health and Human Services Public Health Service. NIOSH, Atlanta, GA.

Zaidman, B. (2008). *Workplace Safety Report 2006*. Minnesota Department of Labor and Industry, St. Paul, MN.