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Focus
New NIOSH programs for preventing occupational traumatic injury

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1. Introduction

Safety-and-human-factors engineering has historically included a broad array of preventive activities at the human–machine interface to prevent injury and disease. It involves the disciplines of epidemiology, engineering, life and behavioral sciences, and customarily deals with such issues as injury analysis, productivity, workplace design, postural stress, human motor performance, environmental stress, cognitive performance, and safety management. In 1991, NIOSH received a congressional appropriation to expand occupational safety and health research at its Appalachian Laboratory for Occupational Safety and Health (ALOSH) facilities in Morgantown, West Virginia. This authorization included construction funds for a new research facility and for recruitment of additional staff for conducting leading-edge research to enhance worker health and safety. NIOSH decided that a portion of this research effort should be directed at safety-and-human-factors engineering which specifically focused on the prevention of occupational traumatic injuries. A conceptualization of six research themes that will constitute the NIOSH research program for the prevention of traumatic injuries is presented.

Occupational traumatic injuries, including acute musculoskeletal injuries, pose a continuing major threat to the health and well-being of American workers. They account for a significant amount of human suffering, loss of productivity, and economic burden to employers. In 1991, the Bureau of Labor Statistics estimated six million non-fatal injuries occurred in US workplaces. These injuries resulted in approximately 60 million lost workdays (US Department of Labor, 1993). The leading causes of these injuries were overexertion, contact with objects or equipment, and falls. In addition, according to the National Traumatic Occupational Fatalities (NTOF) surveillance system, an average of 17 workers died each day from a traumatic injury from 1980 to 1989 (NIOSH, 1993). The leading causes of death were motor vehicles, machines, homicide, worker falls, electrocution, and workers being struck by objects. Construction and agriculture industries are among the industries with the highest injury and fatality rates.

It is suspected that many of these incidents resulted from a poor interface between the worker and the work environment, machines, and tools. To

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develop effective preventive technologies we require better understanding of human sensory and strength capabilities, anthropometric characteristics, and cognitive and behavioral responses to hazardous work situations. Increased understanding of these human factors will contribute to the evaluation, design, and development of new and improved safety engineering systems and controls, work practices, and personal protective equipment to protect workers from acute traumatic injury.

2. Mission and strategies

The mission of the NIOSH safety-and-human-factors-engineering program is to conduct research in laboratories, simulated workplaces, and actual workplaces to identify effective approaches to increase worker performance and to promote the proper use of engineering controls to prevent workers from traumatic injuries.

In order to ensure the success of this mission, DSR has proposed the following main strategies: (1) establish state-of-the-art research laboratories to facilitate research; (2) collaborate with partners and stakeholders to identify problem areas, conduct research, and develop products/methods to reduce the exposures of workers to hazardous environments; (3) develop models/hypotheses of injury processes and validate the models through laboratory-and-field-based studies, (4) focus initial research efforts on the construction and agriculture industries; (5) convey the identified/validated safety knowledge and technologies to safety professionals; (6) transfer research results into practical applications and lay-language for employers and employees.

The Division has proposed a systematic approach for safety-and-human-factors-engineering research. The approach uses injury surveillance systems, such as the National Traumatic Occupational Fatalities (NTOF) system and the National Electronic Injury Surveillance System (NEISS), along with the Fatality Assessment and Control Evaluation (FACE) program to identify target occupations for research. The NTOF surveillance system is a census of traumatic workplace fatalities occurring in the US (NIOSH 1993). The system uses death certificates as the source of fatality data. NEISS is maintained by the Consumer Products Safety Commission (CPSC). Through a collaborative effort between NIOSH and CPSC, data on work-related injuries that were treated in hospital emergency departments can be collected to describe injury circumstances. The FACE program is conducted by the NIOSH Division of Safety Research. This program collects epidemiologic data from investigating selected occupational fatalities to identify factors that may increase the risk of work-related fatal injury.

Targeted occupations are investigated for the prevalence of safety hazards by epidemiologists and engineers to identify the critical elements that contribute to the traumatic-injury incidents, near-miss incidents, or stressful tasks of the occupations. Engineers then work together with partners to identify and evaluate task characteristics, perform computerized simulations, conduct laboratory and field studies, develop engineering control strategies, introduce new designs, and evaluate the efficacy of the new systems.

3. Research themes

The Division has proposed to organize the new research efforts for traumatic injury control around six themes. These themes were identified from studies of occupational injury databases and reviews of current safety engineering and human factors research literature (Hsiao and Stanevich, 1996; NIOSH, 1993; US Department of Labor, 1993; DHHS, 1991). These research themes have been selected to (1) address the most compelling occupational injury problems, (2) advance the understanding of traumatic and acute musculoskeletal injury mechanisms, and (3) to develop prevention strategies to reduce the risk of work-related trauma. The themes are described below.

3.1. Stress exposure assessment and measurement: Developing advanced methods for hazard exposure assessments

Technologies to measure human responses (e.g., video image analysis, heart rate monitoring, electromyography examination, postural stability, and others) have been widely used in health care settings to investigate human health conditions. Recently, field investigators and laboratory researchers have started to use the same technologies to quantify the stress and safety exposures of workers in the workplace. However, industrial work frequently involves widely varying tasks and environmental factors that make quantitative exposure assessments of industrial worker stresses and safety extremely challenging. So far, very few methods have been developed to identify the critical task elements that contribute to the overall human stress or safety hazard exposure.

This program will develop an advanced remote monitoring system for stress/hazard-exposure assessments. The system should allow researchers to oversee, quantify, and correlate job activities and hazard exposures by video, electromyography, heart rate, energy consumption, and other measurements in a real-time and synchronized manner. This monitoring system will lead to identification of the most pressing problems and the critical task elements that contribute to occupational injuries and physical stresses in a variety of industries and occupations. The information is important for the development of engineering controls to address worker stress or safety hazards. The Division's final goal for the program is to develop simplified models of injury/incident processes. These models will be validated through laboratory-and-field-based studies. For example, these remote biomonitoring systems/models could be used to evaluate ironworkers' physical stresses and fall exposures at different steel-erection phases and at different heights. Therefore, more effective measures to reduce their injuries can be developed and implemented.

3.2. *Computerized anthropometry research and evaluation: Improving the fit of workplace systems to workers*

Anthropometry is the empirical science that defines physical measures of a person's size, form, and functional capacities. In occupational injury prevention applications, anthropometry measurements are used to evaluate the interaction of workers with tasks, tools, machines, vehicles, and personal protective equipment. These data (i.e., size, body segment volumes, and mass) need to be collected as part of the design process. Most of the current anthropometry data were taken from military populations. Reliable information on anthropometry of civilian, female, minority, and occupational populations is nonexistent nationally.

This program will establish fundamental human-form databases of US workers. A state-of-the-art 3-D laser scanning system (a whole-body scanner, a facial scanner, and a hand scanner with graphic computer workstations) will be utilized to accurately reconstruct human images and create the database. This new technology will advance anthropometry measurement in a highly quality-controlled and time-efficient manner.

This program will initially focus on construction and agricultural applications. These data will contribute to better design (e.g., sizing, functionality, and comfort) of construction tools, eye protection, protective clothing, fall-protection devices, and other equipment. In addition, the data will provide fundamental information for occupational biomechanics which is essential for the development of strategies to prevent traumatic injuries and musculoskeletal disorders. The data can also be used in human modeling applications for evaluating high-risk job activities, thereby reducing the involvement of human subjects in studies of hazardous environments.

Initial efforts will develop optimal facial and hand models for designing eye/head/face/hand protective equipment, and will develop optimal whole-body models for designing fall-protection equipment. Expected outcomes include development of standard procedures for computerized anthropometry measurement, determination of target measurements of the hands and full body for glove and fall-protection harness evaluation, and establishment of sampling strategies. The final products of this project will be anthropometry databases of US construction and agricultural workers and sizing recommendations for a variety of personal protective equipment.

The study will be extended to support computerized human modeling applications to determine (1) the optimal clearance of roll over protective structures for farm tractors, (2) the optimal height and step clearance for construction vehicle access systems, (3) the optimal width of ladders and distances among ladder runs, and (4) the appropriateness and limitations of children and older workers operating various machinery and other injury prevention efforts. Inter-institutional collaborations with trade associations, construction unions, research institutes, and partners are currently in progress.

3.3. *Multifactorial assessment research on construction hazards: Evaluating synergistic stresses of construction tasks*

Construction workers are frequently exposed to various types of hazardous energy, such as electrical energy, hot and cold environments, tasks involving machinery, manual handling of bulky and heavy materials, or whole body vibration. At present, the interactive or synergistic effects among biomechanical, environmental, physiological, and psychological factors upon construction-worker populations are unknown.

This program will utilize exposure-assessment technologies in both field and laboratory studies to assess these job risk factors and to quantify the synergetic effects among them. Studies will include biomechanics, kinematics, heat stress, postural stability, manual dexterity, motor response, and perception issues. DSR's initial goals are to develop practical information for (1) preventing injuries during manual handling of large-size materials, (2) the safe erection, dismantling, and use of frame scaffolds, (3) safe drywall installation, and (4) preventing heat stress. While the program will initially emphasize the construction industry, it is expected to be a continuing program that will address agriculture and other industries in the future.

3.4. *Simulation and analysis of fall exposure: Understanding and reducing the fall hazards at workplaces*

Falls from elevated work surfaces are one of the major causes of occupational injuries and fatalities. This program will study fall injury characteristics, risk factors (basic causes) for occupational falls, and fall exposure assessment technologies, as well as develop new fall-prevention technologies.

The initial investigation phase in this program will concentrate on construction fall research and prevention. This effort will systematically study construction activities, human capability, and human–environment–tool interactions, as well as existing fall-prevention technologies. Instrumented manikins will be used to study body property behavior, such as impact-energy transfer, fall patterns, and the impact of fall-protection equipment on the human body. In addition, construction activities will be simulated in a large-scale computer-aided virtual environment using a mini-super computer and a kinematic measurement system to study human behavior and human physical responses during elevated work. The contribution of energy expenditure, whole-body vibration, biomechanical stress, perceptual and decision-making skills, footwear and floor materials, and postural stability to occupational falls will also be assessed. With this information, computer simulation models to evaluate/predict fall potentials will be developed and validated. Fall-prevention methods and fall protection technologies will then be developed accordingly.

Initially, the Division will focus its research on (1) developing improved ladder designs, (2) establishing a computer-aided virtual environment system for simulating and evaluating construction work at elevations, and (3) developing improved fall-protection technologies.

3.5. *Computer-aided equipment design and research: Developing appropriate equipment for jobs*

Engineering improvement of equipment can reduce the risk of occupational injuries. This research program will evaluate the human–equipment interface to improve the safety and performance of existing tools, machines, and safety devices. System safety analysis and human–equipment interface models and software will assess the safety, feasibility, and efficacy of the proposed designs and modifications. Final prototypes will be produced via computer numerically controlled (CNC) machine tools. The division will begin this program by evaluating construction tools and personal protective equipment, as well as developing safe construction vehicle access systems and tractor rollover protective structures (ROPS). Inter-institutional collaborations with equipment manufacturing industries, construction trades, and other partners have been initiated.

3.6. Solutions for urgent or priority problems of occupationally related tasks: Technical support for hazard evaluations and control development

DSR has been frequently called upon to provide technical assistance and consultation to other components of NIOSH, other Federal agencies, and public and private organizations on the investigation of injuries and the use of protective technologies to reduce exposures to safety hazards that lead to injuries. This program is proposed to meet such needs for technical assistance and consultation. Activities of this program may involve either field-site observations or laboratory tests of current or prototype safety devices and equipment. They may also include identifying, recommending, and assisting occupational safety and health personnel in introducing mechanical and electronic devices or systems for preventing injuries in the workplace. DSR will focus its support efforts on traumatic injury investigations and prevention, as well as on the reduction of whole-body overexertions due to the handling of large materials.

4. Laboratories

The programs will utilize seven laboratories which are described below:

4.1. High Bay Laboratory

The 1050 square foot (30 by 35 ft by 37 ft high ceiling) High Bay Laboratory will host efforts to reduce fall-related injuries and to improve the safety of large industrial, construction, and agricultural equipment. The lab is equipped with a 5 t bridge crane and will house a test bed and hydraulic power supply and actuator system. The 10 by 15 ft, 7 in thick cast steel test bed is composed of four sections, so that the bed can be positioned by the overhead crane. T-slots in the bed surface provide for the attachment of equipment under test. The hydraulic power system features a 10 gpm pump and two 22,000 lb actuators. The actuators can be fully controlled through a personal computer to produce loadings, deflections, or vibrations of desired amplitude and frequency.

Studies of scaffolding systems and ladder stability will benefit from the lab's 37 ft ceiling. Dynamic loading on the anchorages and straps of fall-restraint equipment will be produced by the free-fall of an instrumented manikin from a catwalk area above the main lab area or from scaffolding systems erected on the lab floor. The integrity of scaffold, ladder, and fall protection components can also be tested using the hydraulic actuators. Other studies will include strength analyses of alternative protective structures for industrial equipment. These studies will utilize strain gage transducers or accelerometers mounted at locations identified in computer simulations. The High Bay Lab will also house a graphical mini-super computer in a separate area at the rear of the lab.

4.2. Human Factors Laboratory

The Human Factors Laboratory is a unique facility for research in the areas of biomechanics, applied physiology, and industrial psychology. The 1200-square-foot (30 by 40 ft) laboratory has a 17 ft. high ceiling to permit the study of a variety of work practices. The lab environment can be controlled for temperature (35°F to 95°F, ± 3°F), humidity (30–95%, ± 5%), and lighting (completely dark to 100 footcandles).

This laboratory will be equipped with a video-based motion measurement system and an infrared camera-based motion measurement system, two force platforms, electromyography (EMG) and electrocardiography (EKG) instrumentation, energy consumption instrumentation with telemetry, a treadmill, and other equipment. Each of the motion measurement systems will use five cameras – one in each room corner and one overhead. The infrared camera-based motion measurement system automatically calculates body positions, velocities, accelerations, and interfaces directly to prediction programs for the calculation of joint forces. These features make the system ideal for the rapid analysis of motions where all the body markers are visible throughout the movement. For movements during which markers become hidden, images from the video-based system will be manually digitized to complete the data set. The force platforms will rest on a sunken concrete pad so that the plate surface is in level with the floor surface. The supporting pad is isolated from the rest of the floor to reduce the effects of building vibration. Signals from the motion measurement systems, force platform, and the EMG and EKG systems will be synchronized for accurate correlation of the data sets.

The Human Factors lab will support studies of postural stability, human motor and mental response, machine safety, acute musculoskeletal injuries, and specific heat stress evaluations. An additional 110-square-foot area adjacent to the High Bay Laboratory computer room and the Human Factors Lab will be a virtual-environment-development work area. This central location, between the High Bay and the Human Factors Laboratories, will facilitate the development of virtual-work environments by directly connecting the graphical mini-super computer system to work environment mock-ups in either lab.

4.3. *Protective Systems Laboratory*

The Protective Systems Laboratory will host efforts to develop improved designs for agricultural, construction, and industrial equipment; sensor and instrumentation systems for measuring work stressors; and computer-aided design, modeling, and analysis methods. This 800-square-foot (20 by 40 ft) facility will house UNIX-based graphical computer workstations and sensor-systems-development instrumentation.

Equipment for developing sensors and tests includes digitizing oscilloscopes, function generators, digital voltmeters, and computer workstations. Computer workstations will be connected to the building's network through a 100 Mb/s Fiber Distributed Data Interface (FDDI) network. Computer-aided design and other software will be used for drafting, 3-D drawing, and solid modeling. A finite element analysis software program will be used for strength, vibration, heat transfer, and fluid flow analyses. Mechanical dynamic-simulation packages will be used for force, acceleration, and velocity analyses.

The graphical workstations and computer-aided-design software will be used to improve the safety of industrial equipment. Finite element and dynamic-simulation software will be used to analyze these designs, gain a better understanding of the design, and reduce the need for extensive physical testing. The electronics test and sensor-systems-development instrumentation will be utilized for the development of integrated sensor systems.

4.4. *Computerized Anthropometry Research and Evaluation Laboratory*

The Computerized Anthropometry Study and Evaluation Laboratory is a 600-square-foot (20 by 30 ft) facility for the development of an anthropometric database of the US working population and for improving the ergonomic performance of safety equipment and industrial tools. This laboratory will house three laser-based scanning systems, two UNIX-based graphical workstations, and a subject change room.

Each of the three scanners housed in this laboratory serves a different purpose. The largest of the three is a whole-body scanner, which will produce an image of the human body surface with a 3 mm resolution. A head scanner with a 0.7 mm resolution will provide increased accuracy for facial features. A 0.7 mm resolution is also available on the third scanner, which will be used to produce surface images of hands, hand tools, and any other mechanisms that can fit in the scanner system's field of view. One UNIX workstation will be used to control and process images from the whole-body scanner; the second workstation will perform these functions for the head scanner and the hand and product scanner.

The scanning systems will provide anthropometric data for the development of an occupational anthropometric database. The hand and product imaging platform will provide accurate images of safety equipment, tools, and tool components for the rapid development of prototypes. Importation of these images into computer-aided-design software will accelerate the equipment development.

Specific examples of how this technology may be applied include the use of representative facial forms to test and improve the fit and function of respirators and eye protection, and verification or improvement of reach and positioning guidelines for equipment controls, operator stations, and guarding standards.

4.5. Functional Capacity Evaluation Laboratory

The Functional Capacity Evaluation Laboratory will host equipment for physiological and biomechanical evaluations of human subjects. This 300-square-foot lab (20 by 15 ft) will house a work simulator (10 ft by 10 ft by 7 ft 6 in high), a lifting evaluation system (10 ft by 10 ft by 7 ft 6 in high), and a computer workstation.

The work simulator and lifting system will allow researchers to perform simulations of jobs and to determine biomechanical hazard exposures. Tasks can be simulated by selecting a protocol and tool attachments which allow workers to assume the postures and motions required in the performance of the desired tasks. Both static localized muscle functions and static whole-body exertions can be tested using existing attachments. Muscle function analyses and whole-body exertion evaluations can also be performed through dynamic strength-testing protocols on both machines. This lab will serve as a human-subject-strength test station for most biomechanically related projects.

An additional area adjacent to the Functional Capacity Evaluation Laboratory will be a virtual reality simulation space. The space will host efforts to understand human behavior, physical responses, and decision-making skills during elevated work as well as to investigate fall risk factors, injury processes, and fall prevention technologies. The laboratory will be equipped with a graphics projection system and semi-spherical screen (or cave screen) for creating virtual-work environments. Head-mounted virtual reality simulation tools and software are also available.

4.6. Vibration Research Laboratory

The Vibration Research Laboratory, a 240-square-foot facility (20 ft by 12 ft) will be used to investigate vibration effects on human postural stability, performance, and stress. The research will be conducted using a vibration generator and motion monitoring systems to investigate the effects of vibrations on workers under simulated and controlled laboratory conditions.

The vibration–generation system creates bidirectional sine and random vibration motions, one direction at a time. The system is composed of an electrodynamic shaker with a mounting table for vertical vibration and a slip table for horizontal vibration, a power amplifier to provide the driving current to the shaker, a computer workstation to control the power amplifier, and two accelerometers to monitor the vibration. The system provides up to 4G acceleration on a maximum 250 kg payload. The size and the capacity of the vertical slip tables will accommodate a vehicle seat and a human subject for conducting whole-body vibration testing. A force plate will be used to evaluate the worker's postural stability and motor performance before and after vibration exposures. A seat pressure measurement system will be used to determine seat cushion and suspension designs that will not impair circulation or produce leg fatigue.

The Vibration Research Laboratory will allow the study of the effect of whole-body vibration frequency, acceleration, velocity, magnitude, direction, and period of exposure on physiological and psychological disturbances. Potential studies include investigations of the effects of long-term construction vehicle vibration on human balance, the effects of horizontal whole-body vibration on vision, and the effects of whole-body vertical vibration on human ability for fine manual control.

4.7. Engineering Video Editing Laboratory

The Engineering Video Editing Laboratory will host human performance evaluation and research efforts for the Division. This 200-square-foot (10 ft by 20 ft) laboratory will house a nonlinear video editing system. The video-editing system will be used for the ergonomic analysis of postures and motions. Video footage from the field will be digitized by this system. Once digitized, individual frames demonstrating work practices of interest can be examined without distortion. Appropriate video segments will be organized, stored in digital format, and exported for further analysis by supplemental programs such as strength prediction programs and velocity and force analysis programs.

This laboratory will also provide room for the assembly and testing of video equipment and other computer-based data collection systems. Many of the planned safety-and-human-factors-engineering studies will involve the collection of physiologic data simultaneously with video. Preserving the synchronization of such data throughout the analysis is expected to provide insight into work stressors.

4.8. Human resources

It is expected that a multidisciplinary team of scientific, technical, and administrative support personnel will staff the injury control research efforts described in this paper.

5. Summary

With the opening of a new laboratory facility, NIOSH is expanding its safety-engineering-and-human-factors research efforts on traumatic injury prevention. The mission is to conduct research in laboratories and simulated and actual workplaces to identify effective approaches to increase workers' safety performance and to promote the proper use of engineering controls for protecting workers from acute traumatic injuries. Six research themes and seven laboratories have been proposed. Partnerships with industries, workers, academia, research institutes, and others are a vital component of preventing workers' traumatic injuries. NIOSH will continue its "visiting scientist" program and other collaborative methods to make the laboratory facilities available to external research groups. In addition, external peer review of proposals and research progress continues to be an essential process for the NIOSH traumatic injury prevention program.

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