SENSING CONSTRUCTION WORK-RELATED MUSCULOSKELETAL DISORDERS (WMSDs)

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ABSTRACT: Much of the developed world's construction workforce is increasing in average age, and yet construction workers typically retire well before they reach the age of sixty. One reason is that their bodies are worn out because of the nature of the work. We therefore face the challenge of both reducing their physical stress and increasing their productive work life, if we wish to avert an economic and social crunch given the demographic trends towards an aging population in most developed countries. In particular, recent statistics from the U.S Department of labor show that 6.9% of all Work-related Musculoskeletal Disorders (WMSDs) among workers in 2008 affected shoulders; this percentage becomes much larger for electricians, carpenters, and related construction crafts. The cost to our industry and to society is huge, and it is unnecessary. Reduction of certain types of movements and improvements in posture can result in reduced rates of shoulder WMSDs and in extended work lives. This can be done with a combination of robotics, work re-design, and work monitoring. This paper provides the statistical background and economic analysis that supports the scope of the problem, presents background on the kinematics of shoulder movement, and explains the biomechanics and causes of shoulder injuries. Then, preliminary results are presented for a prototype of a simple, low-cost, sensing solution for automatically monitoring undesirable movements and patterns of motion. It is expected that this could be broadly implemented to help reduce Construction Work-related Musculoskeletal Disorders (WMSDs).

Keywords: *Robotics, Construction, Workers, Ergonomics, Musculoskeletal, Wireless, Fatigue, Gerontechnology*

1. INTRODUCTION

Construction injuries are costly to workers' health, to projects, to constructors, and to the economy. Therefore, many organizations [1] have tried to limit the number of injuries among workers through: establishing guidelines and manuals on how to perform specific tasks [2], funding research to investigate injuries causes and effects, organizing seminars and workshops to educate workers and employers, redesigning work tasks, and developing technologies such as robotic rebar tying machines, exoskeletons [3], and sensing systems [4].

Many of the manuals, guidelines, and suggested methods to solve the problems, are not applicable in the field because of workspace complexity, industry fragmentation, psychological barriers, and the effort required to manually monitor whether correct procedures are being followed at the work site. Therefore, there is a need for devices that can monitor actions leading to WMSDs without: interfering with the workers, delaying the workflow, resulting in negative psychological feedback, or costing too much. At the same time those new methods have to be accurate and reliable as they will become important sources of information to indicate whether a particular worker is being exposed or is subjecting himself to potential WMSDs, or whether a construction activity, such as attaching ceiling soffits, is destructive to workers in the way it is being done.

In this preliminary research, we focus on Work-related Musculoskeletal Disorders (WMSDs) related to shoulder injuries, since this type is one of the major injuries that affect a worker during his/her work life. Recent statistics published by the US Bureau of Labor Statistics (BLS) [5], showed that 6.9% of all injuries among workers in 2008 affected shoulders. We believe that this large number of injured workers can be significantly reduced, thus avoiding costly treatment and economic losses, by managing workers exposure to certain stressful or awkward positions and activities.

There is a tremendous amount of health, human factors, and biomechanics research focused on upper extremity injuries that include neck, shoulders, and arms. One of the first steps in the research described here was to identify the problems related to shoulders; identify the causes of those injuries; and understand how workers develop shoulder injury. The literature was analyzed to identify the dominant injury classes and their causes. We deduced that monitoring a critical range of shoulder angles, for construction workers in particular, would indicate the key causes of shoulder related WMSDs in those workers. A low cost sensing system designed for this purpose is described, and its performance is partially validated, in the last section of this paper. Results from human subject testing are forthcoming shortly.

2. ANALYSIS OF SHOULDER INJURIES IN CONSTRUCTION

Definition of Musculoskeletal Disorders (MSDs) is still a debate, which accentuates the importance and the severity of the problem. One of the complications in dealing with MSDs is the fact that MSDs have many definitions in the literature. The National Research Council (NRC) definition is, "The musculoskeletal conditions that may be caused by (non-accidental) physical work activities include disorders of inflammation, degeneration, and physiological disruption of muscles, tendons, ligaments, nerves, synovia, and cartilage involving limbs and trunk. These entities are included in categories 353-355, 722-724, and 726-729 of the International Classification of Diseases (ICD-9)." [2] NRC made a conditional statement that, MSD cases may not result from accidents, this condition can be waived knowing that we are defining MSDs as a general term not due to certain cause. A subdivision of MSDs is called Work-related MSDs (WMSDs), which refers to any MSD that was caused by working circumstances or activities.

We focus on the shoulder, as explained later, because this is the part of the body experiencing the worst MSD's in construction. Shoulder refers to the synergetic muscles, tendons, and joints that work together allowing full motion of the upper arm around the shoulder joint. It consists of two bones: the scapula and clavicle. Musculature of the shoulder includes trapezius, pectoralis, deltoid, and latissimus. Shoulder pain is any kind of pain that reduces the ability of a person to perform the full range of arm motions, namely:

- flexion and extension in the sagittal plane,
- abduction and adduction in the frontal plane, and
- internal-external rotation in the transverse plane.

Shoulder pain can be classified into four basic categories: shoulder impingement, tendonitis/bursitis, instability, and arthritis.

Since this work deals mostly with worker's posture, a brief definition of the terms used to describe them is in order. Overhead work is the situation where a worker performs tasks that require lifting his/her arm to reach locations above the worker's head level. An, "awkward position," is a posture that scientific evidence indicates within which work will increase the likelihood of sustaining injury to the shoulder.

Musculoskeletal Disorders formed 29.44% of all cases that required days out of work in 2008 in the US [5]. This percentage reflects the level of danger that WMSDs, arising from various causes, pose to workers in all fields. The median days out of work due to shoulder injury was 20 days, which ranked it as the WMSD injury requiring the longest period of time to heal, [5] indicating that shoulder injuries were particularly debilitating to the worker and the work progress. On the other hand, Frost et al. [6] reported that the prevalence of upper extremity injuries among workers in jobs that require overhead work rose within their first 5 - 8 years on the job, decreased, then rose again after spending more than 25 years on job. These results, which are in agreement with BLS data on WMSDs, indicate that upper extremity injuries are cumulative in nature, since they appear as an outbreak after 5-8 years on the job. Workers who acquire proper technique to reduce the risk factors of work-related musculoskeletal stress do not suffer that outbreak accounting for the drop in those injuries beyond 5-8 years on the job. Literature review indicates a pattern of prevalent upper extremity WMSDs among construction workers who spend significant time working in overhead postures due to risk factors accumulating over time rather than individual or discrete incidents.

Four main risk factors are cited in the literature as causes of shoulder WMSDs. A review by NIOSH was conducted in 1997 of evidence to the relationships among movement types, occupations, and shoulder WMSDs [7]. The study reported that the most frequently cited causes for Shoulder WMSDs were: highly repetitive work, vibration, sustained awkward posture, and forceful work [8-12]. Considering the level of significance of the relationship between those factors and shoulder WMSDs, it was concluded that available evidence did not justify considering highly repetitive work and vibration as major causes for shoulder WMSDs [7]. Furthermore, the prevalence of shoulder WMSDs was low in occupations where forceful work was not combined with awkward postures. Since most construction-related occupations involve forceful work, sustained awkward postures are likely to cause shoulder WMSDs among construction workers.

In defining awkward shoulder-posture in this project, we tried to balance elimination of those postures with the strongest evidence as risk factors while retaining the worker's ability to perform tasks efficiently. Three definitions are available in the literature for an awkward posture. The first considers positions where the upper arm lies at an angle larger than 45 degrees with respect to the torso as an awkward shoulder-posture. The second definition considers arm elevations between 60 – 120 degrees to lie in a dangerous work envelope. The third definition considers arm elevations of more than 90 degrees as an awkward shoulder-posture. The first definition [10] is based on biomechanical and epidemiological studies. The second definition [11] is based on pathological studies of localized muscle fatigue. The third definition [13] is based on biomechanical modeling and estimation of the forces and moments in shoulder joint. Therefore, all evidence agrees that shoulder postures where the arm lies at angles larger than 90 degrees to the torso are awkward.

On other hand, analysis of construction industry requirements indicates that minimizing the time workers spend in awkward postures is feasible, since:

- Most construction tasks can be done with an arm below 90 degrees of elevation.
- Where that is not possible, most workplaces can be redesigned to allow workers to perform their tasks while the arm is elevated at angle below 90 degrees.

Therefore, avoiding awkward shoulder postures will not affect productivity noticeably while minimizing Shoulder WMSD's.

In agreement with these conclusions, Svendsen et al. found that in 3.9% of all supraspinatus and in 18.3% of shoulder pain without disability cases, a worker was performing 6-9 % of his/her tasks above 90 degrees of elevation [14]. In the same study, the researchers found 5.4% of all Supraspintaus cases and 15.3% of all shoulder pain cases without disability were among workers who have spent more than two years performing tasks requiring arm elevations above 90 degrees [14].

This study proposes the use of a programmable angle sensor to track the worker upper arm motion. The sensor stores this data which upon post processing can be used to determine: (a) whether a particular worker has exceeded a threshold per month of hours spent in awkward shoulder-posture, or (b) that a job, as designed, cannot reasonably be carried out by a typical worker without exceeding safe time limits in awkward positions.

3. EXTERNAL MUSCULOSKELETAL JOINT SENSOR SYSTEM DESIGN

Over the years, researchers have used many techniques to track the movement of the human body in real time and off line. However, many of those techniques cannot be implemented for worker protection in an industrial setting. Gyroscopes and accelerometers require complicated post-processing and are error prone to drift over extended monitoring sessions. Motion capture techniques interfere with the work flow at a work site. Ultra-Wideband and Ultrasonic sensors are prone to interference with their signals in an un-structured work site. Further, the accuracy of their measurements is inadequate for the purposes of motion analysis. The use of a magneto-resistive angle sensor to measure human joint angles presents a unique solution for this problem combining accurate measurements, low-cost, and applicability to wide-scale field deployment.

The magneto-resistive angle sensor detects the change in the orientation of a magnetic field using the property that certain permalloys change their resistivity when exposed to an external magnetic field depending on the direction of the field lines [15]. As a result, it can be used to determine the orientation of magnetic field flux lines as they change over time. Magneto-resistive sensors are usually used in the field of mechanics. For example, they have been used to count the rotations of a bearing system over time [16]. In this application, the sensor consists of two main parts; a magnetic field source (permanent magnet) attached to a moving frame and a sensing element attached to a reference frame. As the moving frame rotates, the sensing element measures the change in the field line orientation over time and, thus, the relative angle between the moving frame and the reference frame.

The main component of the proposed External Musculoskeletal Joint Angle sensor system is the sensing element; a programmable KMA200 angle sensor. In addition, it uses an electronic control unit to acquire data from the sensing element, a memory card for data storage, power supply, external magnetic source to ensure saturation-level magnetic flux, and an external case to maintain the physical integrity of the system in the field. The magnetic source used is an off-the-shelf magnet with an intensity of 5000 Gauss to meet the requirements of the KMA200 angle sensor [15] for saturation level internal magnetization. The control unit employs a Microcontroller Unit (MCU PIC18F4550/ PIC18F87J50) for the bench-top and the portable versions respectively to communicate with the sensor in both digital and analog modes and to send commands and read data. The power supply is composed of a 5V battery and a voltage regulator

Because the sensor used in this project cannot withstand shocks, as the wiring and the IC element might broken if touched or hit by an object, the sensing element is packaged in plastic coating as shown in Figure 1 and connected to the electronic circuit so as not to interfere with the worker movements and to guard against entanglement with the surrounding objects, tools, and other workers in the field. Wires were grouped as a bundle and then attached to the worker's body by tape extending from the sensor to the external case that includes the control unit.

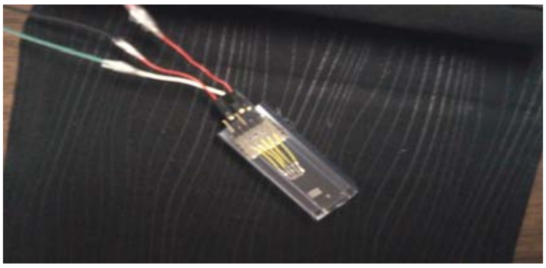

Fig. 1 Packaged KMA200 sensing element

For initial field trials, the rest of the sensor system is enclosed in 12 x 8 x 6 cm lightweight steel box as shown in Figure 2. It contains the MCU, SD memory card, and the rest of the components as shown in the figure. This box is to be mounted on the worker's belt. Although the current dimensions are fairly large, the system can be easily miniaturized for mass production.

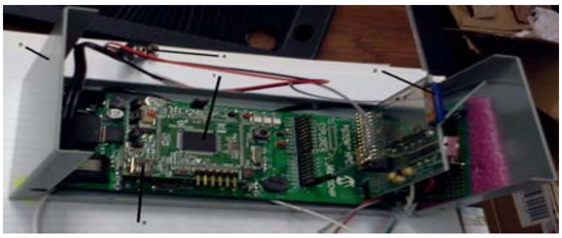

Fig. 2 Components inside the processing unit

Using Velcro tape, the sensing element and the magnet are tightly mounted on the torso and the upper arm, respectively, to eliminate movement artifacts due to clothes as shown in Figure 3. Once mounted in their respective positions, they describe the relative angle between a moving arm frame and a reference torso frame. When the upper arm moves from zero degree flexion towards 180 degrees flexion, the flux lines of the magnet mounted on the upper arm rotate with the same angle. As the flux lines rotate with the upper arm, the sensor detects the change in angle of the flux lines and converts it to an angle from 0 to 180 degrees.

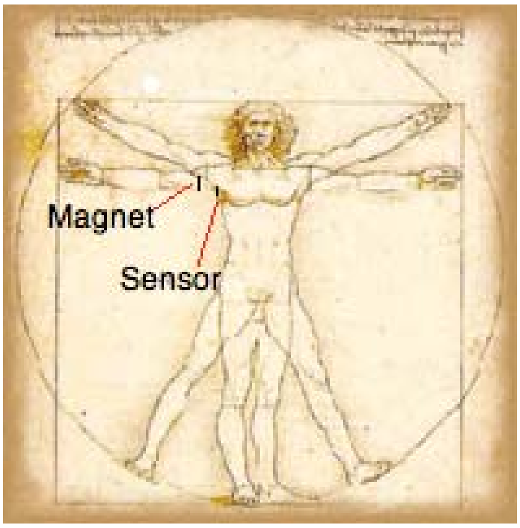

Fig. 3 Sensor mounting configuration

A limitation of this prototype is that it can only measure movements in one plane, the sagittal plane in this case. Measurement of this two-dimensional angle is adequate for the safety of workers in the construction trades since these jobs mainly involve postures in the sagittal plane rather than the frontal plane. Therefore, the two-dimensional sensor prototype is adequate in this case. The sensor system will then be upgraded to measure the full-three-dimensional joint angles required for other, more complex, applications.

4. RESULTS OF BENCH-TOP TESTS

A bench-top version of the External Musculoskeletal Joint Angle sensor was developed as a proof-of-concept. A stepper motor was used to provide a known angle signal. A permanent magnet was attached to the shaft of the motor and placed at a distance of 3 cm above the KMA200 angle sensor using a stationary bracket. The motor was commanded to perform 100 steps in 105 seconds. At a step size of 1.8 degrees, this command corresponded to the sensor full range of motion, 180 degrees. The angle measured by the sensor was recorded using a computer. The sampling rate was set to 103 samples per second.

The ideal time-history of the stepper motor angle (angle versus time) is a staircase-like curve. The angle measured by the sensor is shown as a function of time in Figure 4. The angle-time curve has the expected staircase shape. Two types of noise are detected in the measured signal:

1) Measurement noise due to the sensor observed during the period of time when the stepper motor has come to rest (the horizontal segments of the staircase), and
2) Process noise due to backlash in the motor, observed during the vertical segments of the staircase and as the motor settles down to the desired angle.

The motor was allowed to settle down after each step and the mean measured angle was calculated for each step and is shown in the Figure 4.

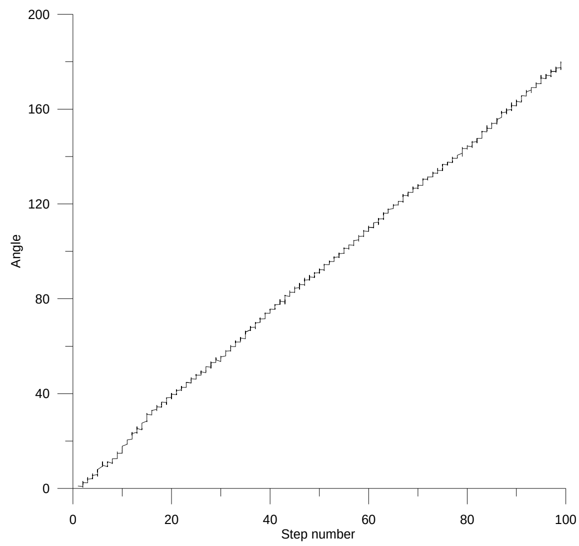

Fig. 4 Mean angle for 180 degree rotation

Only measurement noise is relevant to the sensor system since it corresponds to the sensor system resolution. The data sheet of the KMA200 programmable angle sensor [15] specifies a resolution and an ability to detect angle changes, as small as 0.05 degrees. The standard deviation for each step was calculated to range from 0.12^0 to 0.34^0, which corresponds with the reported sensor resolution. This accuracy level is quite adequate for the purposes of measurement and quantification of human movement. This is particularly the case, since the line between safe and awkward postures is not discrete.

4. CONCLUSIONS AND RECOMMENDATIONS

Bench-top and field prototypes for a simple, low-cost, and robust External Musculoskeletal Joint Angle sensor were developed. The field prototype is appropriate for monitoring undesirable motions and patterns of motion at work sites. The sensor system can be used to monitor workers' onsite exposure to dangerous postures providing data that can be used help reduce WMSDs. Those measurements can also inform efforts to redesign the workplace to make it ergonomically safer for workers. Further, the prototype has been shown to have adequate accuracy to meet the requirements of field safety applications as well as other needs to measure human joint angles in biomechanics and exercise science.

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