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A COMPREHENSIVE RISK ASSESSMENT MODEL FOR WORK-RELATED MUSCULOSKELETAL DISORDERS OF THE UPPER EXTREMITIES

Andris Freivalds and Yongku Kong
The Harold and Inge Marcus Department of Industrial and Manufacturing Engineering
The Pennsylvania State University, University Park, PA 16802 USA

Heecheon You
Department of Industrial and Manufacturing Engineering
Wichita State University, Wichita, KS 67260 USA

Seikwon Park
Department of Industrial Engineering
Korea Air Force Academy, ChoongBuk 363-849, South Korea

A quantitative risk assessment model determining the likelihood of incurring work-related musculoskeletal disorders of the upper extremities has been developed based on grip force and hand motion data input from an innovative 'touch glove'. This glove utilizes a commercial CyberGlove to measure hand and finger movements and UniForce pressure sensors to measure grip pressure during work. These are incorporated directly on-line to a laptop with the risk assessment model leading to a predicted incidence rate. The model explains 50% of the variance due to job stressors, with the remaining variability due to individual and psychosocial factors. These were examined in a pilot case-control retrospective epidemiological study of 97 participants, reducing the unexplained variability to almost less than 10%.

INTRODUCTION

Over the past decade, the incidence of cumulative trauma disorders (CTDs), such as tendinitis, tenosynovitis, carpal tunnel syndrome, ulnar nerve compression, white finger, trigger finger, etc., has increased greatly due to changes in job production rates and standardizing of work procedures. In the United States by 1994, such musculoskeletal injuries comprised 13% of the illness cases involving lost days from work and 69% of the total illness cases. The annual cost of such injuries is estimated to be between \$13 and \$20 billion dollars annually. Individual cases requiring surgery may cost upward of \$30,000. Thus, there is an imperative need for a mechanism of early identification of critical jobs which may give rise to CTDs and ergonomically redesign these jobs before the workers have incurred the debilitating effects.

Previous approaches to CTD risk assessment have been the use of checklists such as RULA (McAtamney and Corlett, 1993), Keyserling et al. (1993) or ANSI (1995) to identify the principal job risk factors of repetition, prolonged static postures, and high force exertions (although, vibration, cold temperatures and constricting gloves may also play a part) as part of job or methods analysis. However, these checklists, although useful in identifying risky factors, have not provided an overall assessment of the job and its potential for producing CTDs and typically have not been very quantitative. One exception to these approaches has been the semiquantitative Strain Index score by Moore and Garg (1995).

The purpose of the study was to develop a more quantitative risk assessment model using objective grip force and hand motion data using an external 'touch glove'.

THE CTD RISK MODEL

The risk assessment model described here is a modification of the quantitative model described in Seth, Weston, and Freivalds (1999). In using that model for analyzing industrial jobs, several limitations needing improvement were found. Because of the limited data in the literature on grip strength, wrist deviations in only one plane could be addressed. Obviously, the wrist has a wider range of motion. Therefore additional grip strength data was collected on interacting wrist angles, i.e. simultaneous radial/ulnar deviations and flexion/extensions. Also, previously only the worst gross posture was considered. That was not considered to provide an accurate representation of posture stress. Therefore, a multiple posture score was implemented in the revised version. The revised version is presented below in a step-by-step approach.

Wrist Posture and Grip Span

Wrist deviation and arm rotation cause a significant grip strength decrement as compared to a neutral wrist posture. These effects can be expressed as equations for maximum voluntary contraction (MVC) for power grip and various pinches produced in five wrist positions (neutral, flexion, extension, radial and ulnar deviation) and in three arm rotations (pronation, mid-position, and supination).

Similarly force decrements occur for both power and pinch grip depending on the grip span utilized. These effects were quantified as equations yielding average grip span strength decrements for spans ranging from 0 to 11 cm. The complete set of equations for wrist postures and grip spans are found in Kong and Freivalds (1998) and provide values for *Force Capacity Wrist* and *Grip Span Force*.

Fatigue

Obviously repeated exertions will result in muscle fatigue and reduced capacity for further exertions. This effect can be quantified as the maximum *MVC Allowed* for a particular wrist motion based on the exertion time for the motion and the rest time between exertions or motions.

$$MVC\ Allowed = 45.1 \times TW^{-0.394} \times TR^{0.2216} \times MW^{-0.258} \qquad 1)$$

where:

TW = work time of grip or motion (min)
TR = rest time between grips or motions (min)
MW = total work time for one shift (min)

Force and Frequency

For each motion a *Force Capacity* is calculated as the product of *Force Capacity Wrist* and *Grip Span Force*:

$$Force\ Capacity = \frac{\underline{Force\ Capacity\ Wrist \times Grip\ Span\ Force}}{100} \qquad 2)$$

$MVC\ Required_{Adj}$ is calculated based on *MVC Required* to perform the motion and the previously calculated *Force Capacity. MVC Required* is typically found by dividing the subjective job force requirement (collect on-site from the operators using a grip or pinch dynamometer) to the operator's MVC.

$$MVC\ Required_{Adj} = 100 \times MVC\ Required\ /\ Force\ Capacity \qquad 3)$$

The $MVC\ Required_{Adj}$ is then compared to the *MVC Allowed* for Eq. 1. If the *MVC Allowed* is greater than the $MVC\ Required_{Adj}$, then no penalty is assessed to that hand motion and that motion will have a *Force Frequency Score* (FFS_i) of one. If the *%MVC Required* to perform the motion is greater than allowed, then a penalty is assessed to that motion:

$$FFS_i = n \times MVC\ Required_{Adj}\ /\ MVC\ Allowed \qquad 4)$$

where:

n = number of such hand motions per job cycle

The FFS_i values for each type of individual hand motion are then summed to obtain an overall force frequency score:

$$FFS = \sum FFS_i \times N\ /\ 10{,}000 \qquad 5)$$

where:

N = number of job cycles per shift

The scaling factor of 10,000 is the NIOSH maximum recommended number of damaging wrist motions that can be performed in an 8-hour shift. The model then assesses whichever hand has a higher overall *FFS* and uses that value for further calculations. Thus, the analyst should only use the hand that performs the most motions, if apparent, thus, saving analysis time.

Upper Extremity Postures

Gross torso posture of a worker while performing a job is important because awkward postures can lead to fatigue. The resulting fatigue, defined as *Endurance Capacity*, can be quantified in a manner similar to Eq. 1:

$$Endurance\ Capacity = \{1 - [1.0996 \times F_{MVC}{}^{1.863} \times TW^{0.734} \times TR^{-.413} \times MW^{0.481}]\} \times 100 \qquad 6)$$

where:

TW = work time posture held (min)
TR = rest time between postures (min)
MW = minutes worked in one day (min)
F_{MVC} = relative weight as normalized by 51 lbs

Five postures are considered: neck and back flexion, elbow and shoulder flexion and shoulder abduction. For sake of simplicity in interpreting angles from job videotapes, *Points* are assigned to various angles as follows: for back flexion 0-10°=0, 10-20°= 0.5, 20-45°= 1, and >45°= 2 points; for neck flexion 0-30°=0, 30-45°= 1, 45-60°= 2, and >60°= 4 points; for elbow flexion/extension (with a 90° bent elbow being considered the neutral posture) 10° flexion to 30°extension = 0, everything else is 0.5 point; for shoulder flexion 0-20°=0, 20-45°= 1, 45-90°= 2, and >90°= 4 points; and for shoulder abduction 0-30°=0, 30-60°= 1, 60-90°= 2, >90°= 4 points.

The *Posture Score* for each body part is obtained by multiplying the point value by 50 (the limit for acceptable fatigue or endurance) scaled by the *%Endurance Capacity* (Eq. 6):

$$Posture\ Score = 50 \times Points\ /\ Endurance\ Capacity \qquad 7)$$

An *Overall Posture Score* is calculated as the average of the individual posture scores.

Final Risk Score

The final risk score is the weighted average of the *Force Frequency Score (FFS)* and the *Overall Posture Score (OPS)* in the form of a predicted incidence rate (*IR*) normalized to 200,000 exposure hours:

$$IR = -14.1 + 5.14\ FFS + 16.7\ OPS \qquad 8)$$

THE TOUCH GLOVE

The 'touch glove' consists of the lightweight commercial CyberGlove (Virtual Technologies Inc., Palo Alto, CA) to measure hand and finger movements with superimposed UniForce pressure sensors (Force Imaging Technologies, Chicago, IL) to measure grip pressure during work. The original CyberGlove features 18 patented extremely thin and flexible resistive bend-measuring sensors that are linear and robust (later versions have 22 sensors). These include two bend sensors for each finger, four abduction sensors, a thumb-crossover sensor, a palm arch sensor, a wrist flexion sensor and a wrist abduction sensor. On the four fingers, the two sensors measure the MP and PIP joints. The DIP joint is estimated from the PIP joint angle in the software. The CyberGlove is connected through an interface unit to a host computer and, because of differences in hand sizes with corresponding glove fits, must be calibrated for each person.

The UniForce sensor is a conductive polymer sensor similar the Force Sensitive Resistors used in previous studies (Fellows and Freivalds, 1991). They are of low mass, small size and very flexible, thus, not limiting hand movements. The sensors consisted of a 14 mm disk at the end of a 114 mm tab, with a sensing area of 6.5 mm. As a force is applied to the sensor, two polymer layers compress changing the resulting resistance in a very non-linear manner. A relatively simple circuit involving two operational amplifiers compensates for some of the non-linearity and produces a voltage which is fed into an analog-to-digital (A/D) converter into the host computer. The final output is linear on a log-log plot (Fig. 1).

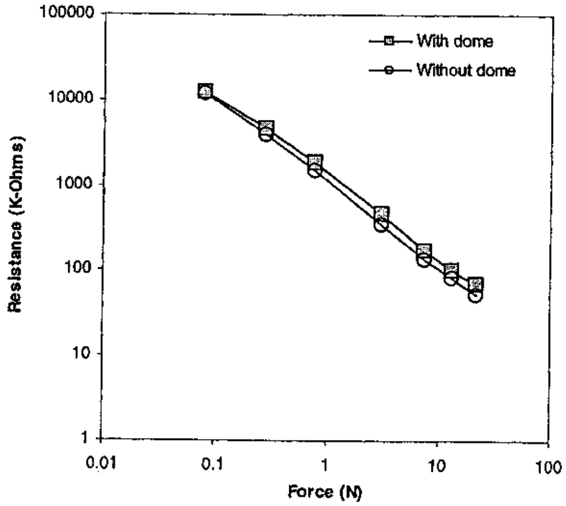

Figure 1- UniForce force-resistance calibration curve

One tradeoff is that sensor flexibility creates a high variability in force readings depending on the direction and contact area of the force. This problem was overcome by applying an epoxy dome to even distribution of the load over the sensor's sensing area (Jensen *et al.*, 1991). Another potential problem is the non-repeatability of sensor readings from day to day. Sensors without the epoxy dome were more much variable (9 to 25%) than sensors with the dome (6 to 13%). Furthermore, the sensors tend to loose sensitivity with successive measurement sessions, ranging from 1% per day for sensors with the dome to 1.7% for sensors without the dome (Fig. 2). Once the sensors have lost 30% of their initial sensitivity, the calibration curves tend to flatten and the sensors can be considered to have failed. Extrapolation of Fig. 2 to the 30% cutoff yields 19 sessions as the limit for sensors without the dome and 34 sessions for sensors with the dome. Obviously, these problems are mitigated by careful calibration prior to each experimental session.

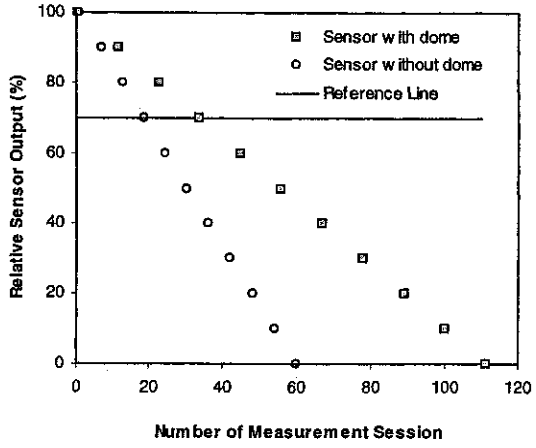

Figure 2 - Performance decrement vs. number of sessions

In order to control both measurement systems from the same portable computer, a pre-emptive multitasking operation was set up. In pre-emptive multitasking, the scheduler can interrupt and suspend (swap out) the currently running task in order to start or continue running (swap in) another task. The scheduler must ensure that when swapping tasks, sufficient state information is saved and restored so that tasks do not interfere. This was achieved through Windows 95 using a main Visual Basic program linking the device driver dynamic link library of the CyberGlove and the A/D converter for the force sensors. Further details on the 'touch glove' can be found in Park (1999).

VALIDATION AND DISCUSSION

The weights for the final risk score were determined from a detailed analysis of videotapes and grip/pinch dynamometer data from 24 industrial jobs (11 in the garment industry and 13 in the printing industry) and regression of actual incidence rates experienced on these jobs. The regression was significant at $p<.001$ with an $r^2=0.523$.

Novice ergonomists required at least several trials in becoming proficient with the risk assessment model. However, by the 5th trial, average time required for job analysis had decreased to 12 minutes and test/retest reliability was up to $r^2=.99$. The only limitations were found for very short cycle jobs (typically under four second cycle times), in which case any error in miscounting motions could be amplified into a large error for the final predicted incidence rate.

The CTD risk model was compared with Moore and Garg's (1995) Strain Index for 11 jobs that allowed calculation of the Strain Index. For the CTD risk model, regression of the predicted IR with actual IR yielded a significant ($p=.05$) regression with $r^2=.51$ while the Strain Index with actual IR yielded a nonsignificant ($p=.20$) result with r^2=.17.

One potential limitation of this risk assessment model is that a purely job-stress model can never explain all of the variance, much of which is due to individual variability such as age, gender, fitness, hormonal changes and psychosocial factors. A preliminary epidemiological study surveyed two case- and one control groups: 1) 25 non-work related carpal tunnel syndrome (NW-CTS) patients, 2) 22 work-related CTS patients (W-CTS) and 3) 50 healthy workers having had no symptoms history. The CTS patients were classified into one of the case groups according to the type of insurance covering their medical costs: health insurance for NW-CTS and workers' compensation insurance for W-CTS. The assumption was that most NW-CTS patients are highly susceptible to CTS and most W-CTS patients are moderately susceptible compared to healthy workers. Exposure to physical and psychosocial risks is higher in the W-CTS groups than in both the NW-CTS and healthy groups and the distribution of the NW-CTS and healthy groups for psychosocial and physical exposure are similar to each other.

The risk assessment questionnaire included 106 risk scales (63 personal factors, 7 psychosocial factors and 36 physical factors). A test-retest of 20 participants indicated the reliability of each risk scale to be ≥ 0.7. A 'pseudo' univariate logistic regression analysis screened out the majority of risk scales leaving 25 for further screening using a forward selection algorithm of multiple logistic regression. The final three CTS risk assessment models showed between 84% and 89% correct classification performance supporting the validity of the proposed protocol in assessing personal risk factors for CTS. Further refinements in questionnaire selectivity and patient selection should improve the overall CTD risk assessment model even further.

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