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Validation of a frequency-weighted filter for continuous biomechanical stress in repetitive wrist flexion tasks against a load

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This experiment validates a frequency-weighted filter for continuous measurements of force, posture and repetition using a stimulated industrial task. A peg transfer task was used requiring subjects to repetitively insert pegs into holes with controlled resistance. Ten subjects performed the task for six conditions. All wrist flexion angular data were recorded continually using an electrogoniometer and processed through the filter. Subjective discomfort was reported after performing the task for 1 h using a 10 cm visual analogue scale. Results from linear regression analysis showed that the instrument reliably estimated subjective discomfort ($r^2 = 0{\cdot}873$). Applications and limitations of this instrument are explored.

1. Introduction

In order to provide ergonomic guidelines in work design and for preventing discomfort and musculoskeletal disorders in repetitive hand-intensive tasks, biomechanical (Moore *et al.* 1991, Wells *et al.* 1994, Gilad 1995, Moore and Garg 1995) and psychophysical (Saldaña *et al.* 1994, Stuart-Buttle 1994) exposure assessment approaches have emerged. The objective of this study was to validate a quantitative exposure assessment instrument that can process and integrate continuous biomechanical data into an exposure index proportional to psychophysical acceptance levels.

The exposure assessment strategy used was built upon a series of previous studies. Radwin *et al.* (1994) studied and modelled the effects of posture and repetition on subjective discomfort and demonstrated how frequency-weighted filters could be applied for reducing large amounts of biomechanical data into a single quantity. That study revealed that it was feasible to use subjective discomfort response for developing frequency-weighted filters for biomechanical data and described a theory for an exposure assessment instrument. Lin and Radwin (1998) established a continuous discomfort model that associated physical stress of force, wrist flexion and repetition with subjective discomfort. A frequency-weighted filter was developed based on the discomfort model for processing wrist angle signals from an electrogoniometer. Force factors were introduced for adjusting the frequency-weighted angular data to account for force. Results from that study showed that the force and frequency-weighted filter network could be used to process and integrate continuous biomechanical measurements into a single quantity. Although the integrated filtered data were proportional to subjective discomfort, they were relative measures.

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This study utilizes the filter network (Lin 1995, Lin and Radwin 1998) and psychophysical acceptability data from other studies (Marley and Fernandez 1995, Snook *et al.* 1995) in order to develop an exposure assessment instrument that could process and integrate large quantities of continuous biomechanical measurements into a quantitative exposure index. The exposure index is a scale proportional to psychophysical acceptable levels based on continuous biomechanical measurements. A simulated industrial task is used to validate this exposure assessment approach.

2. Methods

2.1. *Exposure assessment*

2.1.1. *Continuous discomfort model*: Lin *et al.* (1997) and Lin and Radwin (1998) conducted experiments that investigated the relative effects of force, wrist flexion angle, and repetition on subjective discomfort involving repetitive wrist flexion from a neutral posture to a given angle against a controlled resistance. A linear model was developed for describing the relative relationship among these task variables and discomfort. The discomfort model was used to generate the attenuation slope for a frequency-weighted angle filter and to determine force factors for processing continuous wrist flexion angular data in the current study.

2.1.2. *Frequency-weighted filter*: A frequency-weighted angle filter weighs postural signals by the corresponding repetition frequency in proportion to the equal discomfort function, so that the filter angular data accounts for wrist flexion and repetition. The attenuation slope for the frequency-weighted angle filter is determined by the relative relationship between angle and repetition and can be obtained by algebraically solving the discomfort model at a given exertion and discomfort level. Similarly, a frequency-weighted force filter weighs force signals by the corresponding frequency in proportion to the equal discomfort function and its attenuation slope can be determined by solving the discomfort model at given angle and discomfort level. Based on the discomfort model, the attenuation slope was 24 dB/decade for the frequency-weighted angle filter and 14 dB/decade for the frequency-weighted force filter.

The frequency-weighted angle filter was modelled as a digital filter using MATLAB™ (Lin and Radwin 1998). The cut-off frequency for this filter was arbitrarily set at 1 Hz because of limitations in the filter design algorithm, which was constrained by the attenuation slope and the desired band width. The upper bound for wrist flexion was set to 75° in order to accommodate the range of motion for the wrist. This angle was used as the reference for determining angular attenuation (dB) for a given frequency and force level by solving the discomfort model at discomfort level 10 (very high discomfort). Discomfort level 10 was used to define the 0 dB angular attenuation at the cut-off frequency.

2.1.3. *Force factor*: The force factor f_E for exertion level E was expressed as:

$$f_E = 10\left(\frac{34.88 \log E - 58.67}{20}\right).$$

The root-mean-square (RMS) of the force and frequency-weighted postural data ($X_{FE}(nT)$) was used to describe the relative exposure level $\overline{X}_{FE}$. Thus:

$$X_{FE}(nT) = X_F(nT) \times f_{E(nT)},$$

where $E(nT)$ was the exertion level corresponding to sample time nT. Force was assumed to be held constant.

2.1.4. *Exposure index:* Although relative exposure levels were correlated with discomfort, they were still relative measures. In order to provide an absolute output, relative exposure levels were anchored by psychophysically acceptable exposure levels from other studies (Marley and Fernandez 1995, Snook *et al.* 1995). The discomfort level of 3·5 (Lin and Radwin 1998), corresponded to posture and force conditions that were acceptable to 90% of the female subjects in these studies. This criterion was implemented by anchoring the exposure index of 1 to the exposure limit (X_L), which was defined as the relative exposure level corresponding to a discomfort level 3·5. Exposure index for a repetitive wrist flexion task was given by:

$$\text{Exposure index} = \frac{\overline{X}_{FE}}{X_L},$$

where $\overline{X}_{FE}$ was the relative exposure level for the repetitive task. Exposure indices of less than one unit should accommodate the psychophysical acceptability for 90% of the subjects in these studies. The resulting exposure assessment instrument is shown as a block diagram in figure 1.

2.2. *Validation experiment*

2.2.1. *Apparatus*: Special peg boards were used for controlling force during peg insertion (Lin *et al.* 1997). These are described in detail in Lin *et al.* (1997). The force needed to insert the pegs into the holes was controlled by ball detents, which were calibrated against a strain gauge load cell. Wrist flexion angle during peg insertion was controlled by adjusting the height of a horizontal bar located in front of the peg board. Two 2 × 4 peg boards were placed adjacent to each other to form a 2 × 8 matrix of peg holes. The two peg boards were located on a table, which was adjusted so that subjects were at seated elbow height. Subjects continuously received a supply of pegs from a chute located next to the seat on the dominant side. They were instructed to insert pegs in a left to right fashion from the top row to the bottom, and to finish one peg board before inserting pegs into another. While the subject was

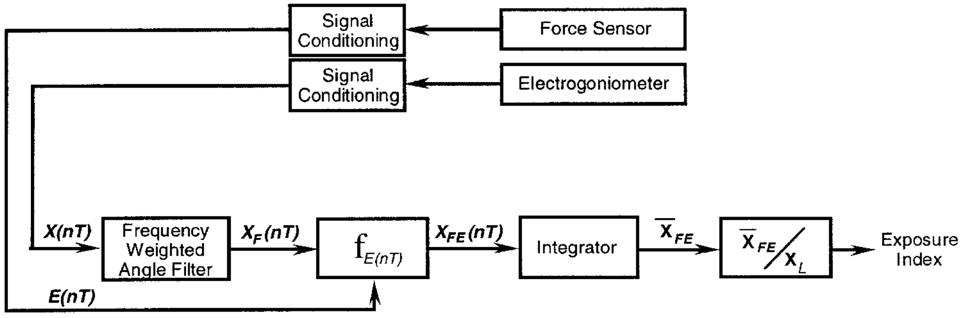

Figure 1. Block diagram of the exposure assessment instrument.

filling in a peg board, the experimenter replaced the filled peg board with an empty one, removed pegs from the filled peg board, and fed the pegs into the chute.

Continuous wrist flexion angles were measured using a Penny and Giles model M110 strain gauge twin axis wrist electrogoniometer (Penny and Giles Biometrics Ltd., Gwent, UK). The electrogoniometer was zeroed for a neutral wrist posture (Schoenmarklin and Marras 1989). A MacAdios 12-bit analog-digital converter (GW Instruments, Somerville, MA, USA), LabView® software (National Instruments Corp., Austin, TX, USA) and a Macintosh II/fx microcomputer were used for sampling posture signals from the electrogoniometer and for implementing the frequency-weighted filter. Wrist flexion angular data were sampled at 20 samples/s.

2.2.2. *Experimental design and procedures*: The experimental task involved repetitively transferring a peg across a horizontal bar and inserting it into the peg holes. All experimental conditions are summarized in table 1. The experimental conditions were presented to each subject in a random order. Only one experimental condition was presented to a subject on a given day. A 2-min warm-up period was provided at the beginning of each session. Subjects performed each condition continuously for 1 h. Five minutes before the end of the 1-h period, subjects were asked to assess discomfort. Discomfort ratings were taken at the conclusion of the 1-h period. Continuous wrist flexion angles were processed through the exposure assessment instrument illustrated in figure 1.

Discomfort was defined in this study to include sensations such as fatigue, soreness, stiffness, numbness, or pain. Subjects were required to be free of discomfort at the beginning of every session. Discomfort was measured using a 10-cm visual analogue scale anchored as 'none' at 0 cm, and as 'very high' at 10 cm, where 'none' meant that none of the discomfort sensations were experienced during the experiment and 'very high' corresponded to a very high level of these sensations. A thin, 0·5 cm vertical line was placed on the scale to indicate the mid-point. Subjects drew a vertical line across the horizontal scale to indicate discomfort. Subjective discomfort was regressed against expected discomfort predicted by the discomfort model based on the experimental conditions in order to test the model. A linear regression equation was fitted using subjective discomfort ratings as the dependent variable and the relative exposure level as the independent variable in order to validate the force and frequency-weighted filter network.

2.2.3. *Subjects*: Ten subjects (six males and four females) ranging between 21 and 24 years in age participated in the study. All subjects were recruited by broadcasting

Table 1. Experimental conditions for the validation experiment.

Experimental condition		
Force (N)	Wrist flexion (°)	Pace (s/motion)
5	10	10
5	45	10
5	45	4
45	10	4
45	45	7
45	45	4

electronic mail announcements and posting signs on the university campus. One subject was left-handed and the rest were right-handed. Subjects were required to have no history of hand/arm disabilities and no restriction of hand/arm motion. Subjects were paid on an hourly basis.

3. Results

Results from linear regression analysis showed that the discomfort model predicted relative discomfort for the experimental conditions tested. The resulting regression model was:

$$D = 0.460 + 0.894\ \hat{D}$$

($r^2 = 0{\cdot}983$, $F(1,4) = 230{\cdot}818$, $p < 0{\cdot}0001$), where D was subjective discomfort and $\hat{D}$ was expected discomfort predicted by the discomfort model. Mean and standard deviation of the subjective discomfort ratings and the relative exposure levels are shown in table 2. A linear regression model was fitted using mean subjective discomfort as the dependent variable and mean relative exposure level as the independent variable. The resulting regression model was:

$$D = 1.411 + 0.527\ \overline{X}_{FE}$$

($r^2 = 0{\cdot}873$, $F(1,4) = 27{\cdot}617$, $p < 0{\cdot}01$), where D was subjective discomfort and $\overline{X}_{FE}$ was the relative exposure level. According to this regression model, the relative exposure level corresponding to the maximum discomfort acceptable for 90% of the female subjects in Marley and Fernandez (1995) and Snook *et al.* (1995) was 3·96. This level represented the exposure limit (X_L) for repetitive wrist flexion in this study and was anchored as exposure index 1. Mean relative exposure levels for all experimental conditions were divided by X_L to obtain the exposure index. Results showed that exposure indices for 45 N conditions were all greater than 1. Exposure indices are listed in table 2.

4. Discussion

The strong correlation between subjective discomfort and the expected discomfort supports the discomfort model by showing that the discomfort model had significant capability to predict relative discomfort for the experimental conditions used. The results also showed that relative exposure levels could be used to predict a discomfort response relative to maximum acceptable psychophysical levels. This finding

Table 2. Mean and standard deviation for subjective discomfort ratings and the corresponding relative exposure levels and exposure indices.

	Subjective discomfort	Relative exposure level	
Condition	(0–10 scale) Mean	(0–10 scale) Mean	Exposure index
1	0·90 (0·88)	0·08 (0·02)	0·02
2	1·48 (1·14)	0·10 (0·02)	0·03
3	2·21 (0·95)	0·17 (0·04)	0·04
4	3·26 (1·42)	5·31 (0·84)	1·34
5	4·49 (1·12)	5·40 (1·18)	1·36
6	5·57 (1·19)	6·87 (1·20)	1·73

demonstrates the feasibility for using force and frequency-weighted filters for processing and integrating large quantities of biomechanical data into a single value that accounts for physical stress of force, flexion angle, and repetition in proportion to relative discomfort. Since force was treated as a constant, all filtered angular data within one condition were weighed by the same force factor, even though exertion only occurred during peg insertion. Consequently the influence from force was magnified in the resulting relative exposure levels, although the general trend within each force condition was not altered. This may be able to explain the wide gap in relative exposure levels between high force and low force conditions. Subjective discomfort, on the other hand, might have been influenced by extraneous motions in elbow and shoulder, which were not as controlled as the wrist in this experiment.

The significance of psychophysical acceptance levels has been well established. Studies have shown that the risk of injuries increases when psychophysical acceptance is exceeded (Snook 1978, Liles *et al.* 1984, Herrin *et al.* 1986). Psychophysical responses have also been considered as design evaluation criteria (Ulin *et al.* 1993, Genaidy and Karwowski 1993, Dul *et al.* 1994, Graf *et al.* 1995, Marley and Fernandez 1995). Results from Snook (1978) indicated that risk of low-back injury increases three times for manual handling tasks that are acceptable for less than 75% of the working population. Herrin *et al.* (1986) used psychophysical acceptability data from Snook (1978) to estimate the percentage of the industrial population capable of performing a task. They concluded that minimum percentage of the population capable of performing a job was a good predictor for musculoskeletal incidents, and it was related to severity of contact incidents that was elevated for all jobs except those that could be performed by more than 90% of the population. The lifting index in the NIOSH Work Practices Guide for Manual Lifting (NIOSH 1981) is based on the tolerance data for L5/S1 disc compression forces, metabolic energy requirements, and psychophysically acceptable load for 75% of the female and 90% of the male industrial population. Similar biomechanical and physiological tolerance data, however, are currently unavailable for repetitive hand-intensive tasks.

Psychophysical acceptance levels were used in this investigation to define the exposure limit for repetitive wrist flexion. Snook *et al.* (1995) used the method of adjustment to estimate the maximum acceptable force for wrist flexion tasks. Subjects were instructed to work as hard as they could without developing ‘unusual discomfort’ at the end of a 7-h session by selecting the maximum acceptable forces. Marley and Fernandez (1995) used the same method to estimate maximum acceptable frequency for a drilling task. These psychophysical acceptability data were incorporated into the discomfort model to determine maximum acceptable psychophysical discomfort levels. This study used discomfort level 3·5 to establish the exposure limit for wrist flexion tasks. The 3·5 level was established by solving the discomfort model for conditions that corresponded to the psychophysical level acceptable for 90% of the subjects in Marley and Fernandez (1995) and Snook *et al.* (1995). This exposure limit was anchored as an exposure index of 1. Such an index may be used as an evaluation criterion, so that objective biomechanical stress in a task could be measured and should be controlled not to exceed an exposure index of 1.

Subjective discomfort survey programmes have been developed for use as a surveillance tool for identifying tasks that are associated with high discomfort (Saldaña *et al.* 1994, Stuart-Buttle 1994). These types of survey programmes can only be used when jobs are established and workers have familiarized themselves with the tasks, therefore they may not be practical for establishing preventive measures at the design stage. Information obtained from subjective surveys also tends to confound with other factors irrelevant to the task and sometimes fails to recognize the relative influence of individual task variables on discomfort. Consequently, applications of survey techniques in identifying problematic tasks and developing ergonomic intervention strategies are limited.

Since an exposure assessment instrument such as the one described in this study processes continuous multi-factor biomechanical measurements directly from electrogoniometers and force sensors, it eliminates potential bias from observers and provides an objective assessment. There are several advantages of using these types of indices for exposure assessment. Such an exposure index is proportional to relative discomfort and may be used to evaluate motions and exertions in an arbitrary manual task in comparison with psychophysically acceptable levels. Exposure indices may also be used for prioritizing tasks for ergonomic intervention. Furthermore, epidemiological studies based on these measurements may prove that exposure limits offering protection from biomechanical hazards may be established.

While results from the current study demonstrate that this instrument provides a promising approach for quantitative exposure assessment, these results are preliminary. The discomfort model was established and tested using repetitive wrist flexion and exertion tasks with a power grip, and therefore it may not be applicable to tasks that involve different motions, articulations, or grip postures. The discomfort model only considered physical stress of force, wrist flexion, and repetition, while there are other task variables and environmental factors that may contribute to discomfort and should be accounted for by ergonomic evaluation and intervention. Lin and Radwin (1998) suggested that this discomfort model might deviate from linearity when exposures reached certain extremes. The boundaries, however, have not yet been defined. Future studies should be conducted to refine and broaden the scope of this model and to define the boundaries for its applications.

Radwin *et al.* (1994) extended the traditional method of time and motion study by using continuous biomechanical measurements for elemental analysis. Continuous biomechanical data for each element were processed using a frequency-weighted filter and integrated into a single quantity. They proposed that exposure could be assessed at a task or job level using time-weighted averages of these quantities assuming a linear duration effect. Future study should be conducted to investigate the duration effect in order to allow task elements with different durations and exposure indices to be combined for exposure assessment. Snook (1978) pointed out that industrial subjects and student subjects might have different perceptions of industrial work, therefore it is important to verify this instrument using industrial workers. The effectiveness of this approach in identifying unacceptable tasks still needs to be verified in field studies by using exposure indices as evaluation scales. Although the scope of this study is limited to wrist flexion, the methodology proposed may be applicable to biomechanical measurements at articulations other than the wrist and may ultimately lead to the establishment of ergonomic work design and evaluation guidelines for repetitive upper extremity tasks.

5. Conclusions

The discomfort model that shaped the force and frequency-weighted filters for this study was validated by showing that it could be used to predict relative discomfort for a less controlled repetitive wrist flexion task. Significant correlation between subjective discomfort ratings and relative exposure levels indicated that the exposure assessment instrument can process and integrate continuous multi-factor biomechanical measurements into a single quantity that is proportional to subjective discomfort. Exposure indices were introduced as outputs of the exposure assessment instrument. An exposure index is proportional to relative discomfort and is anchored to an absolute psychophysically acceptable level. The exposure index may be useful for comparing objective continuous biomechanical measurements against absolute psychophysically determined acceptable exposure levels or for prioritizing different tasks using the same objective criteria. Although results from the current study demonstrated that this method is promising for exposure assessment, these results are preliminary. Future studies should be conducted for considering exposures other than 1 h, to refine and broaden the scope of the model, and to verify the efficacy of this exposure assessment instrument in actual work conditions using industrial workers.

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