Prediction of Drilling Frequency at Varying Working Conditions
(누적외상병 예방을 위한 Drilling 작업 빈도에 관한 연구)

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ABSTRACT

A laboratory experiment was conducted to examine the effect of varying working conditions on drilling frequency for females. Results of ANOVA showed that angle of wrist flexion and force had significant effects on drilling frequency. As angle of wrist flexion and force increased drilling frequency decreased significantly. A set of 4 regression models were developed to predict maximum acceptable frequency (MAF) for drilling as a function of wrist flexion angle, force, and various physiological measures which could be applied in industrial situations.

INTRODUCTION

Cumulative trauma disorders (CTD) of the upper extremity are a major cause of decreased productivity in the manufacturing industry. The occupational risk factors most frequently associated with CTD include repetitiveness, forceful exertion, awkward body postures, duration of task, vibration, cold temperature (Silverstein et al., 1986; Putz-Anderson, 1988). The increase in the incidence rate of CTD can be prevented by reducing levels of risk factors. A conceptual model for establishment of quantitative guidelines to reduce the risk of developing CTD was developed (Tanaka and McGlothlin, 1989). In many hand-intensive industrial tasks such as drilling, it is difficult to keep the wrist in the neutral position while applying excessive force. Thus, one of the objectives of the original study was to determine the effect of deviated wrist position and applied force on drilling frequency which involves potential risk of developing CTD.

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METHODS AND PROCEDURES

Subjects

Fifteen female volunteers from the student at a midwestern university in the America participated as subjects in the study. The mean age was 23.8 years (standard deviation of 5.16)and ranged from 19 to 36 years. Subjects were not recruited on the basis of any relevant industrial experience. Subjects were screened so as not to allow participation of any individual who had a history of CTD of the upper extremities. Also, subjects who were pregnant were excluded from participation. This screening was performed during a selection interview. Phalen's test was administrated to further confirm the acceptability of subjects.

Apparatus

Simulated drilling workstation. The adjustable workstation designed by Marley (1990) was adopted and modified so it could be set at different levels of workload (applied force for drilling). The drilling task frequency was adjusted by a subject using the potentiometer as a control (Kim and Fernandez, 1993).

Anthropometric and physiological measures. Many equipments were used to measure various anthropometric and physiological measures. They were; anthropometric kit, hand dynamometer, preamplified surface electrodes, A/D converter, heart rate monitor, blood pressure monitor, and goniometer.

Procedures

Anthropometric measures. Several anthropometric measures were taken. These included height, standing elbow height, hand length, wrist circumference, wrist thickness, wrist width, hand breadth and thickness of hand at metacarpal.

Range of motion and strength. Maximum wrist flexion was measured in the transverse plane. This measure was repeated twice, once with no tool in the hand and once while the subject was holding the hand drill. Maximum voluntary grip strength was assessed at four different angles (0, 10, 20, 30 degree) of wrist flexion using the hand grip dynamometer. Also, maximum voluntary exertion (MVE) was assessed at four different angles of wrist flexion. A pneumatic drill used in the main experiment was used to apply force through the target hole of the simulated drilling workstation. Subjects gradually increased exertion and maximum effort was maintained for five seconds. The the average values during the middle three seconds was taken as the MVE.

Wrist flexion angle and force. A previous research reported that one-third of maximum wrist flexion yielded significant reduction in the maximum acceptable frequency in a drilling task (Marley, 1990). For this study, the upper limit of wrist flexion was set at 20 degrees from the neutral position of the wrist. The three angles of wrist flexion determined for this study were neutral (0 degree), 10, 20, degrees. A pilot study was conducted to find the force levels for drilling four typical types of sheet metal used in the aircraft industry. Based upon the results of the pilot study, 4 levels of force were determined. They were 2.73, 5.45, 8.18, and 10.91 kg. Thus, twelve combinations of wrist flexion angle and force level were used in the experiment. All tasks in the study were performed with subject's preferred hand. All anthropometric measures, range of motion, and strength were taken for the preferred hand as well.

Simulated drilling task. Prior to the simulated drilling task, the initial work height was determined according to the subject's anthropometric values. Working posture was controlled by adjusting the angle of the work surface relative to the subject. A drilling cycle began with the subject in the starting position holding the pneumatic drill tool. The drill bit was then placed into the target hole of the outer work surface making contact with the fixed surface behind.

Subjects were required to apply a specific force at a specific flexion angle, which was determined from a previously mentioned combination value, to this surface for one second. The task cycle was completed when the subject returned to the starting position. The pneumatic drill tool was not connected to a power source. Therefore, there was no torque or vibration generated by the tool or by its contact with the workstation.

Determining psychophysical frequency. For each of 12 combinations of wrist flexion angle and force level, a psychophysical drilling frequency was determined by the method of adjustment (Kim, 1991; Marley and Fernandez, in press). Twenty-five minute psychophysical sessions were performed. Subjects were allowed to adjust the frequency of the task by adjusting the metronome during the first 20 minutes. They were asked to assume an 8-hour long work shift (including breaks), to work as hard as possible but without overexerting or tiring themselves and to make as many adjustments as they felt necessary in order to arrive at the maximum frequency at which they thought they could perform the task comfortably. The final 5-minute period was maintained at the final frequency selected as reasonable for 8 hours of work. This frequency was considered as the maximum acceptable frequency (MAF). At no time did the subjects have feedback of the task frequency at which they were performing.

Physiological responses. During 25th minute of the psychophysical adjustment sessions, measures of blood pressure and EMG of the forearm flexor and anterior deltoid muscles were recorded. The mean heart rate for the final five minutes (during constant frequency) was recorded as well. Immediately upon conclusion of the task, a rating of perceived exertion (RPE) using the Borg scale was obtained for several body parts. These body parts were: hand, wrist, forearm, shoulder, and the whole body.

Testing regimen. The order in which the tasks were performed by each subject were randomized. No more than two 25-minute sessions were performed in a given day and a minimum of 25 minutes of recovery time (sitting at rest) was permitted between sessions. Typically, one rest day were scheduled in between testing days.

RESULTS AND DISCUSSION

Effect of Wrist Flexion Angle and Force

The analysis of variance (ANOVA) for the effect of wrist flexion angle and force is summarized in table 1. Results from ANOVA showed that both wrist flexion angle and force had significant effects on the MAF. There was no interaction effect. Thus, as force and angle of wrist flexion increased, MAF decreased significantly. Also, various physiological responses (heart rate, blood pressure, muscle EMG) and RPE supported the findings in the MAF. Table 2 provides mean values of MAF at varying wrist flexion angles and forces. For a detailed information, refer to Kim and Fernandez (1993).

Table 1. ANOVA summary for MAF and other responses

Response Variable	Factors: Force F-value(p>F)	Factors: Angle F-value(p>F)	Factors: Force*Angle F-value(p>F)
MAF	244.73(0,0001)*	118.14(0.0001)*	1.32(0.2497)
Heart rate	49.40(0.0001)*	12.61(0.0001)*	0.32(0.9237)
Systolic BP	11.07(0.0001)*	0.14(0.8661)	1.20(0.3070)
Diastolic BP	0.23(0.8785)	1.84(0.1630)	0.38(0.8937)
Mean BP	6.84(0.0002)*	0.22(0.8013)	0.62(0.7174)
Flexor EMG	32.13(0.0001)*	1.22(0.2982)	0.39(0.8870)
Deltoid EMG	82.37(0.0001)*	5.36(0.0001)*	5.36(0.0058)
Hand RPE	55.34(0.0001)*	6.32(0.0023)*	0.49(0.8161)
Wrist RPE	42.88(0.0001)*	29.44(0.0001)*	0.12(0.9945)
Forearm RPE	26.11(0.0001)*	13.44(0.0001)*	0.46(0.8369)
Shoulder RPE	90.46(0.0001)*	15.02(0.0001)*	0.22(0.9700)
Whole body RPE	198.41(0.0001)*	45.54(0.0001)*	0.48(0.8254)

* Value of (p>F) which is less than 0.05 indicates that the effect of the factor is significant on the response at a = 0.05.

Table 2. Mean values of MAF at varying wrist flexion and forces

Force(kg)	Wrist flexion angles (degree) Neutral(0)	10	20
2.73	618*	560	518
5.45	556	466	399
8.18	473	372	339
10.91	377	293	227

* MAF: unit for MAF is cycles/hour

Prediction of Drilling Frequency

An objective of this study was to develop predictive equations for grip strength based upon wrist flexion angle, force, and other parameters. Stepwise multiple regression and R-square selection procedures were used to determine salient equations using various parameters which were angle of wrist flexion, force, and other physiological responses such as grip strength, and maximum voluntary exertion. First, diagnostic tests such as normality checking were performed to assure that there were no major departures from the assumptions of multiple linear regression models. Also, other types of regression models were considered in the selection of model. However, a multiple linear regression model appeared to be the best model in the present study. The results from the residual analysis also confirmed the appropriateness of the multiple linear model. The general criteria for appropriateness and efficiency of these models were: 1) detection of outlier by residual analysis; 2) analysis of multicollinearity and variance inflation factor (VIF); 3) evaluation of F ratio and R^2; 4) evaluation of Mallow's C(p) criterion to check the bias of a model. When the improvement of between models was not significant or small, the model with independent variables which were easy to access or measure was selected. The models were selected to have practicality without significant sacrifice of prediction efficiency. A set of 4 regression prediction equations are presented in Table 3 with corresponding R^2 and Mallow's C(p). These models yielded reasonable accuracy in the prediction of MAF for a drilling task as a function of angle of wrist flexion and applied force. The independent variables in the models appeared to be reasonably easy to measure in many industries without utilization of sophisticated knowledge and expensive equipment. Equations 3 and 4 can be particularly useful when some MAF values are known from an experiment or any related source. Any of these 4 models can easily be used, however, equations 1 and 3 are preferred since they require the least number of independent variables.

Table 3. Regression equations for MAF

Regression equation	R^2	C(p)
1. MAF = 12.006 - 0.113*ANGLE - 0.538*FORCE	0.723	2.99
2. MAF = 11.216 - 0.101*ANGLE - 0.538*FORCE + 0.028*NGS	0.723	4.00
3. MAF = 3.348 - 0.113*ANGLE - 0.538*FORCE + 0.798*MAF012 + 0.045*NGS	0.820	3.87
4. MAF = 2.870 - 0.113*ANGLE - 0.538*FORCE + 0.799*MAF012 + 0.054*NMVE + 0.027*NGS	0.822	4.70

Where, MAF = maximum acceptable frequency (repetitions/min)
ANGLE = angle of wrist flexion (degree)
FORCE = applied force in a task (kg)
NMVE = maximum voluntary exertion in neutral angle of wrist flexion (kg)
NGS = maximum grip strength measured in neutral angle of wrist flexion with elbow at 90 degree (kg)
MAF012 = MAF value at 5.45 kg of force with neutral wrist flexion angle (repetitions/min)

CONCLUSIONS

The results of this study showed that wrist flexion angle and applied force have significant effects on the maximum acceptable frequency (MAF) in a drilling task. As angle of wrist flexion and applied force increased, MAF for a drilling task decreased significantly. It is concluded that MAF for a drilling tasks should be adjusted accordingly as wrist flexion angle and applied force increased to reduce the risk of CTD in hand-intensive industries. The proposed regression models in the prediction of MAF can be applied with acceptable accuracy and practicality in many industrial situations.

REFERENCES

Fernandez, J.E., Dahalan, J.B., Klein,M.G. and Marley, R.J., 1993. The use of the psychophysical approach in hand-wrist work. Proceeding of the M.M.Ayoub Occupational Ergonomics Symposium, 63-70.

Kim, C.H., 1991. Psychophysical Frequency at Different Forces and Wrist Postures of Females for a Drilling Task. Unpublished Ph.D. Dissertation, Wichita State University, Wichita, KS (USA).

Kim, C.H. and Fernandez, J.E., 1993. Psychophysical frequency for a drilling task, International Journal of Industrial Ergonomics, 12(3), 209-218.

Marley, R.J., 1990. Psychophysical Frequency at Different Wrist Postures of Females for a Drilling Task. Unpublished Ph.D. Dissertation. Wichita State University, Wichita, KS (USA).

Marley, R.J and Fernandez, J.E., in press. Psychophysical frequency and sustained exertion at varying wrist posture for a drilling task, Ergonomics.

Putz-Anderson, V., 1988. Cumulative Trauma Disorders: A Manual for Musculoskeletal Disorders of the Upper Limbs. London: Taylor & Francis.

Silverstein, B.A., Fine, L.J., and Armstrong, T.J., 1986. Hand wrist cumulative trauma disorders in industry, British Journal of Industrial Medicine, 3, 779-784.

Tanaka, S. and McGlothin, J.D., 1989. A conceptual model to assess musculoskeletal stress of manual work for establishment of quantitative guidelines to prevent hand and wrist cumulative trauma disorders (CTDs), In A.Mital (Ed.), Advances in Industrial Ergonomics and Safety I, Taylor & Francis, New York, 419-426.