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Machine-cycling errors with foot switches in repetitive tasks

A workstation design simulation experiment

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In this experiment a non-hazardous industrial machine simulator was used to evaluate errors made when using a foot switch to initiate dangerous, repetitive machine motions. Subjects were experienced employees who normally operated metalworking presses and similar hazardous machines on jobs matching the simulation. Four variables (force needed to push switch to closure, the switch's force feedback felt by the subject, subject working posture, and hand task involved in stamping a simulated workpiece) were evaluated for their main and interactive effects upon frequency of machine-cycling errors in a repetitive task. Equipment problems which required immediate correction were introduced at a rate of 4·9 events/h. Also, three covariables (the rate of repetitive use of the switch to make hits on simulated workpieces, subject age and subject experience at foot switch-controlled workstations) were examined for their contribution to cycling errors. Although hand task was a significant effect in error prediction models containing the four primary variables, it was found that a model containing the hit rate covariate (rate of repeated use of the foot switch) provided the best predictor of the frequency of inadvertent actuation errors. An error threshold was observed at about 17·5 hits/min with a high linear correlation between hit rate and machine-cycling errors at higher hit rates. Based on results of the experiment, this report presents design considerations for workstations which use foot controls to help minimise the chance of machine-cycling errors and injury.

Keywords: Errors, foot controls, simulation

Introduction

Inadvertent actuation errors in the use of foot controls can be a factor in machine operator hand and finger amputations as well as in production lost due to incorrectly formed work and to tooling and machine damage. The National Institute for Occupational Safety and Health, a branch of the US Public Health Service, is seeking to reduce amputation injuries significantly by alerting machine users and workstation designers about methods to consider for preventing amputations, such as those occurring at machines controlled with foot switches. Several analyses of injury data have indicated that inadvertent actuation of foot switches is an important injury causal factor. Arndt (1981) found in an extensive review of reported injury causal factors that 48·5% of operator injuries on metalworking machines involved foot controls. The US Department of Labor (Office of Standards Development, 1980) found that 65% of reported mechanical power press injuries between 1975 and 1980 occurred on foot-controlled presses. In a study of Swedish press operator injuries, Garde (1974) reports that between 58% and 97% of the injuries involved foot-controlled machines.

From the injury statistics alone, one cannot necessarily conclude that foot control is a sufficient precursor for injury. However, there is a particularly dangerous correspondence between the use of foot controls and the failure to guard adequately. Foot controls are one of several components in the man-machine system which might be responsible for operator injuries. Machine guards play an indisputable role in injury prevention, but for many reasons guards are not always used properly. Trump and Etherton (1985) reported on an information processing model of inadvertent actuation or erroneous use of foot controls and on general workstation design considerations when injury due to inadvertent actuation is anticipated. The current article examines selected foot control and task variables for their main and interactive effects upon inadvertent actuations in repetitive, self-paced machine operations. The study statistically evaluates the way certain factors can effect an increase or a decrease in machine initiation errors at times when such inadvertent initiation could result in tooling closure and equipment damage or operator injury.

Kroemer (1971) reported an extensive review of the literature on human performance with foot controls. His review contains critical evaluations of studies on four parameters for evaluating the foot as a control channel. The parameters were: speed of a single foot control actuation or closure; force levels applied to the foot control; perception of leg and foot position and motion on a foot control; and power transmitted through rotary pedals. The report emphasises that with sufficient comparative information it should be possible to assign to the feet some of the control functions ordinarily assigned to the hands. Kroemer (1971), Drury (1975), and Glass and Suggs (1977) have reported experimental results on foot pedal location and pedal size as correlates of speed and accuracy for single and reciprocal foot tapping movements of the kind made when operating vehicle brake and accelerator foot pedals. Recommendations on foot control design based on other considerations of performance are to be found in: Damon *et al* (1966), Garde (1978), Grandjean (1980), McCormick and Sanders (1982), Murrell (1969), Van Cott and Kincade (1972), Wilco, Inc (1976), and Woodson (1981). While this literature provides numerous recommendations for the careful selection and use of foot controls in non-repetitive situations such as in aircraft and cars, there are few specific recommendations aimed at the selection and use of foot controls for work-stations where repetitive machine operations are performed.

Foot-controlled machines

In the USA, there are approximately 500 000 work-stations at high-hazard industrial machines which use foot-operated controls. Various machines in the industrial workplace are operated by foot controls. These machines include: mechanical power presses, resistance welders, press brakes, sheet metal shears and riveting machines. Although they perform different industrial processes, these machines share three important characteristics: (a) they use powerful reciprocating ram motions, (b) they are associated with repetitive human performance tasks, and (c) they are susceptible to randomly occurring equipment problems which a machine operator must correct.

Multiple activity charts illustrate the sequences of action by hand, foot and equipment tooling which might occur during a working task at a reciprocating motion machine. Repetition of the sequence in Fig. 1 is the normal situation. If a problem, such as a loose bit of scrap, is noticed in the tooling then the sequence in Fig. 2 would be expected. If the operator does not notice the tooling problem, then the equipment damage sequence in Fig. 3 would occur.

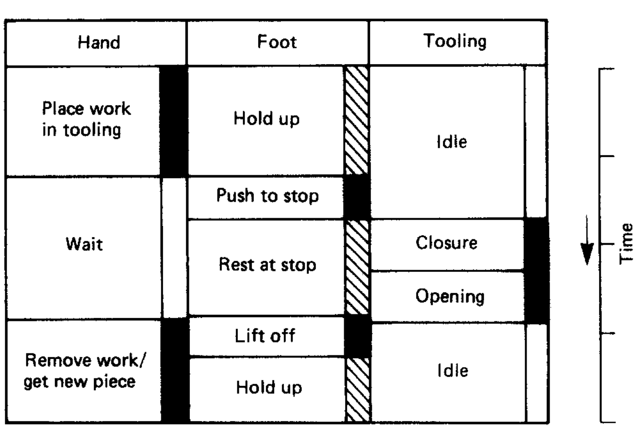

Fig. 1 Worker and machine activities in a repetitive load-cycle-unload task

The act of reaching between machine dies to correct a problem during a repetitive task at a foot-controlled machine sometimes appears to be unmediated. Such reaching movements can be fast, reflex-like responses to an immediate problem and can be made with little or no conscious deliberation. This means that operators may spend insufficient amounts of conscious processing time to analyse stimuli and programme a correct sequence of hand and foot movements. They may quite automatically 'call up' existing responses which have worked in the past, and act.

As illustrated in Fig. 4, whether such unmediated responses are made in order to correct problems on a hazardous production task for which positive guarding may be missing or inadequate, the timely control of switch actuation movements is critical. Equipment problems can occur at any time during machine operations. An operator who repeatedly cycles a stamping machine at 30 cycles/min has 2 s between successive foot movements. If, one second before the next anticipated foot movement, a problem is noticed which triggers a reach response toward the machine

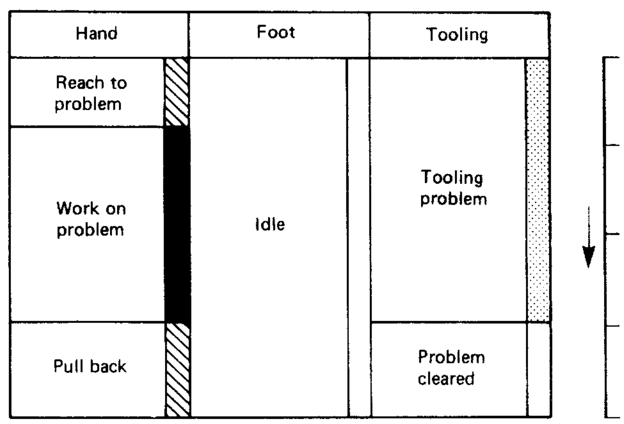

Fig. 2 Worker and machine activities when a machine fault needs to be corrected

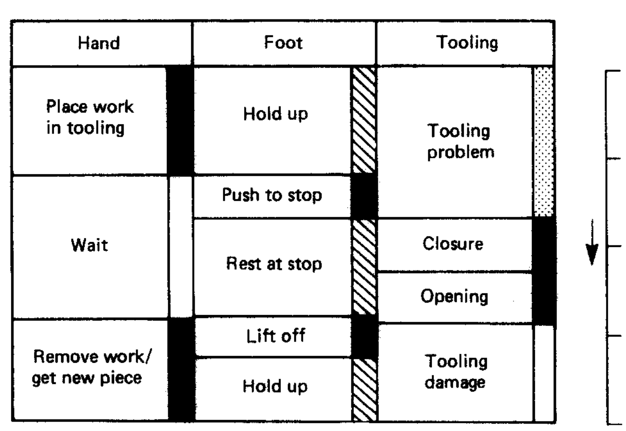

Fig. 3 An inadvertent actuation of the foot control damages the machine's tooling

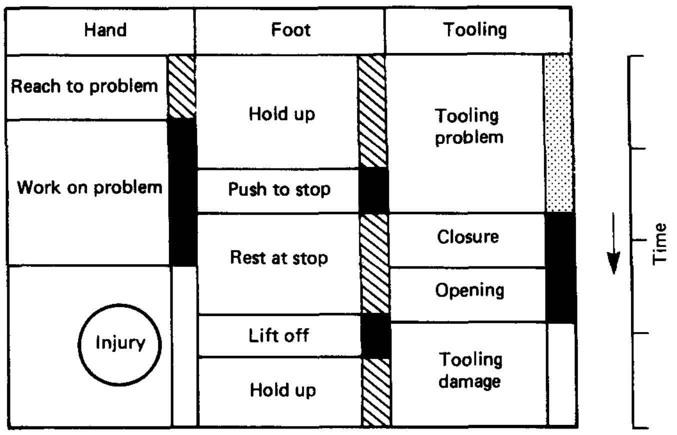

Fig. 4 An inadvertent actuation of the foot control injures the worker

and if it takes 1·5 s for the hand to move in, correct the problem and move out, then the operator could stamp his own hand should he fail to change habit in his sequence of foot movement and should nothing impede his reach or stop ram closure.

Experience indicates that guards alone do not prevent all punch press injuries (US Department of Labor, 1956). This statement represented one early recognition that injuries happen despite guards. If guarding cannot always protect operators of foot-controlled machines, another way to minimise injuries would be to help operators avoid making machine-cycling errors. To this end, an experiment was designed to test for main and interaction effects of four variables (discussed in the section on experimental design) believed to be associated with increasing or decreasing operator machine-cycling errors in unmediated response situations. The experimental variables were selected during a day of discussion with a panel of five university and industry experts who were given a list of 20 possible variables which might have an effect on injuries at foot-controlled machines. They were asked to identify four factors which would have the most likely association with error and which would be the most amenable to practical intervention.

Method

Apparatus

An operational simulator of a workstation at a reciprocating motion industrial machine (Fig. 5) was developed to provide: constant closure time (0·7 s); repetitive task measurement capabilities; random introduction of simulated equipment problems; and a point of operation which does not injure if a subject's hand is closed on by the ram. A sliding cam, reduction gearbox, variable-torque magnetic clutch/brake and ¼ hp (186 W)

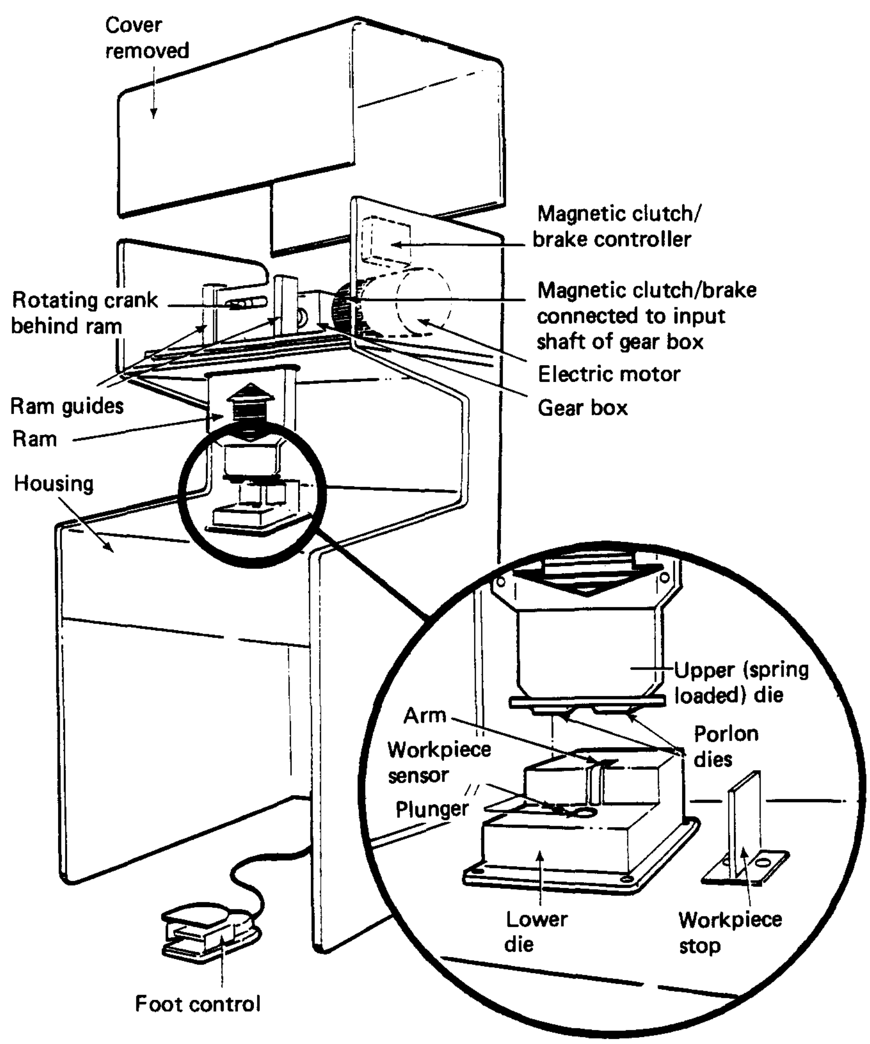

Fig. 5 Industrial machine simulator

motor arrangement provide the reciprocating ram motion. Repetitive task measurement capabilities are provided via a control circuit which cycles the simulator once with every pressing of the foot control. Two electrical solenoid devices introduce randomly occurring equipment problem events. One is a short arm which falls on to the lower die from a pocket in the backstop. The other is a rounded button or plunger which pops up in the middle of the lower die. Both devices simulate scrap-in-die situations which are cleared by resetting the obstruction devices into their pockets with a simple push of the hand. In addition to these two devices there is a loud siren, used to simulate distractions of the type that may be found in a factory.

In this experiment, simulator closure was initiated with one of four interchangeable electric foot controls (Fig. 6). Each of these foot controls was a modified version of a standard control. Modifications in pedal resistance and pedal travel distance were made to provide two levels of 'difficulty to push' and two levels of 'pedal feedback'. The pedal selected is widely used on presses. This type of pedal was not known to have been subjected to an ergonomics study. Each control plugged into the simulator via a cable which allowed the control to be conveniently positioned on the floor.

If an operator cycles the simulator while any part of his/her hand is between the dies, the ram retracts to prevent injury. This is accomplished by a spring-loaded section of the ram which collapses if a force of more than 5 lb (22·25 N) is encountered. This device and a low magnetic clutch torque setting serve as multiple safety devices.

The simulator is interfaced with an Apple II microcomputer via optical isolators and a digital I/O board. The computer and its software activate all electrical devices (e g, arm and button) on schedule and record all data (e g, equipment damage events and simulated injuries) during training and test periods.

Two types of operator error can be indicated with the simulator:

Inadvertent actuation injury errors are indicated via a microswitch which is triggered if the foot switch is depressed and a subject's finger or hand is caught between the closing upper die and the stationary lower die. Only an object equal to or greater than the diameter of a small finger will trigger the switch.

Inadvertent actuation damage errors are indicated if the foot switch is depressed and the subject has failed to correct an equipment problem by removing a button/plunger or backstop arm obstruction before the ram closes. A buzzer sounds when equipment damage occurs.

In addition to counting simulated injuries and equipment damage events, a 1 min video recording was made during each equipment problem or siren distraction. A video recorder was activated 30 s prior to the problem or distraction and remained on for 60 s, recording subject behaviour before, during and after the event. The videotape served as a back-up record in case of a failure in the primary error-measurement device.

Two measures of output were used: workpieces per 10 min interval and the total number of workpieces produced in a 170 min test period. Workpieces were counted by the simulator only if they were properly positioned between the dies when the operator cycled the machine.

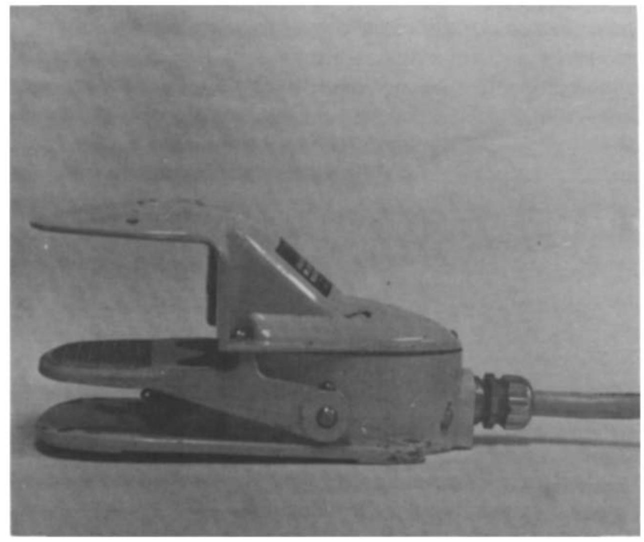

Fig. 6 Foot switch

Subjects

The subjects (n = 64) were volunteers from a large US manufacturing company. Subjects were trained factory machine operators between 21 and 59 years of age having work experience at machines using foot control (6 months to 36 years). The volunteers were selected as subjects on the basis of experience and age. There were 58 male and six female subjects, which is approximately the same ratio of males to females as among machine operators in the stamping shop of this factory. All the volunteers were currently working under incentive rate at their present jobs. No measurements were taken which were indicative of a subject's physiological status, nor were their safety records examined.

A strict company safety programme in the host plant ensures that workers are given proper training before they are permitted to operate any production machines. In addition, the company has a 'no-hands-in-dies' policy which is reinforced through a cumulative point system; that is, workers accumulate points every time they are observed with their hands between unblocked machine dies. When workers accumulate a specific number of points, they receive days off without pay. Although this policy would appear to act as a strong deterrent, there were still reports of workers placing their hands between machine dies.

Experimental design

The experiment was a between-subjects 2 x 2 x 2 x 2 factorial design. The four independent variables selected by the expert panel provided 16 experimental combinations. The variables were:

Hand Task (T). The task was either to stamp the workpiece on one end or on two ends. One-end stamping required the subject to pick up a fresh workpiece, position the workpiece in the lower die, and cycle the machine one time. Two-end stamping required the subject, after stamping the workpiece once, to turn it end-for-end (not over), position it, then cycle the machine a second time. Safety experts from industry had expressed the opinion that the complexity of the task being done by the hands would have a significant effect on inadvertent foot motion.

Working position (P). The subject was assigned to either a sitting or a standing operating posture. Grandjean (1980) recommends that foot controls should not be used if possible for standing tasks because of fatigue.

Pedal difficulty (D). This referred to the degree of force which had to be applied to the pedal for it to reach its trip point (the point at which an internal electrical switch was triggered). Two pedals with different force levels were chosen for this variable. The 'easy' pedal required a force of 27·44 N (6·176 lb) to reach its trip point, while the 'hard' pedal required 63·7 N (14·330 lb) to reach its trip point. These forces seemed appropriate for the short distances required to trip the switch used on the foot control being tested. Corlett and Bishop (1978) recommend a 9 kg (88·2 N) force for the foot pedals typically used for standing tasks at spot-welding machines. Those pedals usually have a longer travel distance than the foot switches used in this experiment.

Pedal feedback (F). This referred to the way the control pedal resistance, or force, felt by the operator increased as the pedal was pushed. One type of force increase selected was strictly linear; the other type contained a step increase. The strictly linear feedback pedal provided a gradual force increase over the entire pedal travel. The step feedback pedal provided a gradual pedal force increase over the first 17 mm (0·669 in) of pedal travel; then it quickly increased to 16·67 N (4·555 lb) in 0·5 mm (0·010 in). From there the pedal force again increased gradually over the next 4 mm (0·157 in) until the trip point was reached. The relatively short distance over which the second step acts was a constraint of the pedal type being tested.

The rationale for providing a step increase in pedal resistance prior to the trip point was to test the notion that providing an attention-getting feedback to the operator would reduce errors. Ely *et al* (1956) suggest that controls which employ spring-loaded resistance will (1) allow the operator's limb to rest on the control without activating it, (2) reduce the likelihood of undesired activation due to accidental brushing against the control, and (3) provide the operator with feedback information ('feel') concerning control position. The concept of a stepped increase in resistance is sometimes incorporated in gun triggers, triggers on aircraft joysticks, on camera shutter-release buttons, and on resistance welder controls to signal a change of heat levels from low to high. Before the off-the-shelf foot controls were modified for the study, their pedal resistance increased linearly from 0 to 41·09 N (9·239 lb) at the trip point.

Two dependent variables and three covariables were considered in the experiment. One dependent variable was simulated injury frequency. A simulated injury was counted if a subject's finger or hand was caught between the dies when the machine was cycled. Although the work of Rubinsky and Smith (1971) and a pilot study on untrained subjects in the present effort indicated the likelihood of sufficient simulated injury events to permit statistical treatment, it was considered prudent to record equipment damage events as a back-up measure for the second dependent variable. Equipment damage events occurred when the subject cycled the machine without correcting a simulated equipment problem. The covariables were subject age, subject experience on factory machines, and the mean number of subjects' hits per minute. Both subject age and machine experience were matched across all 16 experimental combinations, with one subject drawn from each of four groups: old, young, low and high experience. The mean numbers of subjects' hits per minute were calculated based on the number of times the subject cycled the machine (with workpieces correctly positioned) over the 170 min test period.

Subjects were paid their normal day rate plus an incentive based on the total number of workpieces stamped over the 170 min test period less a penalty for the number of equipment damage errors made. The incentive for parts stamped twice was $1.60 per 100 pieces over the standard of 490 pieces/h. The incentive for parts stamped once was $0.85 per 100 pieces over the standard of 909 pieces/h. Subjects tend to make errors performing under an incentive (Rubinsky and Smith, 1971). The equipment damage penalty was instituted to motivate subjects to correct equipment problem events before cycling the simulator. For each equipment damage event caused, the subject was fined the monetary equivalent of 10 workpieces when stamping one end and five pieces when stamping two ends. The incentive used was co-ordinated with the company's work standards staff. Although no information was obtained on subjects' incentive pay history, it did appear that subject speed/accuracy trade-offs in this experiment reflected normal working patterns.

Procedure

The experiment was conducted at the subjects' place of employment in an enclosed space adjacent to production facilities. Subjects were scheduled for the experiment during either the morning or the afternoon of each weekday. Each subject was introduced to the experiment and then familiarised with the machine simulator. Subjects were instructed to cycle the simulator so that two Porlon ink pads attached to the moving upper die would mark workpieces made of 2 in x 19 in (50·8 mm x 482·6 mm) card stock. Each workpiece had to be held in position against stops over a workpiece sensor mounted in the lower die. The foot switch would then be depressed, causing the upper die to make a full cycle down on to the workpiece and back to the top of the stroke. Subjects were informed as to the incentive and penalty rates and were instructed in the procedure for correcting simulated equipment problems.

In this experiment each subject was presented with 14 problems in the simulated tooling (4·9 events/h) which, if not corrected, resulted in simulated equipment damage. The problem events were randomly distributed within the test period. A training session was provided which included task instruction and 20 min of practice on the simulator. The 170 min test consisted of two 85 min segments with a 10 min break. Subject data about past and present work experience as well as data regarding the experiment were collected in a post-test debriefing.

Results

Equipment damage errors (n = 310) were analysed as the measure of operator error in initiating a machine cycle. Simulated injuries alone could not be used because their frequency (n = 16) was too low to permit adequate statistical analysis; nevertheless, this would seem a high number of injuries for 192 h of subject task performance. The simulated injuries were dispersed over nine of the 16 experimental conditions. One condition (hard-to-push, standing, step feedback, difficult task) showed three of the simulated injuries. It is of interest that this condition also had the highest number of equipment damage errors (n = 33). Fault events were properly corrected 65·4% of the time.

A multi-way frequency table of observer errors was constructed and a log-linear model (Nelder, 1974) containing the four variables selected for study without covariates was used to examine the data. A log likelihood test of main and interaction effects yielded a Chi-square statistic appropriate in comparisons of frequency data such as the error frequencies collected in this experiment. Table 1 summarises the results of this test.

As can be seen, the hand task main effect was shown by this model without covariates to be a significant predictor of error (p = ·0001). Of the 11 interaction effects, four were statistically significant (p = ·05). The TPD interaction in the model without covariates is presented in Table 2 because it showed unexpected high error frequencies for both hard-to-push and for easier-to-push switches on jobs with different characteristics.

A forward stepwise multiple regression analysis was performed on the three covariables: hit rate, age and experience. Table 3 summarises the results.

Of particular importance is the result that subject hit rate proved to be the best predictor of damage errors with an R square of ·574. As can be seen, age and particularly post-training experience had little or no effect. An ANOVA was performed to determine if the four variables had any effect upon subject hit rate. A summary of these results is presented in Table 4. As expected, the results show that only the hand task variable was statistically significant.

Table 1: Multi-way frequency analysis showing main and interaction effects of the four experimental variables on foot switch initiation errors resulting in equipment damage events

Effect	DF	Likelihood ratio Chi square	Prob
Hand Task (T)*	1	14·65	0·0001
Working Position (P)	1	0·20	0·6537
Pedal Feedback (F)	1	3·64	0·0563
Pedal Difficulty (D)	1	2·83	0·0923
TP	1	3·09	0·0788
TF	1	3·22	0·0727
TD*	1	4·40	0·0360
PF*	1	4·33	0·0375
PD	1	0·33	0·8544
FD*	1	5·43	0·0198
TPF	1	0·20	0·6541
TPD*	1	5·22	0·0224
TFD	1	1·02	0·3118
PFD	1	1·82	0·1776
TPFD	1	0·61	0·4358

Table 2: Damage error frequencies for working position, pedal difficulty and hand task

		Working position				
		Sitting		Standing		
	Pedal difficulty	Easy to push	Hard to push	Easy to push	Hard to push	Totals
HAND TASK	Stamp 1 end (simple)	40	26	23	32	121
	Stamp 2 ends (complex)	31	54	46	58	189
	Totals	71	80	69	90	310

Table 3: Multiple regression analysis results summary showing the forward stepwise contribution of Hits, Age and Experience to predicting equipment damage errors

	Multiple R	R-square	R-square change
Hits	0·75770	0·57411	0·574
Age	0·78682	0·61908	0·044
Experience	0·78689	0·61919	0·000

Fig. 7 presents a plot which illustrates the indicated correlation between hit rate and error frequency. Particularly worth noting is the fact that no damage errors were made by subjects whose mean hit rate was less than 17·5 hits/min. Since hand task was a significant main effect in separate models for hit rate and for errors, Fig. 2 is plotted with two symbols to clarify the differences which might be associated with hand task. If the subject was performing an easier (single hit) hand task the point is plotted with a numeral 1 and if performing a more difficult (double hit) hand task, with a numeral 2. Careful examination of Fig. 7 indicates a 'cloud' of 1s below and to the left of a 'cloud' of 2s. The mean values for the single-hit task (21·97 hits/min, 3·94 errors/subject) and for the two-hit task (24·33 hits/min, 6·06 errors/subject) appear to lie along the line of the data as a whole. This would seem to indicate that hand task would not be a significant factor in an error prediction model if the effect of hit rate were considered in the model.

The importance of hit rate as a covariate was examined. A new log-linear model (Model 1) which included hit rate (R) was examined.

Model 1 (with estimated coefficients)

$$\text{LOG [Predicted Error Frequency (e)]} = (-1{\cdot}6 - 0{\cdot}02T + 0{\cdot}15R - 0{\cdot}03P - 0{\cdot}02D - 0{\cdot}17F)$$

Table 4: ANOVA summary showing main and interaction effects of the four variables on hit rate

Source	Sum of squares	Degrees of freedom	Mean square	F	Tail probability
Mean	33797·84852	1	33797·94952	1944·37	0·0000
Working Position (P)	0·53097	1	0·53097	0·03	0·8620
Hand Task (T)	113·72027	1	113·72027	6·54	0·0137
Pedal Difficulty (D)	0·09401	1	0·09401	0·01	0·9417
Pedal Feedback (F)	0·05995	1	0·05995	0·00	0·9534
PT	32·14723	1	32·14723	1·85	0·1802
PD	9·13728	1	9·13728	0·53	0·4720
TD	38·61343	1	38·61343	2·22	0·1427
PF	28·97764	1	28·97764	1·67	0·2928
TF	29·10444	1	29·10444	1·67	0·2019
DF	49·05149	1	49·05149	2·82	0·0995
PDT	20·65569	1	20·65569	1·19	0·2811
PTF	2·95789	1	2·95789	0·17	0·6818
PDF	3·95016	1	3·95016	0·23	0·6357
TDF	6·50625	1	6·50625	0·37	0·5436
PTDF	5·45703	1	5·45703	0·31	0·5779

A test statistic for comparing the importance of each of the five factors in this new model is given in Table 5. It can be seen that it is quite important to have hit rate (R) in the model. Table 6 summarises results of the experiment and predictions of error frequency based on Model 1.

Interactions which were significant when the hit rate covariate was not in the statistical model (see Table 1) were similarly tested and found not significant in models containing this covariate.

A Model 2, which contains only error frequency (e), hand task (T), and hit rate (R), was examined to test whether the significance which was previously seen for hand task (see Tables 1 and 4) would still exist or if its apparent significance was only a matter of one task requiring more hits to finish a workpiece than the other task.

Model 2 (with estimated coefficients)

LOG [Predicted Error Frequency (e)] = (−2·52−0·05T + 0·17R)

Table 7 shows a large change in χ^2 when hit rate is omitted from Model 2 but not when the hand task which required more foot tapping is omitted. This suggests that the amount of repeated foot activity and the amount of repeated hand activity have quite separate effects on inadvertent use of foot switches.

Discussion

The most striking result of the experiment was the way that hit rate (hits/min) affected the ability of the subjects to control their foot movements and avoid foot switch initiation errors. While it was expected that damage errors would increase as hit rate increased, it was not expected that the correlation would be as high as ·76 and that speed would account for 57·4% of the variance.

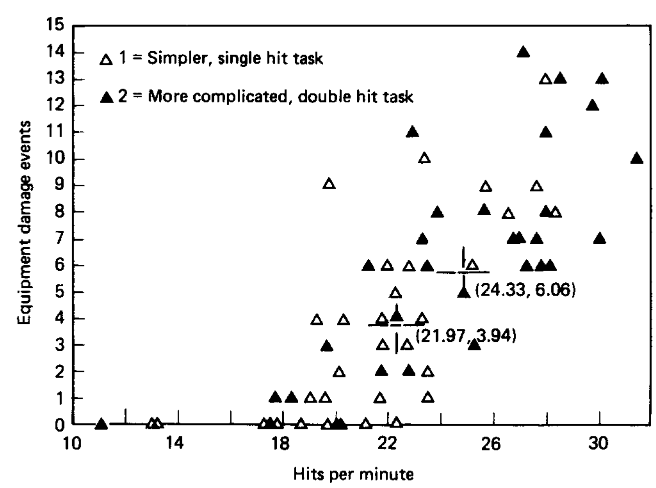

Fig. 7 Plot of equipment damage events as a function of subjects' mean hits

In view of this evidence, hit rate appears to be a major factor contributing to foot switch initiation errors. These results suggest that there may be some threshold or critical speed (approximately 17·5 hits/min for the tasks in the present study) at which operators performing repetitive tasks begin gradually to lose effective control over their foot movements. The covariates for age and experience were not tested for their effect on this error threshold because they had previously been shown to be insignificant predictors of error.

Before conducting the experiment, it was reasoned that more inadvertent actuations would always be expected with the easier-to-push or softer pedal because it would simply be 'easier' to make a mistake. To explain the generally contrary observed result, it is tempting to propose neurophysiologic hypotheses about how the foot's movements are controlled. However, a more practical assumption is

Table 5: Leaving hit rate out of the error prediction model makes a significant difference in its predictive capability

	χ^2
Model 1	83·4
Model 1 without Hit Rate (R)	188·8
Model 1 without Hand Task (T)	83·4
Model 1 without Working Position (P)	83·5
Model 1 without Pedal Feedback (F)	86·0
Model 1 without Pedal Difficulty (D)	83·5

Table 6: Observed and predicted errors in foot switch use for the 16 experimental combinations

		D1		D2	
		T1	T2	T1	T2
F1	P1	E = 4·5 e = 5·0 R = 22·9	E = 7·5 e = 8·2 R = 25·0	E = 4·7 e = 4·1 R = 22·4	E = 2·5 e = 3·2 R = 19·3
F1	P2	E = 6·0 e = 6·2 R = 24·0	E = 7·7 e = 6·5 R = 25·1	E = 3·5 e = 3·3 R = 21·3	E = 7·5 e = 7·5 R = 25·3
F2	P1	E = 2·0 e = 2·3 R = 20·1	E = 6·0 e = 6·2 R = 25·9	E = 6·0 e = 4·8 R = 24·3	E = 5·7 e = 5·1 R = 24·6
F2	P2	E = 2·0 e = 2·7 R = 18·0	E = 6·7 e = 5·3 R = 24·7	E = 2·7 e = 3·1 R = 21·5	E = 4·7 e = 6·4 R = 24·8

Experimental conditions
- D1 = Hard to Push Pedal
- D2 = Easy to Push Pedal
- F1 = Pedal with Step Feedback
- F2 = Pedal without Step Feedback
- T1 = Stamp 1 End (Simpler Task)
- T2 = Stamp 2 Ends (More Complex)
- P1 = Sitting while Working
- P2 = Standing while Working

Observed and estimated results
- E = Observed Errors/hr
- e = Predicted Errors/hr
- R = Rate of Foot Tapping (hits/min)

Table 7: Although a different hit rate is expected with the two different kinds of hand task in the experiment, only the difference in hit rate and not the difference in hand task makes a significant difference in the predictive value of the model

	χ^2
Model 2	113·25
Model 2 without Hit Rate (R)	232·18
Model 2 without Hand Task (H)	113·40

Table 8: Job characteristics and foot switch type having fewer observed errors. Consideration of these results could reduce inadvertent actuation injuries at machine workstations which combine a repetitive hand task with foot switch initiation control

Job characteristics	**Foot switch type having fewer observed initiation errors**
Simple repetitive hand task and operator standing	Easier to push
Simple repetitive hand task and operator seated	Harder to push
Complex repetitive hand task and operator standing	Easier to push
Complex repetitive hand task and operator seated	Easier to push

that a subconscious effort is operative in the inadvertent foot movements being examined here. Therefore the person who has operated a foot switch-controlled machine for a certain period of time has that activity 'ingrained' in his or her central nervous system processing. If one wants to make the operator aware of the foot switch operation, the operation itself must become randomly variable. Perhaps this might be accomplished if a pedal needed more pressure at one time than another, with the changes random so as not to 'ingrain' the response. Such an approach would need to be considered carefully because it could conceivably cause errors due to distraction, annoyance or anxiety if output were reduced.

The lack of a significant difference between hard-to-push and easy-to-push pedals could also be due to the selection of pedal resistance values to be studied. It may be that the ratio between hard and easy (6·50 kg and 2·80 kg, gives 2·3 : 1) was not great enough. If pedals with larger variations in resistance and in distance travelled had been tested, different results may have been obtained. No specific literature was found to guide selection of pedal forces used on this type of switch for the tasks being studied in this experiment. Also, the relatively short distance (4 mm) over which the step feedback acted may have provided an inadequate test of the pedal feedback variable. Greater travel distances for the harder-to-push portion of the step could lead to different test results.

Conclusions

When trying to identify the safest or best control for any machine workstation one should keep the following in mind:

There are no 'good' or 'poor' controls as such: the goodness of any control depends upon its appropriateness to the task for which it is assigned. (Ely *et al,* 1956)

While the simulated damage errors which were observed in this experiment are not workplace injuries, they are related. First, the subjects' tasks and the speeds at which they performed them closely resemble normal tasks at machine workstations. Subjects performed under monotonous task conditions typical of those found in actual workplaces and had an opportunity to develop strong task habits. Second, acting in response to the experiment's error-inducing conditions (equipment problems), subject behaviour (inadvertent foot control activation) was similar to behaviour described in the information processing model of injury described in Trump and Etherton (1985). This model suggests two factors which interact to cause inadvertent actuation of foot controls on industrial machines:

1. People make unmediated hand movements in response to workpiece and machine problems, and
2. Out-of-sequence foot control movements are produced by (a) the effects of normal task rhythm acting upon the operator, and (b) the loss of operator balance.

In the light of the results, there are two considerations worthy of notice by designers of workstations at which foot controls are used to perform repetitive industrial tasks. Taking these considerations into account could help to minimise foot switch actuation errors.

First, consideration could be given to using simulation to predict an error threshold (the limit beyond which the frequency of inadvertent actuation errors begins to increase with increasing rate of foot tapping) for combined foot-switch/manual-handling tasks. A critical hit rate point was determined for the tasks performed in this study (17·5 hits/min). This critical point is probably not generalisable to all repetitive foot-switch/manual-handling tasks at machine workstations. However, within a select set of tasks at a particular machine workstation, a sample of experienced machine operators was found to have a pattern of increasing numbers of erroneous foot switch uses with increasing rate of foot switch tapping. If a critical point does in fact exist, its location would probably best be thought of as a minimum error level as opposed to a zero error level with speed/accuracy trade-offs relating it to the work incentive plan in use.

The use of simulation for error threshold prediction on a particular task in the workplace would permit employers to determine if operators are performing their tasks at dangerously high hit rates. Knowing this critical hit rate, the employer could then choose a course of action to bring operator hit rates below the critical point by altering the task until observed hit rates are below that task's error threshold. For example, multiple dies might be used to lower operator hit rates while maintaining production requirements. Assuming that the loading procedure for each of the multiple dies is similar to the single die loading procedure, elapsed time between machine cycles would be greater for multiple dies than for a single die since die loading time for each cycle would be increased. The results of such a tooling change could bring operator hit rates below the critical rate for this way to do the task, yet still maintain production.

If production is to continue above the critical hit rate, then causes for inadvertent actuation errors should be eliminated. Die stops should be designed so as to ensure that positioning of the workpiece in the die will be correct and parts do not easily slip out of proper location for stamping. Also, if scrap is created, it must be removed effectively so that it does not fall into the die, creating a situation for an inadvertent hit. It may prove practical to assign foot-controlled machines to workers whose hit rate is below the error threshold. Using hand control instead of foot control would be another way to avoid the error threshold problem.

The second consideration for workstation design is having an 'easier-to-push' foot control for some tasks and a 'harder-to-push' foot control for other tasks. In this experiment, a foot switch with one resistance to foot pressure did not have the best potential for error reduction for all of the machine workstation-task combinations examined. The effort needed to break a habit in repetitive foot motion and the depth to which a foot motion can become embedded in a particular multi-limb task stream are human factors yet to be measured.

It is suggested that newly designed foot controls or procedures be tested before they are placed in the workplace, and that the appropriate safety standards be adhered to. Interested readers are referred to Trump and Etherton (1985) for general safety considerations in designing workstations which use foot control.

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