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Foreseeable errors in the use of foot controls on industrial machines

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Foot controls are a productive actuator for many tasks on reciprocating action industrial machines such as power presses, spot welders and press brakes. However, amputations sometimes occur when a foot control is inadvertently depressed when an operator reaches into the danger point of the machine. This report uses occupational injury statistics, workplace observations and a review of selected literature to propose a model of inadvertent use of foot controls. This model serves as the basis for conducting a subsequent machine safety simulation experiment in a metal products fabricating factory. Primary model elements are unmediated hand movement, mental slips associated with task rhythm, and loss of balance. To avoid injury due to inadvertent use of pedals, workstation designers may wish to consider using automated or hand control devices in lieu of foot controls. Alternatively, if foot control is the selected method for actuation, then they may wish to consider mitigating the error-inducing effects of machine tooling problems and repetitiveness by using safeguarding which is difficult to circumvent or redundant safeguarding devices at the point of danger.

Keywords: Errors, safety, machine control

Introduction

Commonly contained in compensation reports as the cause of worker hand and finger amputation injuries at industrial machines is the short phrase "... inadvertently stepped on the foot control." Approximately 700 machine operators each year in the US suffer an injury on a foot actuated machine, at a cost of approximately $2·4 million (based on a conservative 1980 average of indemnity and medical costs in the State of Arkansas). But foot controls remain a productive actuator alternative for many industrial machine operation tasks. Identifying ways to pre-empt critical causal sequences in the inadvertent actuation of industrial machine controls is one method for achieving the US Public Health Service objective to reduce or eradicate the incidence of selected US workplace injuries.

Foot controls have been the focus of previous studies involving control location and pedal resistance, size and surface texture, most notably Ayoub and Trombley (1967), Corlett and Bishop (1978), Drury (1975), Ely *et al* (1956), Garde (1978) and Kroemer (1971). Foot controls have also been discussed in various machine design guidelines and ergonomics handbooks, including Damon *et al* (1966), Grandjean (1980), McCormick (1970), Murrell (1969), Van Cott and Kinkade (1972), Wilco, Inc (1976) and Woodson (1981). While this literature provides recommendations for the selection and use of foot controls in non-repetitive situations such as in airplanes and automobiles, there are few specific recommendations aimed at the selection and use of foot controls for repetitive industrial machine operations.

There may be as many as 2000 various combinations of unsafe operator actions in the use of foot controls (Winsemius, 1965). A human information processing model and simulation tests of such a model can be a means to reduce the perceived variety in certain human movements such as the movement involved in amputations and inadvertent depression of foot controls. By analysing injury report information, workplace observations and selected literature, a description is derived which reduces to a few elements how foot controls are used in the workplace, and a model is proposed of how workers inadvertently actuate them. In a subsequent report, results will be presented on simulation tests of the model.

Foot controls

Foot controls are commonly installed on industrial machines to improve operator performance and to reduce inconvenient and uncomfortable workstation situations. They are also used when the operator must use both hands to move a workpiece in and out of the point of operation or to support the workpiece during machine operation. Alternative means for initiating machine motion include hand contact devices (palm buttons), non-contact sensor devices (light curtains), and automatic initiation circuitry.

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Three popular types of foot-operated controls were observed during plant visits made by the authors (Figs. 1, 2 and 3).

1. *Foot switches*

- Usually have internal electrical switches which, when triggered, cause the machine to operate or cycle.
- Normally have guarding on the sides and top to prevent falling objects from accidentally activating them.
- Are attached to industrial machines by flexible electric cable and can be moved on the floor surface to a location which is convenient and comfortable to the operator.

2. *Pedals*

- Are rigidly attached to the machine and cannot be moved to different floor locations, except on machines which have special tracks to permit them to be moved limited distances, or removed entirely.
- Operate the machine through an arrangement of levers, unless electrical switches have been installed between the machine and pedal.
- Typically have no guarding to prevent falling objects from accidentally activating them.
- Are usually located 6 in (158 mm) or more above the workplace floor.

3. *Treadles*

- Can be thought of as extra-wide pedals, sometimes running the entire width of the machine.
- Are rigidly attached to the machine and cannot be moved to different floor locations.
- Operate the machine through an arrangement of levers unless electrical switches have been installed.
- Seldom have guarding to prevent falling objects from accidentally activating them.

During workplace observations, more than 25 different kinds of foot control were encountered. Most of the foot controls were commercially manufacturerd, although some were fabricated by the employer or were modifications of commercially manufactured switches.

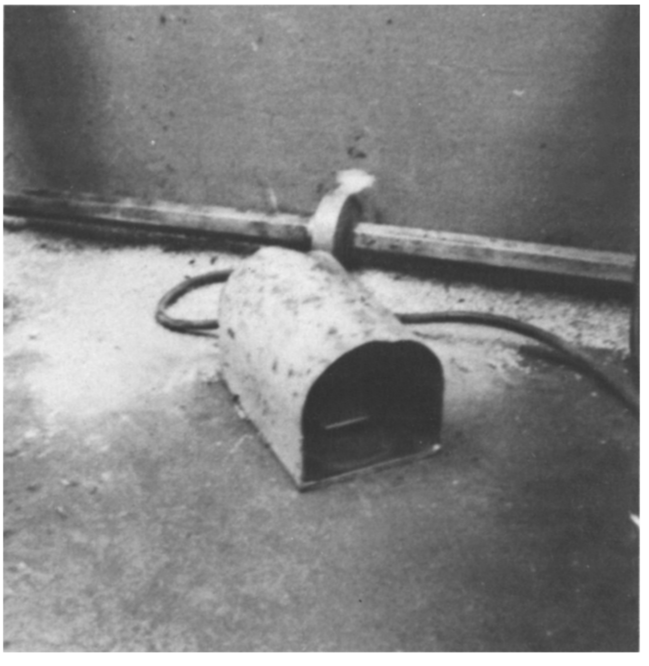

Fig. 1 Foot switch

Fig. 2 Pedal

Fig. 3 Treadle

Tasks at foot control actuated machines

Varied industrial machines are operated by foot controls, including mechanical power presses, resistance welders, press brakes, sheet metal shears and riveting machines. These machines, although performing different industrial processes, have two factors in common: (a) they use vertical reciprocating machine motions and (b) they are associated with repetitive tasks.

Vertical reciprocating machines (opening and closing dies or tooling) delivers the mechanical force needed to cut, bend, form, rivet or weld metal or other materials. The closure of tooling can be relatively slow or can take place in a fraction of a second. Closure can be initiated by foot movement on a foot control when the hands are near the tooling to load and unload workpieces.

Typical task elements include manually picking up a workpiece, positioning it under tooling, pressing the foot control, and removing the workpiece. Jobs performed on industrial machines equipped with foot controls can be highly repetitive. Garde (1974) reports that an employee can insert around 20 000 workpieces into a machine during a single 8 h shift, which means the employee could be inserting work at the rate of approximately one part every 1·25 s.

Statistics

Three data sources on workers injured at machines provide information on the prevalence of foot control on machines at which injury occurred. Arndt (1981) studied a sample of 1164 workers injured in Wisconsin between 1970 and 1977 at presses, shears, press brakes and riveting machines. Foot control was the initiation means on 48·5% of these machines (see Table 1). The US Department of Labor (Office of Standards Development, 1980), in annual reviews between 1975 and 1980 encompassing over 1250 cases of amputation and injury at the point of operation of mechanical power presses, found that between 62% and 68% of the reported injuries occurred on presses equipped with foot controls (see Table 2). In a study of injuries to 1200 Swedish press operators, Garde (1974) reports that 58% of the injuries at part-revolution clutch machines and 97% of the injuries at full-revolution clutch machines were on presses equipped with foot controls (see Table 3). From these figures, one cannot conclude that foot control is a sufficient cause for injury, but it is clear that machines equipped with foot control are involved in a high percentage of injuries. As the next section will show, there is a particularly dangerous correspondence between foot controls and failure to guard adequately.

Foot control and safeguarding

Foot controls, unlike other kinds of machine initiation devices (two-hand controls; presence-sensing device initiation; distance with automated initiation) do not provide an intrinsic means of separating operators from the machine's point of operation during tooling closure. Persons operating industrial machines initiated by foot control have their hands near tooling and must be protected by devices not always directly linked to the control of machine operation.

Table 1: Injuries to operators of several different metal-working machines in Wisconsin (includes presses, shears, press brakes and riveting machines) (%)

	Mode of operation			
	Foot	Hand	Automatic	Other
Years 1970–77	48·5	23·3	5·5	22·7

Table 2: Injuries to mechanical power press operators (Based on about 1250 injury reports from 24 States) (%)

	Mode of operation		
Year	Foot	Hand	Automatic
1975	62	27	11
1976	63	26	11
1977	63	30	7
1978	64	31	5
1979	64	25	6
1980	68	27	5

Table 3: Injuries to Swedish mechanical power press operators (Based on 1200 accidents occurring between the years 1964–1970) (%)

	Mode of operation		
Type of clutch	Foot	Hand	Automatic
Part-revolution	58	12	29
Full-revolution	97	1	2

Some of the recognised safeguarding methods* when foot controls are used include: attachments to the hands which pull them out of or hold them out of a danger point; barrier guards which fully enclose the point of operation; and supervised feeding of workpieces which are large enough to keep operator body parts at safe distances from potential injury points.

Unfortunately, operators are not always protected by properly installed and maintained safeguarding. Some reasons are:

- On machines which work on different shape parts each needing a different guard, it may take more time to implement safeguarding than it takes to run a job.

*In the US see 'Occupational Safety and Health Administration Safety and Health Standards' (29 CFR 1910), US Dept of Labor, for safeguarding methods.

- Operators sometimes defeat safeguarding; e g, remove a guard for their convenience or to increase output.
- Safeguarding is not always adjusted properly. This may be a problem with pullout and holdout devices if people with different hand size and arm length work on consecutive shifts at the same machine.

Also important for operator protection is the use of covers over foot controls to prevent falling objects from accidentally striking a pedal. Typically, these covers are placed over and on both sides of the pedal. Some foot control manufacturers instal 'foot-operated doors' which must be opened with the foot before the pedal can be pressed. Such controls have been observed to have the doors either removed or 'fixed' open.

Current safety considerations for foot controls

Available recommendations for careful selection and use of foot controls are quite general and do not emphasise certain human limitations which contribute to inadvertent use of the control in repetitive industrial applications.

The following considerations on foot controls were compiled from various sources and should be considered within the context of applicable standards and hazard analyses for specific machine systems.

- A foot control should be used only with full barrier guards or with interlocked gates as point-of-operation protection.
- A sitting working position is preferred if a foot control is to be used.
- Riding the pedal (keeping the foot on the pedal when not actually depressing it) is hazardous and should be discouraged by any feasible means.
- A foot-rest near the pedal reduces strain on the foot.
- Protect the foot control against accidental actuation from falling or moving objects or from another person accidentally stepping on the control.
- Provide interlocking safeguards so that the foot control is inoperable when the safeguards are not functioning.

Injury and inadvertent actuations

To comprehend fully the human limitations in inadvertent activations during repetitive tasks, we should understand:

- circumstances under which the operator can make an unmediated hand movement, and
- reasons why the operator is likely to press the foot control out of sequence with an unmediated hand movement.

Unmediated hand movements

Workplace observations, accident report analysis and review of the literature revealed that workpiece and machine related problems can 'trigger' what we will refer to as unmediated hand movements. This is the sort of hand movement seen when an operator sees scrap in the machine dies and quickly attempts to remove it to avoid equipment damage. Unmediated movements primarily involve quick reaching responses, made without lengthy or conscious deliberation, to an immediate problem. The operator spends very little if any conscious processing time analysing stimuli and programming a sequence of responses: he merely 'calls up' an existing response which typically has worked in the past, and then acts. In this regard, Welford (1968) tells us that " . . . the execution of movements is in important ways distinct from the decisions to initiate them." Winsemius (1965), in an investigation of accidents on a repetitive task, reported an example of unmediated hand movements where operators sometimes quickly reached into the dies of book cutting machines to fold back sticking book pages after they had pressed the foot control.

Industrial machines equipped with foot controls can be operated for hours without any problem. However, there are occasional problems which do occur, particularly during long production runs when the equipment as well as the operator is getting tired. Workplace observations and accident report analysis revealed that problems which occur during machine operations which have triggered unmediated operator hand movements are either workpiece or machine related. A response to a *workpiece problem* usually involves a single "reflex-like hand movement" which requires the operator to put his hand in the die area, manipulate a workpiece and then retract his hand; e g, seeing a misaligned workpiece, an operator may impulsively reach to reposition the piece before cycling the machine. A response to a *machine problem* usually involves multiple-step tasks which require the operator to assume several standing and/or sitting positions in order to pick up and return tools, brushes, lubricating compounds and so on, for example, misaligned dies that require operator adjustment before cycling the machine. The US Department of Labor (1981) identified both the workpiece problem and the machine problem in a study of injuries related to servicing industrial equipment. Arndt (1981) reported similar findings regarding operator activity when foot controls were inadvertently tripped (see Tables 4 and 5).

The literature suggests that the process of detecting workpiece and machine problems is an unmediated, rather than a mediated process; that is, the operator is not consciously searching for problems but has learned to recognise if they are present. Norman (1981) and Kahneman (1973) both present evidence indicating that individuals, although they may be attending to other stimuli, can detect stimuli they consider important if they see, hear or feel them.

Out-of-sequence foot movement

Three types of pedal depression by the foot, which are out of sequence with unmediated hand movements, can be identified:

- Accidental – the operator can unknowingly step on the pedal because he is unaware of the control's floor location.
- Mental slips – the effects of the normal task rhythm can cause the operator to 'automatically' press the foot control during an unmediated hand movement.
- Loss of balance – the operator can lose his balance while leaning forward with his hand in the dies and press the foot control.

The mental slip and loss of balance are factors which are only marginally emphasised in the literature on foot controls. This analysis will now focus attention on these factors.

Table 4: Worker activity in dealing with machine and workpiece problems at the time of injury during servicing

Activity	%
Unjamming object(s) from equipment	30
Cleaning equipment	29
Repairing equipment	9
Performing maintenance (oiling, etc)	4
Installing equipment	2
Adjusting equipment	12
Doing set-up work	7
Performing electrical work	3
Inspecting equipment	2
Testing material or equipment	1
Other activity	Less than 0·5

Table 5: Type of operator activity associated with inadvertent activations of foot controls during all phases of operation

Type of operator activity	%
Feeding, removal or holding workpiece	54·8
Stuck workpiece, scrap removal, adjustments	17·1
Other unknown	28·1

Normal task rhythm habit in sequence and in timing

Normal task rhythm develops when: (a) the same task steps are repeated again and again, (b) the task steps are always in the same sequence, and (c) task steps occur at about the same time in the task sequence. Once established, the effects of the normal task rhythm act upon the operator to cause him routinely to press the foot control at regular intervals when performing the task. If an unmediated hand movement (e g, reaching into the dies to remove scrap) is not synchronised with a normal task rhythm, the operator may cycle the machine when his hands are between the dies.

The effects of normal task rhythm develop most quickly and strongly in highly repetitive task situations, like those involving industrial machines operated with foot controls. The primary reason for this is that a repetitive task is quickly learned and is soon reduced to a series of habitual movements. When this occurs, the operator may direct his attention 'internally', thinking about vacations, fishing, ballgames, etc, to relieve the boredom created by the monotonous task, or the operator might direct his attention 'externally', talking with a fellow worker. The important fact is that the operator's attention is directed away from monitoring each movement that he makes. Thus, should some new movement be initiated, such as reaching into the dies to unjam a workpiece, the operator may be unaware that his foot is continuing to press the foot control.

An operator's task that has become a habit may be difficult to change or modify. Operator habit acts in a powerful way to prevent desired change in the task. Once a habit is formed, *real* effort on the part of the operator is required to change it or modify it.

Barnes (1963) reported on a situation which illustrates this point. For years several metal polishers were accustomed to make a definite number of strokes across a polishing wheel to finish a typewriter part. When the part was redesigned to require fewer strokes, the polishers continued to make the same number of strokes. Only after 4 days with constant and persistent attention, did the polishers change their habit and adjust to making fewer strokes.

Miller *et al* (1960) suggest that habits are originally voluntary plans which have become relatively inflexible, involuntary and automatic through overlearning. Certainly the highly repetitive tasks on industrial machines with foot controls qualify as overlearned tasks. This 'habit' could explain why operators sometimes step on foot controls out of sequence with unmediated hand movements.

Other evidence suggesting that habit plays an important role in inadvertent activation of foot controls comes from the report by Arndt (1981). This report indicated that 'accidental trip' (operator did not intend to trip the machine) accounted for 30% of the analysed injuries. These accidents might be attributed to operator habit. Norman (1980, 1981) and Reason and Mycielska (1982) provide us with psychological theories on the role of human errors in accidents through classification of certain human errors as slips where they occur when a person makes an action that is not intended. An important aspect of slips is that the more skilled the person, the more likely the person is to make a slip. Welford (1976) has noted that "One of the most striking gaps in our knowledge of sequential performance is the mechanism of 'timing', whereby various actions are brought into play in correct sequence and at appropriate moments."

The effects of highly repetitive or monotonous task conditions on individuals have been examined by a number of psychologists. Fiske and Maddi (1961) stated that performing under monotonous task conditions presents the problem of maintaining attention and of avoiding distraction. Under these conditions, there is a shifting of attention away from the task toward internalities such as daydreams, aches and pains, lethargy, irritability or restlessness. Typically, a performance decrement may occur 20 to 30 min from task beginning or as much as 1 or 1½ h later. Thackray *et al* (1973) also found that performance decrement occurs within 20 min. Fiske and Maddi (1961) also indicated that performance may improve due to sustained motivation or a break in the monotony, e g, answering a phone.

Thackray *et al* (1973, 1974, 1975) report on physiological, subjective and performance correlates of boredom and monotony as well as correlates of performance decrement on monotonous tasks requiring sustained attention. According to their studies, individuals susceptible in daily life to distraction were found to have difficulty sustaining attention on a monotonous task, while those individuals less prone to distraction did a better job with less decline in attention. Their studies also found that high boredom and monotony caused longer response times, greater heart rate variability and more strain.

Weber *et al* (1980) have found that the psychophysiological effects of repetitious tasks are elevated heart rate and adrenaline production. They also found that repetitive tasks requiring discrimination caused high neck tension.

Loss of balance

Loss of balance is another contributing factor in inadvertent actuation of foot controls. If an operator, who is riding the foot control, reaches forward and loses his balance, he may try to regain his balance by applying downward pressure on his toes to change the body's centre of gravity. The obvious result is that the operator inadvertently actuates the foot control and cycles the machine, sometimes with his hand between the dies.

Safety personnel, supervisors and machine operators interviewed by the authors expressed a common belief that loss of balance while riding the foot control was a factor in many inadvertent actuations. An operator rides a pedal if the foot rests on the pedal surface in its raised, unclosed position as opposed to taking the foot off the pedal and resting it on the floor. This belief seems to be well founded, since at all facilities visited during the field observations, operators were seen riding the controls.

A proposed model

The model represented in Figs. 4 and 5 illustrates: (a) how the effects of an established normal task rhythm and an unmediated hand movement can interact to produce an error in foot control operation, and (b) how this error can lead to a near miss or injury to the operator's hand. Fig. 4 represents a set of co-ordinated hand and foot movements typically associated with the safe operation of industrial machines with foot controls. Fig. 5 shows how these hand and foot movements may become un-co-ordinated and thus unsafe after the operator detects a workpiece problem.

The proposed model assumes that the operator has shifted his attention from monitoring continuous task cues toward internal and external stimuli while performing a highly repetitive task. Consequently, a normal task rhythm has established itself, and the operator's hand and foot motor movements are running on 'automatic'. As noted previously, these operator internal conditions can be affected by such factors as incentive rate motivation, health, environmental aspects (e g, heat stress, noise stress, etc) and social aspects (e g, peer pressure, supervisor pressure, etc). Rubinsky and Smith (1971) found that while individuals operating a simulated foot-actuated power press under incentive rate had a significant increase in productivity over individuals not on incentive, the same incentive-rate individuals had significantly more simulated injuries.

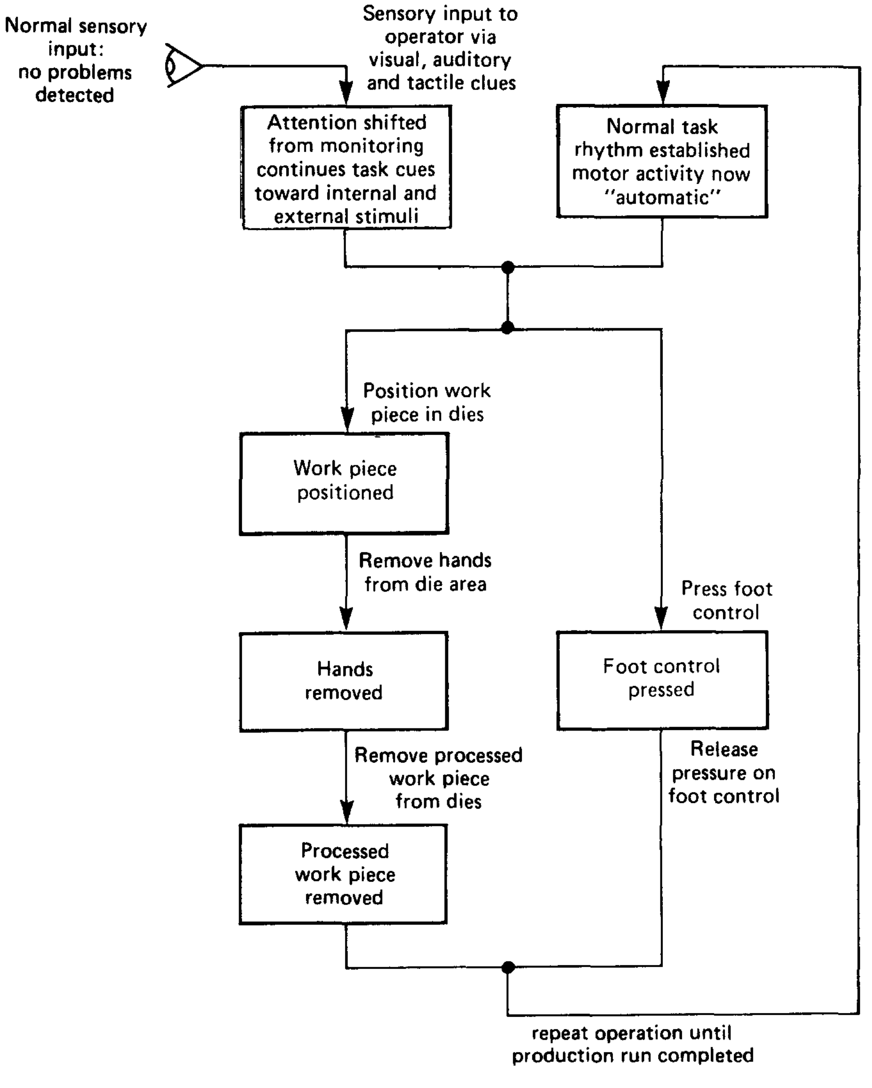

Fig. 4 **Diagram showing operator's foot movement co-ordinated with hand movement**

The proposed model represents a simple repetitive process in which the operator:

- positions a workpiece in the machine dies;
- removes his hand from the die area and at approximately the same time presses the foot control to cycle the machine. This is an important aspect of the model and is depicted in the diagrams by the dual lines which flow downward. Workplace observations revealed that operators typically 'hit' the foot pedal at about the same time they began to remove their hands from the die areas, most likely anticipating the time delay before the machine cycles; and
- removes the processed workpiece following the completion of the machine cycle.

This task would be repeated over and over until the production run is completed, which may take hours or several workdays.

Whenever the operator makes an unmediated hand movement, the routine of this highly repetitive task is affected and can sometimes result in unpleasant consequences, as shown in Fig. 5. Here the operator detects a workpiece problem (misaligned workpiece) just after he positions the workpiece in the dies (block 3) and makes an unmediated hand movement (block 4). Since the effects of normal task rhythm would act to cause the operator to continue to press the foot control (block 6), even though his hand is in the dies realigning the workpiece, the machine is cycled with his hands in the dies. The result is a near miss or injury.

Workpiece and machine problems can occur at any time in the task and may or may not be impulsively reacted to. For illustrative purposes they were shown in the proposed model as detected by the operator at a time when there is an injury or a near miss.

Summary and conclusions

The model presented here indicates that several factors can interact to cause inadvertent actuation of foot controls on industrial machines. Two primary factors appear to be:

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.

This report describes a preliminary effort in an experimental study of independent variables in inadvertent activation of industrial foot controls. The experimental study involves simulation of error-producing situations in the workplace.

Tests on independent variables for inadvertent actuation need to be conducted and evaluated to establish human factors design parameters for the proposed information

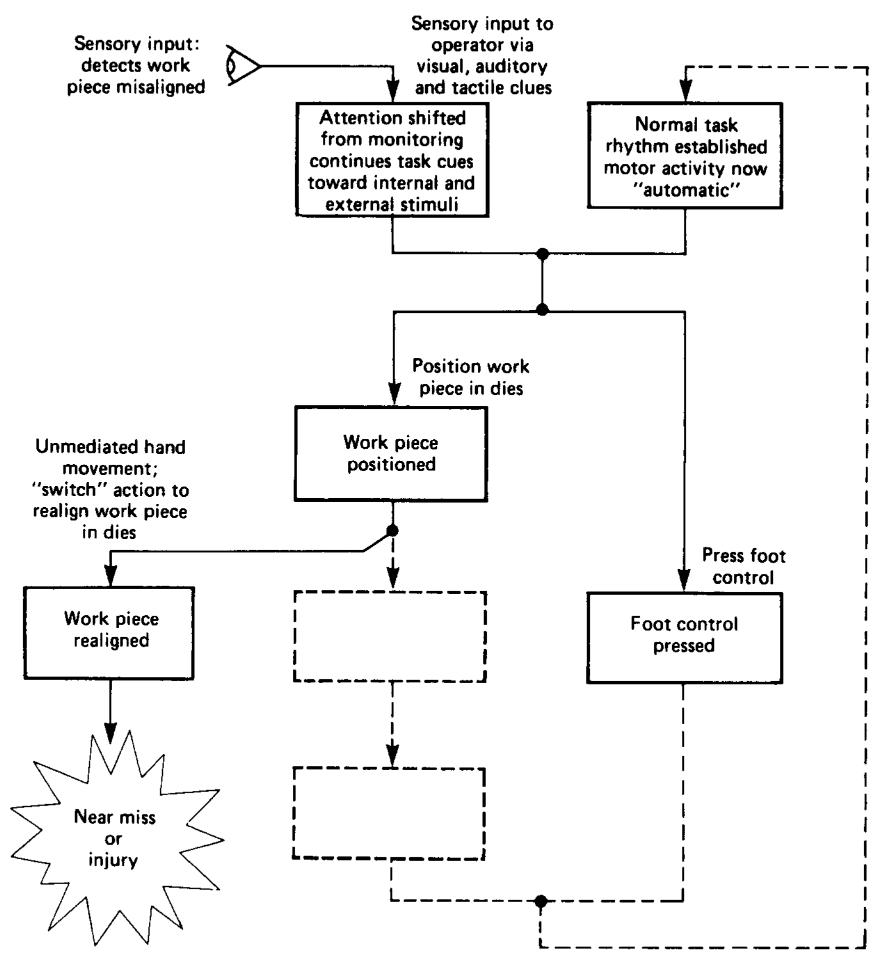

Fig. 5 Diagram showing interrupted co-ordination between hand and foot movement

processing model. In the meantime, general approaches must suffice to the design of workstations and tasks on repetitive machine operations where inadvertent activation of foot controls is considered a likely cause of injury. One should certainly follow recognised principles and standards for safeguarding. Considerations could be given to using another method for initiating hazardous machine action such as two-hand button devices or automated control. Or, if foot control is selected for use, then consider workstation designs which compensate for loss of balance and mental slips under conditions of workpiece or machine problems and repetitiveness and which use difficult-to-circumvent or redundant safeguarding on the point of danger.

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