Safe Distance for Machinery Actuators: Is After-Reach Speed a Constant?

Roger Jensen and Terrence Stobbe

Abstract A common setup for industrial machines is to install a pair of actuator buttons a safe distance from the point of operation. Safety codes specify that minimum distance by assuming a constant hand speed of 1.6 m/s. To examine the adequacy of that value, a simulated power press with a moving ram was set up for measuring actual hand speed for three placements of the buttons. For each placement, a randomized complete block experiment with nine students provided after-reach hand speed data. Results indicated that after-reach hand speed is not a constant because it varies both with placement of the buttons and distance within placement.

Keywords After-reach speed · Safe distance · Machine safeguarding · Power press

1 Introduction

Thousands of workers sustain amputations each year. Using government data, McCaffery estimated that in the year 1977 on-the-job amputations in the United States totaled 21,000 [1]. Of the 21,000 amputations, 96.8 % occurred to the upper

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The first author conducted the experiment as part of his Ph.D. Dissertation entitled *Safe Hand-button Distance for Mechanical Power Presses*, West Virginia University, 1989. The second author chaired the dissertation committee. Neither the experiment nor results have been reported in the open literature prior to this paper.

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extremities (finger, hand, wrist or arm). This finding was followed up by the U.S. Bureau of Labor Statistics with a special survey of workers who incurred a work-related amputation to the upper extremities. Results of the survey indicated that presses were the source of 10 % of the upper extremity amputations [2].

The frequency of press-related amputations prompted a series of investigations by the U.S. National Institute for Occupational Safety and Health (NIOSH) to examine a common hazard in press operations known as "after-reach" [3–5]. The after-reach hazard occurs when the operator reaches toward the point of operation of a power press, shear, or other machine after initiating the down-stroke mechanism by pressing two palm buttons. Such a mistimed reach is thought to be an instinctive reaction by the operator in response to observing that the part was not set squarely in the desired position.

Mechanical power presses and several other types of industrial machines require a method of actuation and a means of safeguarding. A common way to integrate the actuation method with safeguarding is to use a pair of palm buttons for actuation and locate the buttons a "safe distance" from the point of operation. Such buttons are generally referred to as "palm buttons" because they were originally intended to be pushed with the palms of the hands. However, as a precaution against inadvertent pressing of a button, it is considered good engineering practice to surround each palm button with a guard that will make it difficult to unintentionally press a button [6]. This precaution has been incorporated into safety regulations such as those of U.S. Occupational Safety and Health Administration [7]. This protection generally takes the form of a metal ring surrounding the buttons. When a palm button is surrounded by a "ring guard", operators find it difficult to use their palms. Instead they may use their three middle fingers, thumb, or knuckle. Even so, the buttons are still referred to as palm buttons. A survey of mechanical power presses in Finland found that over 60 % are operated with two palm buttons [8].

Safety codes and regulations of industrialized countries specify that when dual palm-buttons serve as actuators for the machine operation, the button must be located no closer than some minimum distance from the point of operation. In a typical mechanical press, this is any location that will be smashed when the ram descends to smash or cut a workpiece sitting on the lower die (or "nest"). This "safe distance" is determined for each press based on two factors: the time to move the hand into the die area (T_{hand}), and the time it takes to remove the hazardous kinetic energy of the descending ram (T_{ram}). One way to remove the hazardous energy is for a brake to stop the descending ram before it impacts the workpiece; the other is for the ram to complete the downstroke.

The current press safety standard used by most countries was derived by making the assumption that after-reach speed can be modelled as a constant. Using this assumption, the standard inequality for calculating safe distance is derived as follows. The operator should be safe when the following condition applies.

$$T_{hand} > T_{ram} \tag{1}$$

The approach used to create a safety regulation out of this inequality has been based on the assumption that the hand movement can be adequately described by the basic equation of uniform motion:

$$distance = velocity \times time, \tag{2}$$

where velocity is a vector. In practice, however, velocity is replaced by speed (a scalar). By replacing velocity in Eq. 2 with speed (S), the equation becomes distance = S × time. Rearranging the equation to have time on the left side gives

$$time = distance/S. \tag{3}$$

By replacing distance with safe distance (SafeD) in Eq. 3, the equation for uniform motion may be expressed as T_{hand} = SafeD/S. Substituting this ratio for T_{hand} in Eq. 1 yields Eq. 4.

$$SafeD/S > T_{ram} \tag{4}$$

Solving Eq. 4 for SafeD gives the standard formula for calculating SafeD,

$$SafeD > S \times T_{ram} \tag{5}$$

Methods are available to determine T_{ram}, but the value for reach speed required experimentation using realistic simulations. A critical review of the experiments used to choose 1.6 m/s as a hand speed constant revealed serious weakness in sample sizes, number of trials, and attempts to simulate press operations and after reaches [9].

Only one experiment, conducted many years after the 1.6 m/s value was entrenched in the standards, provided a realistic simulation, used actual machine operators, and had a large enough sample size for examining variability. That was a NIOSH study reported by Pizatella and Moll, initially presented at a conference [10] and later as a full journal article [4]. Their study participants were 60 machine operators, and nearly all operated a press as part of their job. The participants operated a simulated power press built for the experiment. Each started operating in a standard, rhythmic way until a randomly-timed action caused the part to be displaced. The operators responded, per instructions, by reaching quickly to correct the part location. Their times to reach from the actuator button to the point-of-hazard was measured. The researchers noted that 40 % of machine operators are not always protected by the standard formula using 1.6 m/s because they can reach faster than the 1.6 m/s. Pizatella and Moll concluded that a change in "safe distance" regulations is needed, but a specific recommendation could not be developed from their experiment because only two placements of the buttons were

included. The absence of multiple palm-button placements made it impossible to examine the effect of distance on after-reach speed.

A more recent experimental study of press operator hand speed examined "approach speed" of the hand during regular press operation [11]. Four young and four older subjects participated. The experiment compared approach speed for a press equipped with traditional hand actuators versus being equipped to provide presence-sensing device initiation (psdi). For one part of the experiments, the operators were asked to operate at a fast pace. The operators were significantly faster using the psdi. For the two-hand button trials, the average hand speeds were about: 1.2 m/s for the over 50 participants and 1.6 for the younger participants. The experiment was not designed to simulate after-reach speed when using palm buttons, and therefore, does not directly provide data applicable to the issues addressed in this paper. However, the reported mean hand speeds were in the range predicted by prior studies.

The experiment reported here was undertaken to extend the NIOSH study. The specific purpose of this paper is to address an important initial question: Is after-reach speed a constant or a variable? If after-reach speed is a constant, then it should be the same: (a) for a waist-level and a face-level placement, and (b) for varying distances within each placement.

2 Methods

2.1 Apparatus

In order to conduct an experiment with practical value, a simulated power press was used. It had a moving ram that was designed and constructed to prevent injury if any part of the subject's hand is caught in the point of operation [12]. The same apparatus was also used for the NIOSH study [4] and for other experiments summarized in a paper by Collins et.al. [12].

Like real presses, the simulated press was capable of being set up for actuation by various mechanisms including presence sensing devices, foot switches, and hand buttons. For this experiment, it was equipped for actuation by the operator using both hands concurrently to depress a pair of buttons. The buttons used in this experiment were commercial palm buttons with ring guards.

Three palm-button placements areas were used. Figure 1 shows example placements within each of the three placement areas. Small arrows show the direction an operator presses the buttons. Also depicted in Fig. 1 is a lower die. The ram is not shown.

For this experiment wooden templates were constructed and fastened to the sides of the original simulator housing. Holes were drilled in the templates for bolting the palm-button assembly into the desired positions. The apparatus allowed the operators to set a workpiece on the lower die for stamping, and then remove it after a
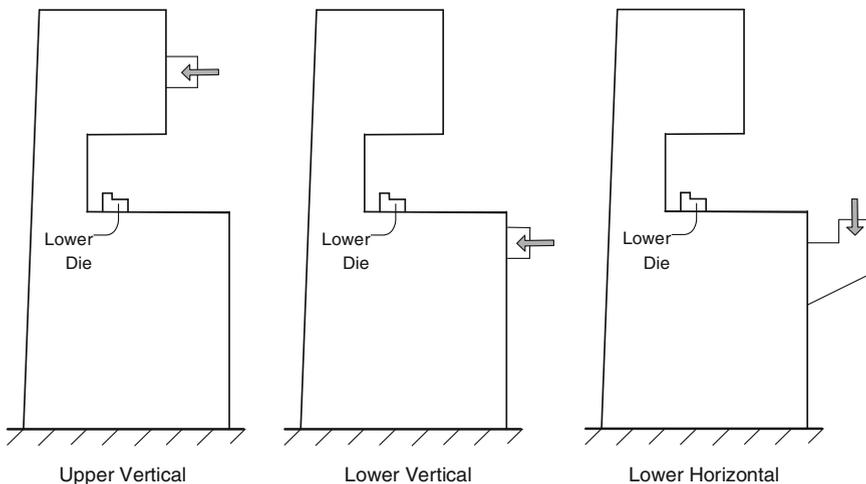
Fig. 1 Side views of simulated press indicating three palm-button placements and direction for pushing buttons

stroke. Video tape recording of the motions were made from one camera placed so as to detect direction of hand motion in the fore-and-aft direction.

The palm buttons were spaced 56 cm (22 in.) apart, the same as in the NIOSH experiment. This is a separation distance commonly found in off-the-shelf palm-button actuators. One study that varied width found that it had no effect on after-reach time other than to affect the reach distance, i.e., reach distance is the important variable, not width [13]. Consequently, the use of a 56 cm separation distance in the experiment was expected to provide a valid simulation of typical hand-button actuated mechanical power press operations in U.S. industry.

After-reach time was measured with timing equipment that started when the left palm button was released and ended when any part of the subject's hand interrupted a light curtain at the near-side of the lower die.

2.2 Experimental Design

The experimental methods were the same as those in the NIOSH experiment, except that in this experiment the distance between the hand buttons and the die was varied. There were actually three distinct experiments, one for each of the placements. The form of each experiment was a randomized complete block design. Each subject was a block; treatments were the eight randomly selected positions of the dual palm-buttons within each placement.

The positions of the palm buttons were varied. This was accomplished by defining, for each placement, an area in which the pair of palm buttons could be

located according to anthropometric data [14]. Within each area, eight positions were randomly determined. In the upper vertical placement and the lower vertical placement, one extra position was also included. These two positions were the same as those used in the NIOSH experiment. The inclusion of these positions provided an opportunity to directly compare mean after-reach speeds of subjects in this study with corresponding speed reported by Pizatella and Moll [4].

2.3   Procedures

Each subject came into the laboratory for testing on three separate days, one for each of the three placements. The order was balanced so that each placement was scheduled as the first day for three subjects, the second day for three, and the third day for three. Before testing after-reach times, each subject practiced the routing feeding operation for 5 min. During the fourth and fifth minutes of the practice session, the subject was presented with at least three after-reach signals. This training was the same as that used in the NIOSH experiment [4].

On the days for upper vertical and lower vertical placements, the initial position of the palm buttons matched those used in the NIOSH study [4]. That position was used to collect the initial after-reach times. This trial was followed on that same day by the randomly ordered 8 test positions in that placement. On the day a subject was scheduled for the lower horizontal placement, the testing started with the eight randomly-ordered positions. For all tests, subject performed the routine operation when, at random times, the part was displaced from the die, providing a visual signal for a trial. A trial consisted of one reach with one hand from the left palm button to a target located on the lower die. In order to make the results comparable to those obtained in the NIOSH study [4], each subject performed four trials in each position, and only the fastest of the four was used as the observation for that position.

2.4   Participants

Nine male subjects participated in all three placements. Men were used for two reasons. First, because data from the 1980 U.S. Census indicated that 69 % of press operators are male; and second, the findings of the NIOSH study [4] indicated that males had faster after-reach speeds than females. Thus, by using male subjects the experiment was expected to be more applicable to those apparently at greatest risk. Subjects were recruited from the West Virginia University, College of Engineering. All were seniors or graduate students in engineering. Their mean age was 28, with a range from 21 to 38 years. Each subject signed a consent form after receiving a verbal explanation of the study. The NIOSH Human Subjects Review Board

approved the experiment and consent form. No injuries occurred during the experiments.

3 Results

The first analysis sought to learn how well the college subjects in this study may be representative of working machine operators in terms of after-reach speeds. Clearly, the most representative data on the after-reach speed of machine operators are those obtained in the NIOSH study [4]. The NIOSH paper reported the mean and standard deviation of after-reach speeds based on a stratification of gender and 10-year age ranges. From these stratified groups, the group selected for comparison was the males in the age range 20–30 years of age. One reason for this selection was that among the NIOSH groups, the young males were faster than any other group; and that means that young males are most at risk of exceeding the protection afforded by palm-button placements established using the 1.6 m/s hand-speed constant. A second reason was the ages of the college students in this study, 21–38 (mean 28), was close to the 20–30 age span used by NIOSH. An additional similarity was in the number of subjects in the NIOSH study (12) and this study (9). The comparisons are presented in Table 1 and Fig. 2.

Figure 2 provides a visual comparison of the after-reach speed distributions for the two identical palm-button placements—upper vertical and lower vertical. The bins for frequency ranges spanned 0.4 m/s. For example, the bin labeled 1.6 actually includes speeds from 1.6 to 1.999 m/s.

For upper placement, the NIOSH subjects had speeds that were more broadly dispersed than the college students in this study. The mean speed of the NIOSH subjects (2.18 m/s) was larger than subjects in this study (1.59 m/s). Of the twelve NIOSH subjects, 10 exceeded the hand-speed constant of 1.6 m/s. For the lower vertical placement, the speeds were similar in the two studies for both mean and distribution.

The second analysis compared the mean after-reach speeds of the two studies and two identical placements. Table 2 shows the mean speeds. The right column indicates that the ratio of mean speeds in the upper placement to the lower placement. In this study, the faster mean speed was in the lower placement—opposite of the NIOSH study. The bottom row of Table 2 indicates the ratio of mean speeds in

Table 1 Descriptive statistical data comparing the two studies of after-reach speed using two identical palm-button placements

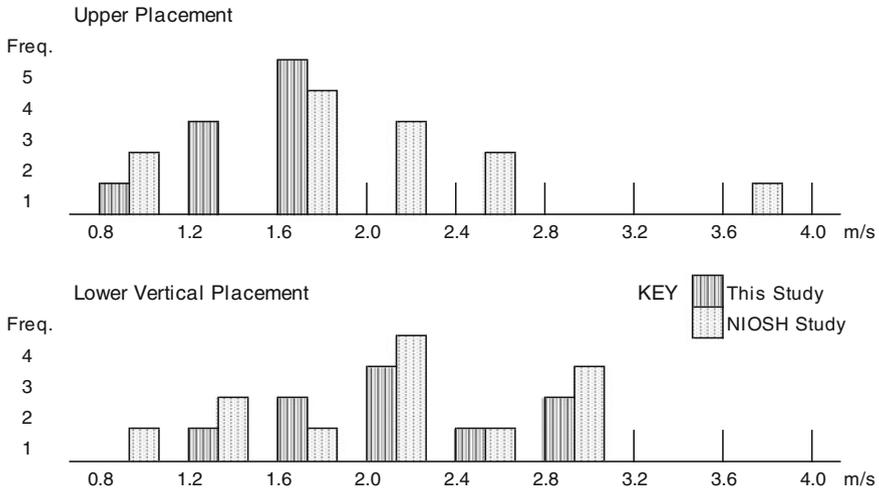| Study	Mean (m/s)		S. D. (m/s)		Percent > 1.6 m/s	
	Upper	Lower	Upper	Lower	Upper	Lower
This study	1.59	2.24	0.32	0.49	56	89
NIOSH [4]	2.18	2.09	0.68	0.70	83	75

Fig. 2 Frequency histograms for comparing distributions of after-reach speeds (m/s) found in the NIOSH study [4] and this study for the upper and lower palm-button placements. These results are for young male subjects

Table 2 Comparison of mean speeds for two matching placements in two studies

Study	N	Placement mean speed (m/s)		Row ratio[b]
		Upper	Lower	
This study	9	1.59	2.24	0.71
NIOSH study	60	1.45	1.23	1.18
Column ratio[a]		1.09	1.82	

[a]Ratio of means speed in this study to mean speed in the NIOSH study
[b]Ratio of upper placement mean speed to lower placement mean speed

this study to the corresponding speed in the NIOSH study. The subjects in this study had faster mean speeds than those in the NIOSH study. This finding was expected because this study involved only young male subjects.

The third analysis tested the null hypothesis that after-reach speed (S) is not affected by distance (D). Data used for this analysis consisted of the after-reach times in the eight positions by the nine subjects. One placement was missed due to a scheduling error. It was replaced using standard missing data procedures, and the degrees of freedom were reduced by one. Results presented in the Table 3 show that this hypothesis is very unlikely for all three placements. The alternative hypothesis, that S is affected by D, is far more probable. This finding contradicts the common assumption that after-reach speed is a constant.

Table 3 Results of linear regression analyses for $S = a + b(D)$

Placement	N	(a) Intercept	(b) Coefficient	Probability that Coefficient = 0
Upper vert.	72	0.255	2.785	0.002
Lower vert.	72	1.022	1.275	0.010
Lower horiz.	71	1.035	1.337	0.015

4 Discussion and Conclusions

The purpose of this paper was to address an important initial question: Is after-reach speed a constant or a variable? First, the mean S for the 60 machine operators in the NIOSH study was faster for upper vertical placements than for lower vertical placements. Although this study with nine subjects found the opposite, the larger sample in the NIOSH study warrants greater confidence. Second, after-reach speed increases with increasing distance of the movement (see Table 3). Taken together, results established that after-reach speed is a variable.

Going beyond the stated purpose of this paper, results also indicate that setting up a press using mean after-reach speed is a flawed concept. If a normal distribution applies to after-reach speeds of press operators, then half will exceed the mean. It would be more appropriate to use, instead of mean speed, a speed suitable to protect a larger proportion of press operators. The subjects in both studies and both placements had substantial portions (see Table 1) of their after-reach speeds exceed the 1.6 m/s value.

A limitation of the present study is the use of sample population of male students. To examine this concern, mean after-reach speeds of the nine subjects were compared with that of the 60 machine operators studied by Pizatella and Moll [4]. Both groups of subjects had the same amount of practice with the press simulator prior to the actual testing of their after-reach speed, and in both experiments the subjects had four after-reach signals to respond to, with the fastest of the four being used for all subsequent analyses. Comparing their respective mean speeds in the same positions of the palm buttons (Table 1), neither group was consistently faster.

Because the subjects in this study were not drawn from a large population of industrial machine operators, applying the findings beyond this study should be done cautiously. These subjects were not greatly different from the NIOSH young males in terms of mean after-reach speed. However, the NIOSH study established that young male operators are faster than the others in their study. Thus, if a revision of the safe distance formula is attempted, it would make sense to base it on young males—if young males are protected, then others will be protected.

The regression equations in Table 3 should not be used to predict after-reach speed for a broad range of machine operators. Firstly, they are based on young males, and secondly, they predict mean after-reach speed without accounting for the variability of individuals.

The subjects showed increasing speed as the movement distance was increased. In reviewing the videotape records of the after reaches, it appeared that the greater

distance simply provided a longer time for the hand to move at a near maximal velocity. That is, the movements began with the hand at zero velocity. This was followed by a period of acceleration to a relatively fast movement speed. For the shorter distance movements, the hand only had a brief time to continue in this fast phase before the fingers entered the hazard area. In the longer distance movements, the hand was able to extend the fast speed phase for a longer time before the fingers entered the hazard area. This resulted in an overall faster average speed through the whole distance.

It is recommended that instead of looking for a constant value of S, a new model be developed for predicting after-reach time of press operators, T_{hand}. An apparently logical approach would be to replace S in Eq. 5 with an equation that more closely matches experimental data. Such an equation should account for placement (upper or lower), distance within placement, and variability.

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