SAFETY BRIEF

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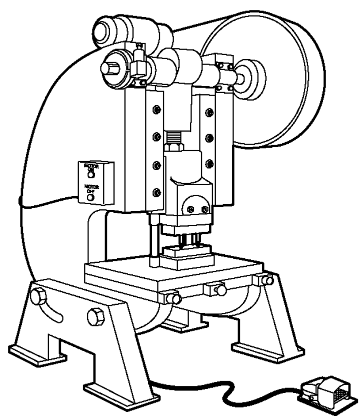
Accidental Foot Control Actuation Equilibrium Bifurcation Method

by Ralph L. Barnett*



Abstract

Accidental actuation of a foot controlled press brake caused a double amputation of a young woman's arms. The electric foot switch leading to this tragedy was protected by barrier guarding on five sides and employed a pedal latch that had to be released before the pedal could be activated. The manufacturer of the foot switch also marketed the same design with the addition of a front gate that must be raised with the toe to gain access to the pedal and pedal latch. To explore the difference between these two advanced safety designs in a laboratory setting, a protocol was developed involving a bifurcation of equilibrium positions. One equilibrium posture naturally tended to engage an unprotected foot switch; a second stance balanced the operator after disengagement. Efforts to engage the foot pedal using the bifurcation protocol does not involve cognition. The gate eliminated accidental actuation; the non-gated foot switch was actuated in 93% of the trials.

Keywords

Accidental activation, accidental operation, foot controls, foot pedal, foot switches, foot treadles, unintended actuation.

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1. Introduction

There are many machine tools that require foot controls for at least some of their operations, e.g., press brakes, shears, forging machines, and power presses. Operators, in addition to controlling the machines, are frequently called upon to hand feed work pieces, remove and examine finished product, dispose of scrap, lubricate, adjust, clean, monitor the machine, and change tooling. Usually, these activities involve walking in the neighborhood of the foot controls and the points of operation. Operators rarely look down at the workplace floor, and consequently, inadvertent foot contact with the foot control pedals or treadles may occur.

Data on foot control accidents related to inadvertent actuation have been gathered from a number of sources. In a Swedish study of press operator injuries, Garde [Ref. 8] reported that in 1974 between 58% and 97% of the injuries involved foot controlled machines. In 1980, the Office of Standards and Development [Ref. 9], U.S. Department of Labor, recorded that 65% of the reported mechanical power press injuries between 1975 and 1980 occurred on foot controlled presses. In an extensive review of reported injuries, Arndt [Ref. 10] found that in 1981 the causal factor in 48.5% of operator injuries on metalworking machines involved foot controls. Etherton and Trump [Ref. 11] indicated that 700 machine operators in the U.S. were injured in 1985 on foot switch actuated machines.

When a machine's controls are accidentally actuated, the operator's unintended response can cause personal injury and property damage. Hundreds of safety organizations have responded to this eventuality by developing admonitions and recommendations for machine designers. The spirit of their recommendations is revealed in the following selection of quotations from the literature:

General:

A. "The operating control on hand-held power tools shall be so located as to minimize the possibility of its accidental operation, if such accidental operation would constitute a hazard to employees. [Ref. 1]"

B. "Controls shall be free from possibility of accidental operation by normal movement of the machine, operator or work. [Refs. 2, 3]"

C. "Controls shall be located so that unintentional operation by normal movement of the machine, operator, or work will be unlikely. [Ref. 4]"

D. "Controls shall be free from possibility of accidental operation either by normal movement of the equipment or the operator. [Refs. 5, 6]"

E. "Controls. All controls (especially those for use by operators in the normal working of the machine), including levers, buttons, switches, pedals and hand wheels, should be designed and positioned to be easy of access (sic) to the operator, clearly identifiable, and not likely to be operated by mischance. They should be so placed that the operator normally has them within easy reach without stretching or moving from the usual operating position. [Ref. 7]"

Foot Controls:

F. "Each operating treadle shall be protected against unexpected or accidental tripping. [Ref. 12]"

G. "Foot pedals (treadle), (i) The pedal mechanism shall be protected to prevent unintended operation from falling or moving objects or by accidental stepping onto the pedal. [Ref. 13]"

H. "Foot operated devices. All foot operated devices (i.e. treadles, pedals, bars, valves, and switches) shall be substantially and effectively protected from unintended operation. [Ref. 14]"

I. "Foot-operated switches shall be protected so as to prevent accidental actuation by falling or moving objects and from unintended operation by accidental stepping onto the switch. [Ref. 4, Ref. 15]"

J. “Protect foot switches or foot valves and any attached mechanism. This prevents unintended operation caused by falling or moving objects, or by someone accidentally stepping on the foot control. [Ref. 16]”

These admonitions run the spectrum from unlikely to shall prevent. Shall prevent is impossible to achieve with an operable control; unlikely violates technical methodology by not incorporating the notion “compared to something.” These rules are performance objectives. They cannot serve as guidelines because they lack specificity; their enforceability is questionable because they are not rational.

Accidental activation of a foot control by stepping into the foot control and onto the pedal is called “stepping contact.” As discussed in Barnett (2009) [Ref. 17], this phenomenon was almost unheard of with old fashioned foot controls (circa 1930) that were positioned six inches above the floor. The introduction of the modern foot control that is ergonomically designed to reduce operator fatigue and increase stroke rate led to an increase in accidental activation. The modern pedal is about one and a half inches off the ground; so is the foot lift in normal human gait. Furthermore, the foot control can be placed or misplaced anywhere in the workspace because it is tethered by a wire or hose increasing the chance of inadvertent activation. For these reasons foot control designers have tried to harden against accidental foot control activation by using top covers, side-shields, pedal locks, and front gates of various styles. As these stepping contact preventives become more aggressive Barnett (2009) has shown that there is an inverse relationship with the hazardous practice of “riding-the-pedal.”

Riding-the-pedal is one of four machine activating strategies identified by Barnett and Barroso (1998) [Ref. 18] for machines that are rapidly activated without ambulation between strokes. Here, one foot is continually poised above or just touching the foot pedal until a machine stroke is required. The foot then depresses the foot pedal eventually returning to its position above the pedal. It is never withdrawn from the foot control. Riding-the-pedal is analogous to a hunter “keeping his finger on the trigger.” When an operator’s foot is deployed over the pedal, accidental actuation can occur when the operator sneezes, reaches forward, slips, is pushed or bumped from behind or his foot gets tired. Riding-the-pedal is an insidious practice motivated by the reality that stroke-rate, operator comfort, and hand steadiness are all maximized. The more difficult it is to step into and out of a foot control, the more likely it is that operators will "ride-the-pedal."

This paper focuses entirely on the problem of hardening foot controls against the stepping contact hazard. In particular, a testing protocol is described that distinguishes between candidate protection systems.

2. Pedal Latched Foot Controls

Twelve candidate foot controls taken from Barnett (2009) are ordered by decreasing stroke-rates in Fig. 1. The stroke-rates, measured as strokes/30 sec., were determined under speed provoking conditions. To assess the effectiveness of foot control hardening strategies, a protocol was developed for use in a laboratory. The challenge of such an undertaking is accounting for the unbounded number of circumstances that can result in accidental activation.

An examination of Fig. 1 indicates that there is something special about candidates 9 and 10. Candidate 10 is the first of the foot controls that adopts a front gate. It has the highest stroke-rate of the gated controls; indeed, it's twice as fast as candidate 12. Furthermore, it is designed with a pedal latch that must be released before the pedal can be depressed. Consequently, it is the only gated foot control that tends to resist the "ride-the-pedal" hazard.

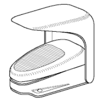
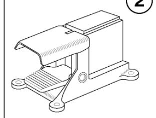
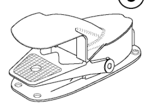
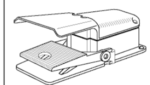
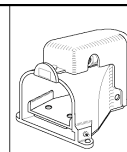
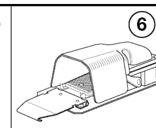
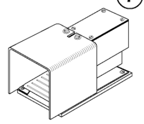
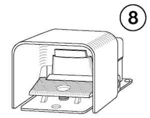
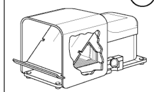
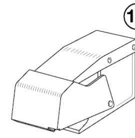
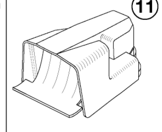
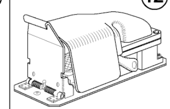
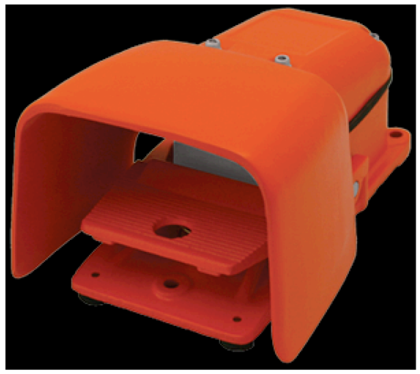
Foot Controls	①  **Linemaster Clipper** No. 632-S	②  **Rees** Style 1814	③  **Square D** Type AW2	④  **Linemaster Hercules** Type AW2	⑤  **Schrader** 1888W	⑥  **Allen Bradley** 805-A54316S (Front guard taped open)
Reciprocating Strokes/30 sec.	*Avg.* 48.72 *St'd Dev.* 8.95 n = 39	*Avg.* 48.36 *St'd Dev.* 10.40 n = 39	*Avg.* 47.66 *St'd Dev.* 12.59 n = 39	*Avg.* 46.69 *St'd Dev.* 7.73 n = 39	*Avg.* 46.44 *St'd Dev.* 8.41 n = 39	*Avg.* 46.30 *St'd Dev.* 9.58 n = 45
Foot Controls	⑦  **Rees** 04937-000	⑧  **Linemaster Hercules** 511-B2 (Pedal Latch)	⑨  **Linemaster Hercules** 511-B2G (Pedal Latch and Gate)	⑩  **Minster** Type ELL	⑪  **Square D** AW-117	⑫  **Allen Bradley** 805-A54316S
Reciprocating Strokes/30 sec.	*Avg.* 44.69 *St'd Dev.* 10.29 n = 39	*Avg.* 36.66 *St'd Dev.* 6.97 n = 39	*Avg.* 32.82 *St'd Dev.* 6.23 n = 51	*Avg.* 28.86 *St'd Dev.* 6.02 n = 39	*Avg.* 25.50 *St'd Dev.* 4.61 n = 39	*Avg.* 16.94 *St'd Dev.* 3.80 n = 39

Fig. 1: Foot Controls - Speed Provoked Actuation Rates

Candidate 9 is distinguished from all preceding candidates because it too has a pedal latch in addition to barrier guarding on the top and sides. This candidate is clearly superior to the other ungated foot controls because the latched pedal provides resistance to both the "stepping contact" hazard and the "ride-the-pedal" hazard. This resistance to unwelcomed actuation has a price; it has the lowest stroke-rate of the ungated controls.

Stroke-rate is a statistical variate that correlates with several properties of the foot control. Certainly, it has an intrinsic value for rate sensitive production activities associated with immobile operators where "riding-the-pedal" is the primary hazard. This speed provoked measurement is effected by any characteristic of the foot control that inhibits the reciprocating movement of the foot. Consequently, it correlates with operator comfort, operator fatigue, resistance to stepping contact, and with the incentive for "riding-the-pedal."

Our study concentrates on the resistance to stepping contact provided by the only two latched pedal controls, candidates 9 and 10. Except for the gate, the two foot switches are nominally identical. Candidate 9 is Linemaster® Hercules Model 511-B2; it is illustrated in Fig. 2 together with its geometry. Candidate 10 is a gated Linemaster® Hercules Model 511-B2G; it is characterized in Fig. 3. The pedal is accessed by kicking the gate open. The use of a gate has caused the stroke-rate to drop 10.5% below the open configuration candidate 9. This raises the question, “is the increased protection provided by the gate worth the drop in stroke-rate, operator comfort, and the additional cost?”



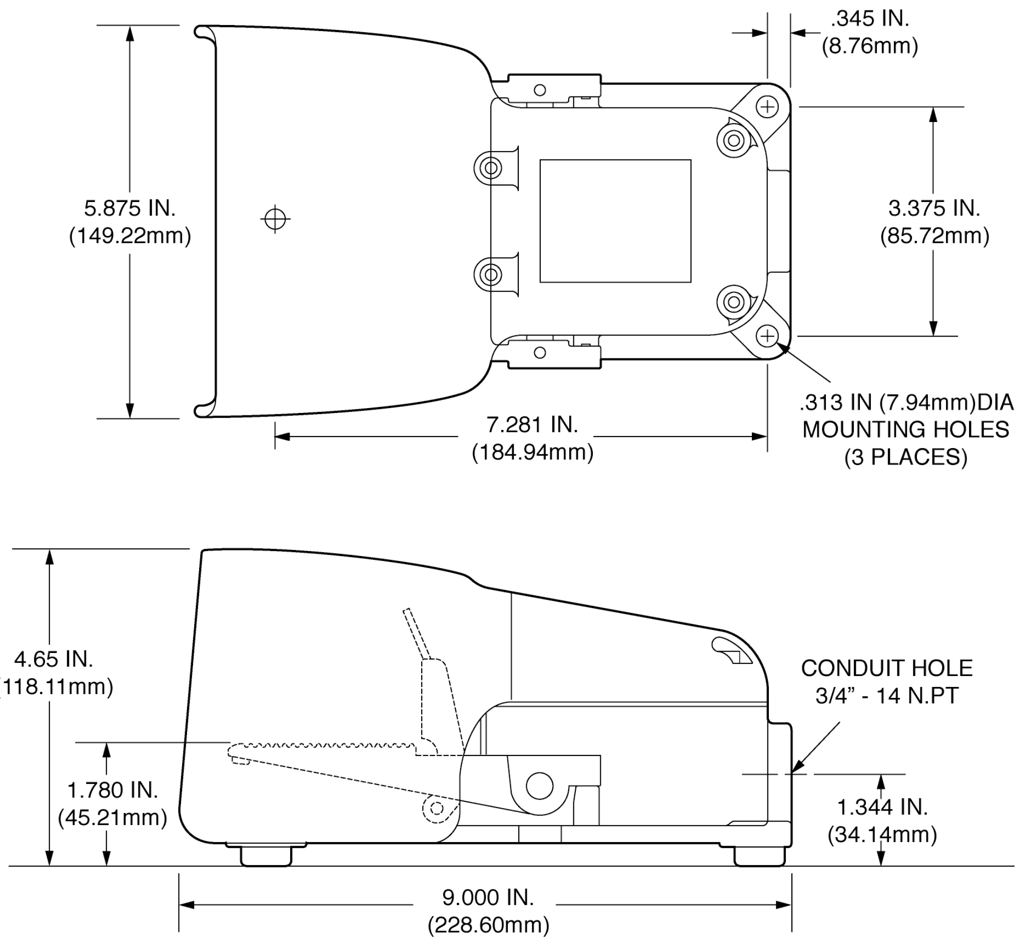
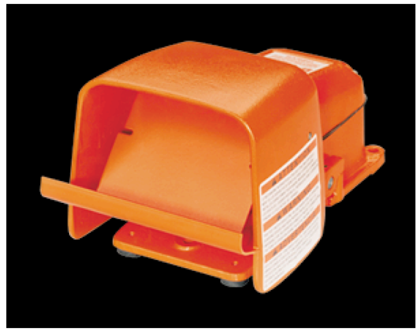


Fig. 2: Linemaster® Hercules Model 511-B2



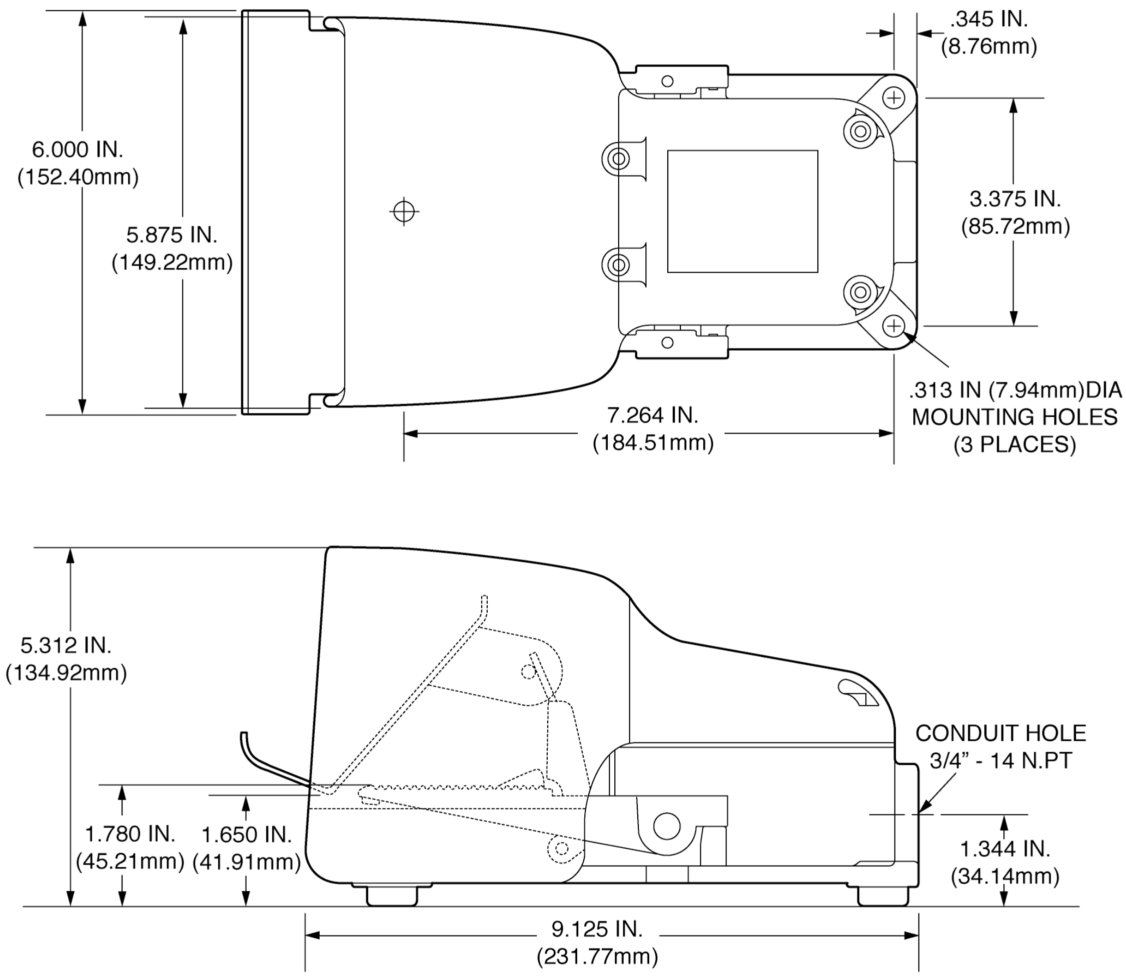


Fig. 3: Linemaster® Hercules Model 511-B2G

3. Bifurcation of Equilibrium Positions

To study the stepping contact resistance of the two Linemaster® foot controls a protocol was developed with the following characteristics:

A. A test subject is initially positioned in front of the foot control with the right foot fully inserted into the foot control and resting on top of the pedal or treadle. This foot placement activates the control.

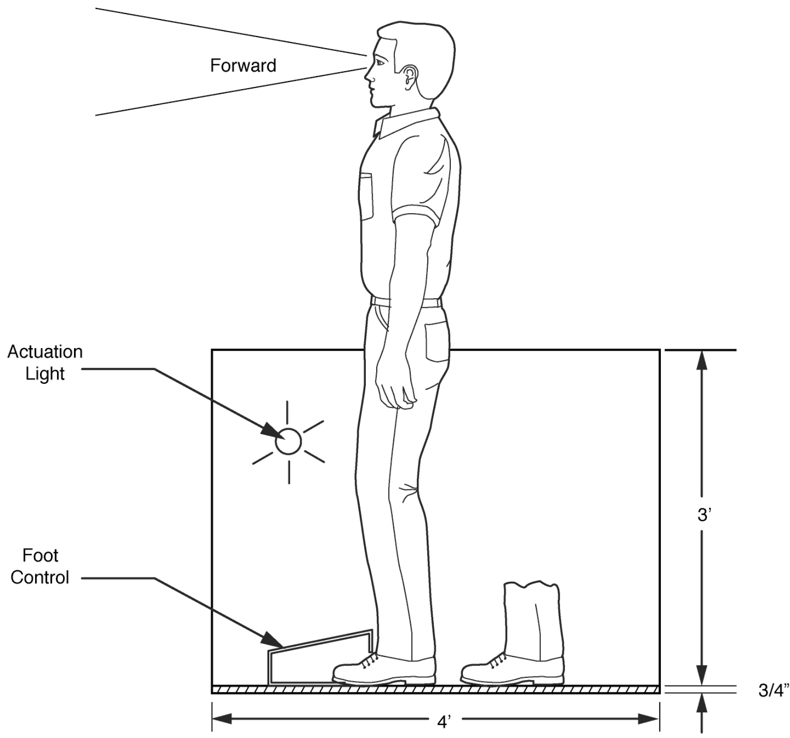
B. The subject's left foot is positioned on the support surface to be even with the inserted right foot. Both feet are parallel to the foot control. This posture represents the actuation equilibrium position. Figure 4 illustrates the test set-up.

C. To deactivate the control, the test subject removes the right foot from the pedal and places it in a comfortable rearward location on the support surface. The left foot remains in its original position; it works with the rearward right foot to maintain a second equilibrium position.

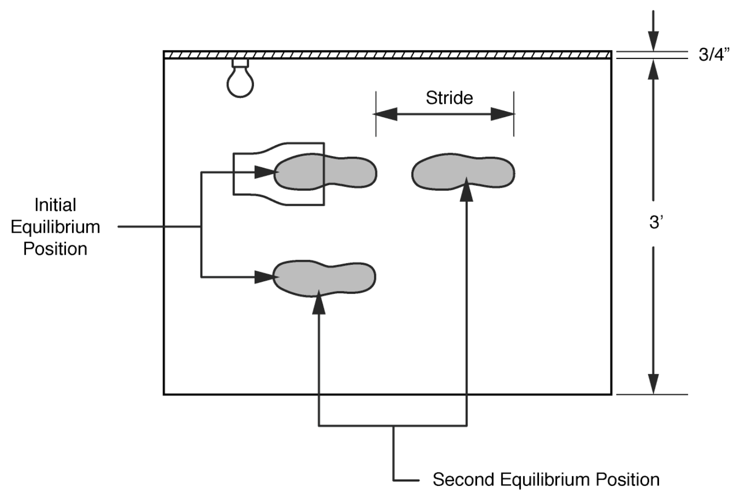
D. The test subjects always look forward and not at the foot control. They move between the two equilibrium positions; forward towards the control and rearward away from the control. This constitutes one cycle.

E. When the foot control is activated, a light is illuminated to inform the monitoring personnel that contact has occurred.

F. Each test subject executes multiple cycles at an unhurried rate of their choice.



a) Elevation - Test Fixture



b) Plan View - Foot Placement

Fig. 4: Foot Control Test Set-Up

Using the preceding protocol, five male and five female test subjects executed approximately ten cycles on each of the open and gated Linemaster® foot switches. The total number of cycles and the total number of foot control actuations are recorded in Table I. In every forward movement with the open foot switch the test subjects contacted the pedal; when they moved sufficiently far forward they also contacted the pedal latch and activated the foot switch. For the gated footswitch no one penetrated beyond the gate.

Table I indicates that candidate 9 with the open front, the latched pedal, and the full guarding, prevented accidental actuation six times in 86 cycles; the failure rate = 80/86 = 93.02%. For candidate 10, the gate and guarding prevented all 93 actuation attempts; the failure rate is zero.

Table I - Foot Control Accidental Activation Tests

Test Subjects	Age (yrs.)	Weight (lb.)	Height	Hercules 511-B2 Pedal Latch		Hercules 511-B2G Pedal Latch and Gate	
				Total Cycles	Total Actuations	Total Cycles	Total Actuations
Technician (M)	30	155	5′-11″	13	11	10	0
Technician (M)	26	165	5′-11″	10	10	9	0
Engineer (M)	66	185	5′-8″	10	10	10	0
Technician (M)	42	132	5′-11″	11	11	11	0
Scientist (M)	75	165	6′-0″	-	-	8	0
Secretary (F)	58	140	5′-7″	6	2	7	0
Business Manager (F)	41	150	5′-9″	9	9	11	0
Secretary (F)	36	120	5′-5″	6	6	6	0
Librarian (F)	37	130	5′-6″	11	11	12	0
Secretary (F)	59	175	5′-4″	10	10	9	0
			Totals:	86	80	93	0
			Failure Rate:	80/86 = 93.02%		Failure Rate: Zero	

4. Comments and Observations

A. Does the equilibrium bifurcation protocol as presented provide a reliable method for characterizing stepping contact resistance?

1. The protocol will register a 100% failure rate for every ungated foot control without a pedal latch. Even with the pedal latch we measured a failure rate of 93%. If we remove the one outlier test subject who failed to activate the footswitch four times in six attempts, the failure rate becomes 98%. Intuition supports the removal of ungated foot controls where ambulation between machine strokes is prevalent.

2. The equilibrium bifurcation method will never activate a foot pedal elevated over four inches. Intuition, ergonomics, and accident statistics also support this hypothesis.

3. The equilibrium bifurcation method will never activate candidate 12, the old bulletproof Allen Bradley foot control with the drawbridge flap. It properly predicts a zero failure rate. (Note: Allen Bradley no longer manufactures foot controls.)

4. Activation of a foot switch pedal is affected by reciprocation or rotation of an operator's foot. The bifurcation protocol cannot be used to study the foot rotation strategy that is associated with open-sided foot controls..

B. The equilibrium bifurcation method appears to be more sensitive than stroke-rate for assessing hardening against accidental activation. It identified a discontinuity in behavior between candidates 9 and 10. The "method" may be useful for studying differences in footwear, e.g., tapered toes.

C. The bifurcation method preserves the notion of "blind reach." The test subjects and real operators do not view the foot controls.

D. The method incorporates an initial actuation equilibrium position that is included in the set of real methodologies.

E. The gated foot control candidates 9, 10 and 11 are designed to be activated by exceeding some threshold force on their gates. The force environment created by the equilibrium bifurcation method can be intensified by increasing the cycle frequency with a metronome, or enlarging the stride between equilibrium positions, or perhaps by using treadmill like hand railing to improve the forward thrust of the test subjects.

F. The best case scenario for activating a foot control occurs when test subjects watch the control; the equilibrium bifurcation protocol does not allow this.

G. The equilibrium bifurcation method provides an extremely aggressive attack on a foot control especially if the foot speeds mimic the ambulation speeds.

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