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Consultants in Safety Philosophy and Technology

5950 West Touhy Avenue Niles, IL 60714-4610 (847) 677-4730

FAX: (847) 647-2047

e-mail: infoserv@triodyne.com

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## Hand Trajectories Under Free Fall

by Ralph L. Barnett<sup>1</sup> and Suzanne A. Glowiak<sup>2</sup>

### ABSTRACT

*Can the hands elevate during a free fall scenario? This question arises in the design of fall intervention devices, during accident reconstruction and in the study of safe climbing strategies. This paper calculates the maximum simple reaction time that will enable the hands to elevate during a "drop" event.*

### I. INTRODUCTION

Under the influence of gravity, when a person falls all portions of the body initially descend. During such an excursion, sensory receptors are stimulated and after a time interval called the *simple reaction time* [Ref. 1] the hands will begin to counteract the fall by reaching upward. The race begins. Gravity has a headstart during the simple reaction time interval; after that, reaching upward will proceed at the hand speed constant  $v_h$  [Ref. 2,3,4,5,6].

### II. FREE FALL

There are collapse scenarios where the support literally drops out from under a worker. Consider, for example, the vertical fixed ladder shown in Fig. 1 where the climber has grasped the side rails adjacent to a rung. If his feet were to slip or if the rung supporting his feet were to fracture, he might try to release his ineffectual friction grip on the side rails and grab instead the adjacent rung with an interference or "power grip." Is this possible?

Referring to the coordinate defined in Fig. 1, it is assumed that the supporting rung collapses at  $t = 0$  when the climber's hands are located at a fall distance  $x = 0$  and their speed  $v = 0$ . Standard free fall equations for these boundary conditions describe the downward motion of the hands and body;

$$\text{fall distance } x: \quad x(t) = \frac{gt^2}{2} \quad \text{Eq. (1a)}$$

$$\text{fall speed } v: \quad v(t) = gt \quad \text{Eq. (1b)}$$

$$\text{fall acceleration } a: \quad a = g \quad \text{Eq. (1c)}$$

where  $g$  is the gravitational acceleration (32.2 ft/sec.<sup>2</sup>). After a time interval equal to the simple reaction time  $t_r$ , these equations will define the free fall location  $x_r$  and the free fall speed  $v_r$  of the hands; namely,

<sup>1</sup> Professor, Mechanical and Aerospace Engineering, Illinois Institute of Technology, Chicago, and Chairman of the Board, Triodyne Inc., Niles, IL.

<sup>2</sup> Senior Mechanical Engineer, Triodyne Inc., Niles, IL.

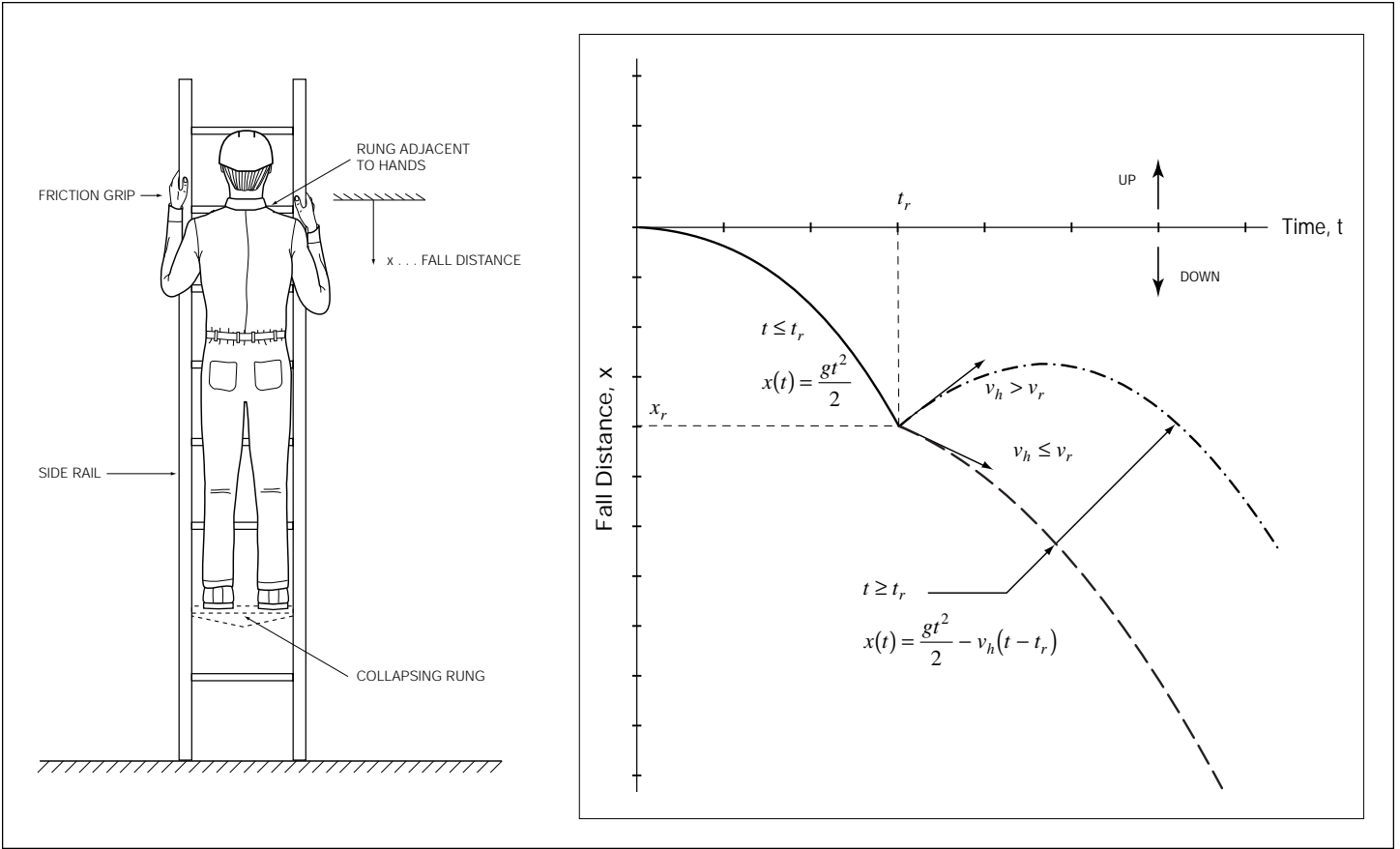


Fig. 1 Vertical Fixed Ladder

Fig. 2 General Trajectory - Definition of Terms

$$x_r \equiv x(t_r) = \frac{gt_r^2}{2} \quad \text{Eq. (2a)}$$

$$v_r \equiv v(t_r) = gt_r \quad \text{Eq. (2b)}$$

At this time,  $t = t_r$ , the climber's hands begin to move upward at  $v_h$  giving rise to a combined speed of  $(v_r - v_h)$ . If the hand speed constant  $v_h$  is greater than the free fall speed  $v_r$ , a net upward hand speed will be obtained and accordingly, the fall distance  $x$  will *begin* to decrease as shown in Fig. 2. On the other hand, if  $v_h \leq v_r$  the combined speed is downward and the fall distance continues to increase, albeit, at a slower rate.

Because the climber's hands are reaching upward at times greater than  $t_r$ , an upward (negative) component must be added to the free fall distance given by Eq. (1a);  $-v_h(t - t_r)$ . Thus,

$$x(t) = \frac{gt^2}{2} - v_h(t - t_r) \dots t \geq t_r \quad \text{Eq. (3)}$$

This parabola describes the hand motion after the time  $t_r$  when the climber begins to react. The complete hand trajectory is given by Eqs. (1a) and (3). Using the hand speed constant  $v_h = 63$  inches/sec. specified by OSHA [Ref. 7], a series of trajectories are plotted in Fig. 3 for various values of simple reaction time  $t_r$ .

We observe that all of the curves have a relative minimum ( $\frac{dx}{dt} = v = 0$ ) at their origin. When  $v_h < v_r$ , where there is no possibility of a net upward movement, no other relative

minimum exists as illustrated by the bottommost curve in Fig. 3 where  $t_r = 0.2$  seconds. When  $v_h \geq v_r$  and  $t \geq t_r$ , a relative minimum may always be found at the crest of the parabola defined by Eq. (3). The three top curves in Fig. 3 illustrate that there is an optimum time  $t_{opt}$  where  $x(t)$  has a relative minimum  $x_{min} \equiv x(t_{opt})$ . Both  $t_{opt}$  and  $x_{min}$  are established using traditional calculus procedures; thus,

$$\frac{dx}{dt} = 0 = gt - v_h \quad \text{Eq. (4a)}$$

$$t_{opt} = \frac{v_h}{g} \quad \text{Eq. (4b)}$$

$$\frac{d^2x}{dt^2} = g > 0 \quad \text{for all } t \quad \text{Eq. (4c)}$$

$$x_{min} = x(t_{opt}) = v_h \left( t_r - \frac{v_h}{2g} \right) \quad \text{Eq. (4d)}$$

Equation (4c) indicates that the relative minimum  $x_{min}$  given by Eq. (4d) is also the absolute minimum. Indeed,  $x_{min}$  represents the very best a climber can do to elevate his hands. In order for a climber to achieve a net upward reach,  $x_{min}$  must be negative. Equation (4d) may be used to establish a general criterion for "falling up"; thus,

$$x_{min} = v_h \left( t_r - \frac{v_h}{2g} \right) < 0 \quad \text{Eq. (5)}$$

or

$$t_r < \frac{v_h}{2g} \quad \dots \text{net upward hand motion} \quad \text{Eq. (6)}$$

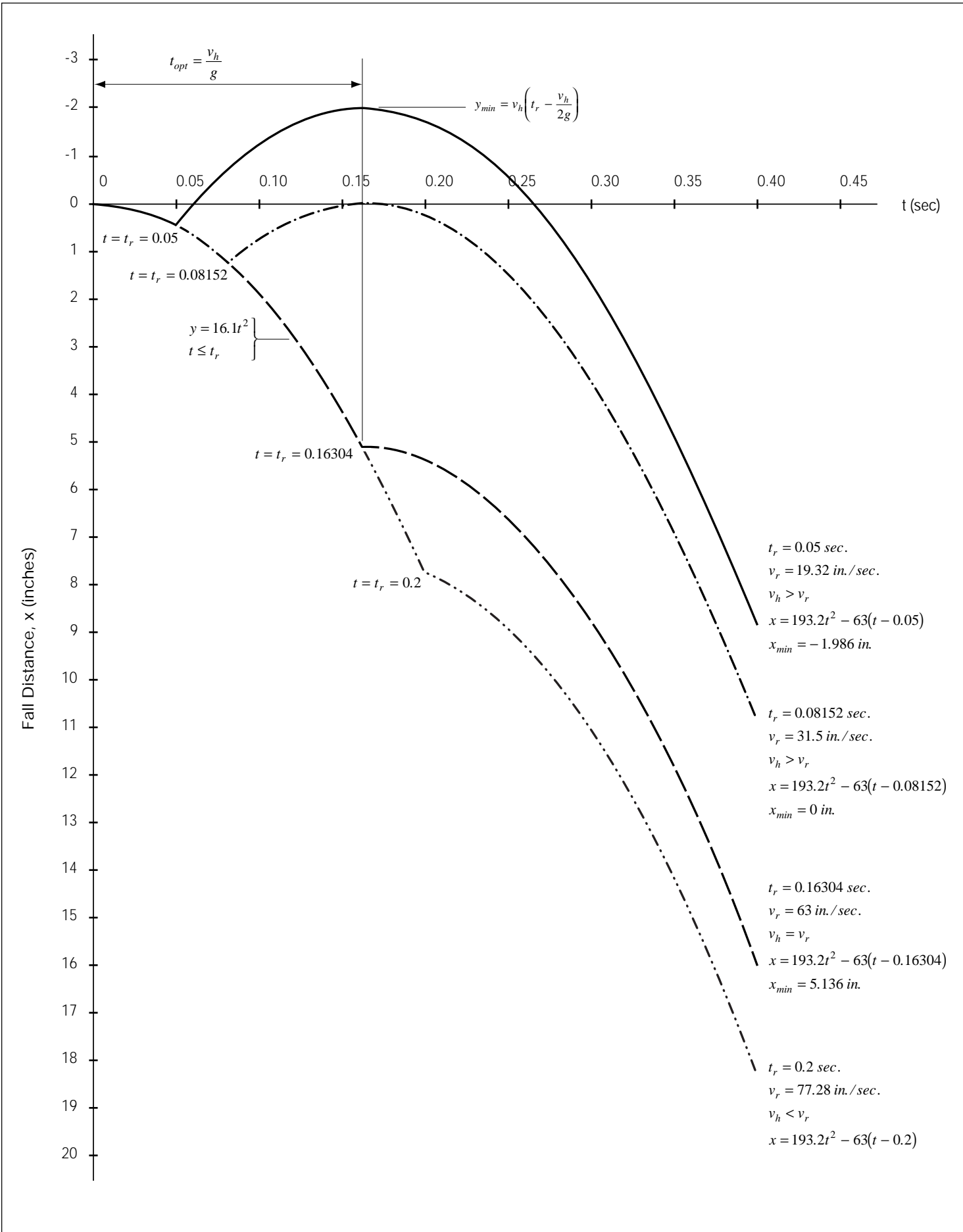


Fig. 3 Hand Trajectories ( $v_h = 63 \text{ inches/sec.}$ ;  $t_{opt} = 0.16304 \text{ sec.}$ )

Using  $v_h = 63$  inches/sec., a net upward reach of zero occurs at  $t_r = \frac{v_h}{2g} = 0.08152$  seconds. This case is depicted in Fig. 3 where the parabola just touches the line  $x = 0$ .

**Observations:**

1. The simple reaction time must be shorter than  $(\frac{v_h}{2g})$  to attain a net upward reach during a "drop" event. This does not appear to be possible since simple reaction times are greater than 0.0815 seconds. Quoting McCormick and Sanders [Ref. 1],

"Simple reaction time is the time to make a specific response when only one particular stimulus can occur, usually when an individual is anticipating the stimulus (as in conventional laboratory experiments). Reaction time is usually shortest in such circumstances, typically ranging from about 150 to 200 ms (0.15 to 0.20 s), with 200 ms being a fairly representative value; the value may be higher or lower depending on the stimulus modality and the nature of the stimulus (including its intensity and duration), as well as on the subject's age and other individual differences."

2. According to Eq. (6) a net upward hand motion during free fall is possible only when

$$\frac{v_h}{t_r} > 2g$$

This criterion relates two independent human factors concepts; simple reaction time and the hand speed constant.

3. The consequence of foot slippage or rung breakage while climbing a ladder is minimized by climbing procedures that utilize only rungs and not side rails.

4. Hazards located above a worker's hands cannot be contacted while dropping. Forensic positions which contradict this finding in similar situations must not be accepted without accident reconstruction involving human factors.

5. Grab bars used for fall intervention must not be located above the normal hand positions. Because free fall speeds exceed the hand speed constant in only 0.163 seconds, continuous hand contact with railings and supports should be encouraged. Note,  $v = gt = v_h$ ;

$$t = \frac{v_h}{g} = 0.163 \text{ sec.}$$

**REFERENCES**

1. McCormick, E.J. and M.S. Sanders. 1982. *Human Factors in Engineering and Design*. 5th ed., p. 198. New York: McGraw-Hill.
2. Crawford, Alex. 1984. "'Hand Speed Research Need Questioned,' in Power Presses Regulations are Thwarted." *Health & Safety at Work* 6, no. 7 (March): 45.
3. Horbury, C.R.J. et al. 1992. "European Standards for Machinery Safety" in *Contemporary Ergonomics*. Edited by E.J. Lovesey. Washington: Taylor & Francis.
4. Knass, P. 1974. "Safety of Metalworking Press Operatives when Reaching Back into the Ram Zone of the Press During Ram Travel." Translated by the Health and Safety Executive Translation Services. July 1981. *Die Berufsgenossenschaft* (June): 239-246.
5. "Mechanical Power Presses," 29 CFR 1910.217. Washington: Occupational Safety and Health Administration, effective March 7, 1996 (as published in 29 CFR Parts 1900 to 1910.999, Revised as July 1, 1996, pp. 590-591).
6. Roobazar, A. 1977. "Ergonomics of Machine Guarding." *National Safety News* (July): 53-59.
7. "Mechanical Power Presses," 29 CFR 1910.217. Washington: Occupational Safety and Health Administration, effective March 7, 1996 (as published in 29 CFR Parts 1900 to 1910.999, Revised as July 1, 1996, p. 590).

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