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Hand Trajectories Under Free Fall

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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;

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

fall speed v: $$v(t) = gt$$ Eq. (1b)

fall acceleration a: $$a = g$$ Eq. (1c)

where g is the gravitational acceleration (32.2 ft/sec.^{2}). 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,

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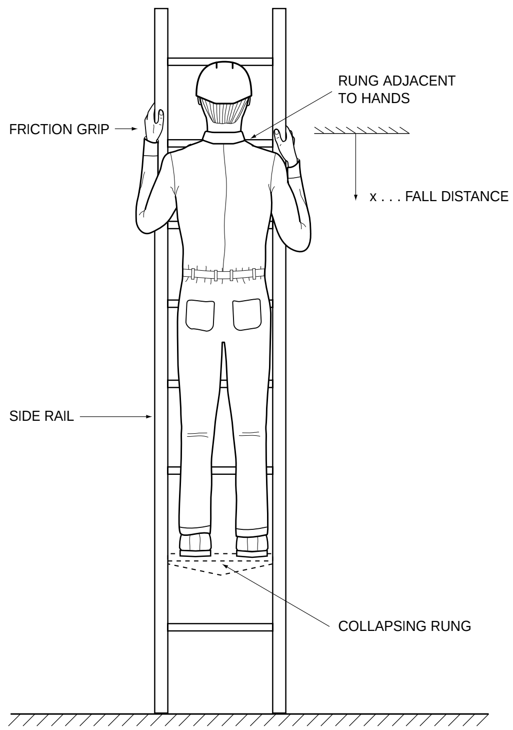

Fig. 1 Vertical Fixed Ladder

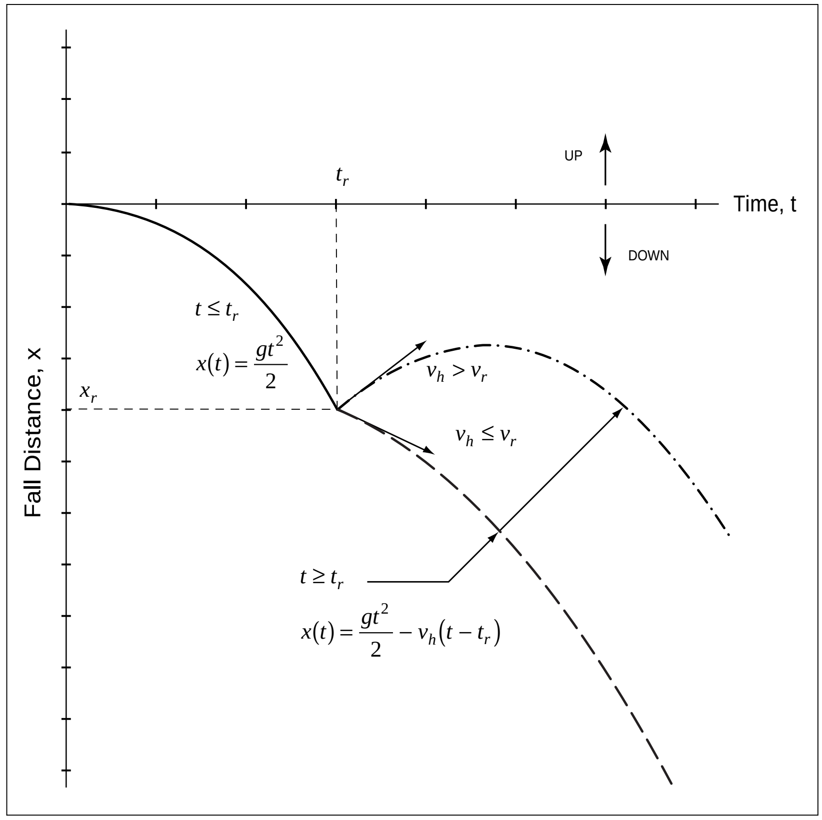

Fig. 2 General Trajectory - Definition of Terms

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

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

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 $v_h \le v_r$ 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,

$$x(t) = \frac{gt^2}{2} - v_h(t - t_r) \ldots t \ge t_r \qquad \text{Eq. (3)}$$

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 $v_h \ge v_r$ and $t \ge t_r$, 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,

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

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

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

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

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,

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

or

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

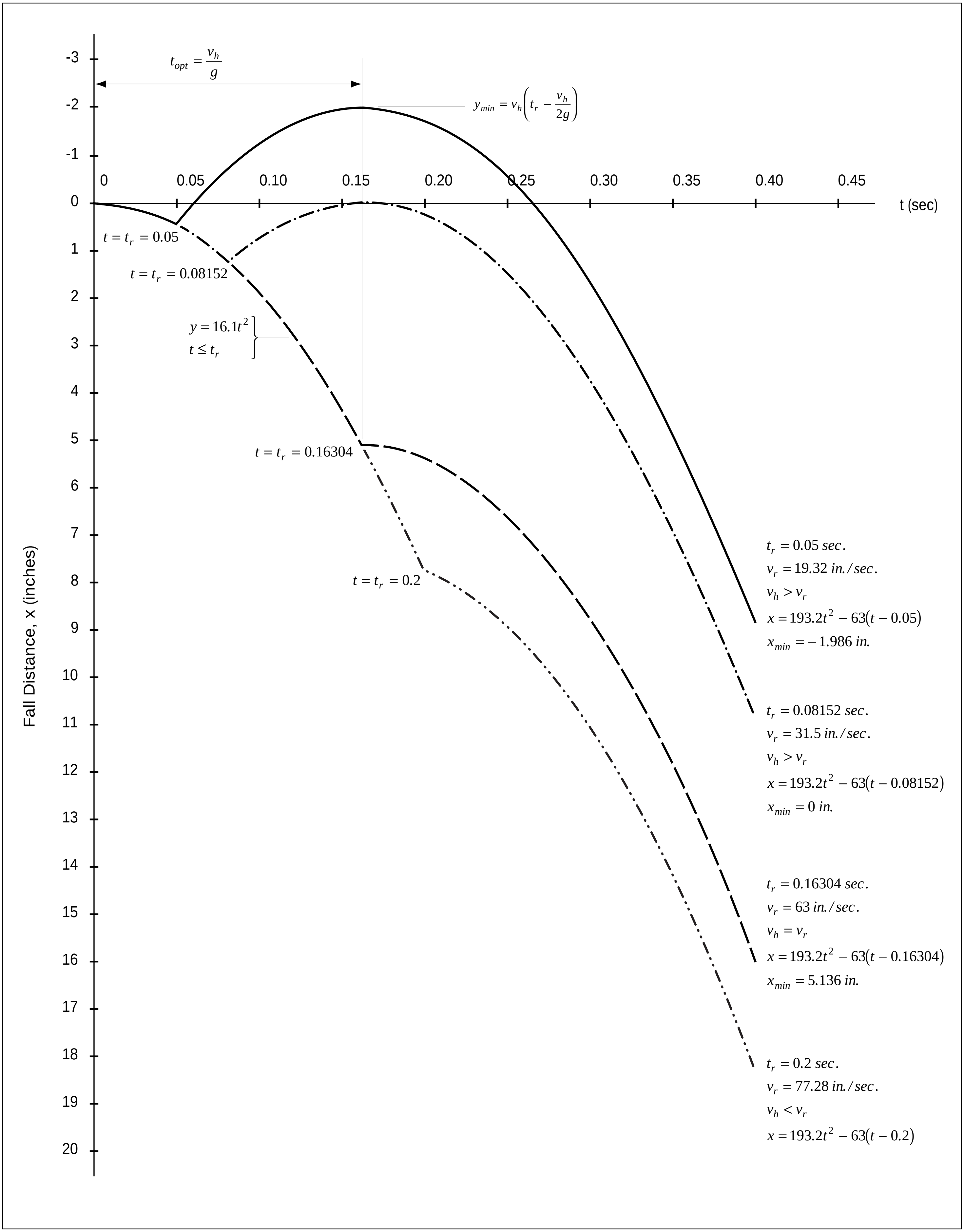

Fig. 3 Hand Trajectories (v_h = 63 inches/sec.; t_{opt} = 0.16304 sec.)

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, $v = gt = v_h$;

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

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