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HAND MOTION DURING TRIP AND FALL SCENARIOS

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ABSTRACT

The location of workplace hazards, the design of fall intervention systems, the development of climbing and walking strategies, and the forensic analysis of slip and fall accidents all benefit from a knowledge of hand motion under the combined effects of gravity and human response. This paper calculates the maximum simple reaction time that will enable the hands to elevate during a drop or trip event. Hand trajectories are characterized for both scenarios.

INTRODUCTION

Under the influence of gravity, a person's hands initially descend during a slip or fall event. During such scenarios, 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 head start 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].

The problems of free fall and pure tripping are studied to define the motion of the hands and to determine the maximum simple reaction time which permits the hands to recover their initial (before accident) elevation. In both cases the form of the trajectories are found to be similar; the maximum reaction times are short.

FREE FALL

There are collapse scenarios where the support literally drops out from under a worker. Consider, for example, the collapsing scaffold shown in Fig. 1. Will the illustrated bricklayer be able to grasp the ledge during such an event?

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

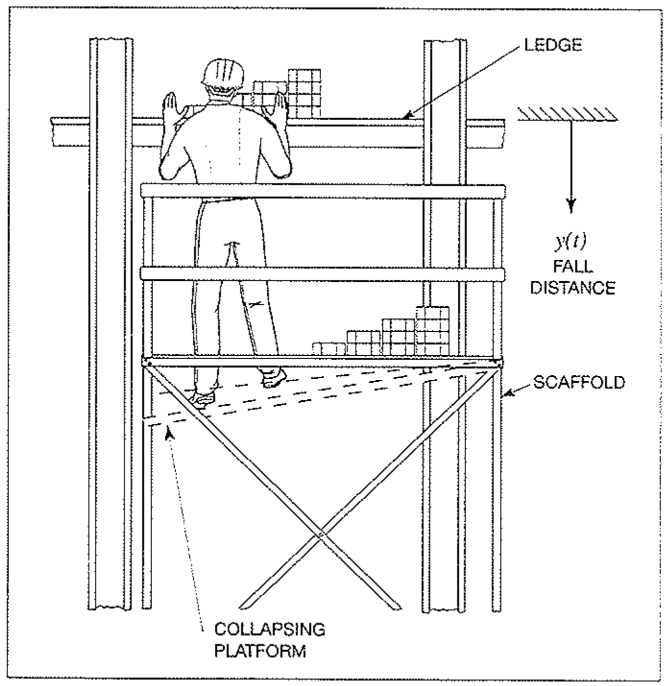

FIG. 1 COLLAPSING SCAFFOLD

fall distance y: $$y(t) = \frac{gt^2}{2} \tag{1a}$$

fall speed v: $$v(t) = gt \tag{1b}$$

fall acceleration a: $$a = g \tag{1c}$$

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 y_r and the free fall speed v_r of the hands; namely,

$$y_r \equiv y(t_r) = \frac{g t_r^2}{2} \qquad (2a)$$

$$v_r \equiv v(t_r) = g t_r \qquad (2b)$$

Because the bricklayer'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,

$$y(t) = \frac{gt^2}{2} - v_h(t - t_r) \qquad t > t_r \qquad (3)$$

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 $v_h = 63$ in./sec. specified by OSHA [Ref. 7], a series of trajectories are plotted in Fig. 2 for various values of simple reaction time t_r.

The hand velocities associated with these trajectories are the derivatives of Eqs. (1a) and (3) and, by definition, are vectors that are tangent to these parabolas; the associated speeds are

$$v = gt \qquad t > t_r$$

$$v = gt - v_h \qquad t > t_r \qquad (4)$$

At time $t = t_r$, the bricklayer's hands begin to move upward at the hand speed constant v_h giving rise to a combined speed of $(v_r - v_h)$. The related velocity vectors $\bar{v}$ have their origins at the intersection of the parabolas shown in Fig. 2 and point in the direction illustrated, for example, in the topmost curve. If the hand speed constant v_h is greater than the free fall speed v_r, a net upward speed will be attained and accordingly, the fall distance y will begin to decrease as shown in the two top curves in Fig. 2. On the other hand if $v_h < v_r$, the combined speed is downward and the fall distance continues to increase, albeit, at a slower rate. This is illustrated by the lowermost curve.

We observe that each of the trajectories portrayed in Fig. 2 has a relative minimum at the origin, i.e.,

$$\left.\frac{dy}{dt}\right|_{t=0} = v(0) = 0 \qquad (5)$$

This recaptures the boundary condition of Eq. (1) where the hands are stationary. When $v_h < v_r$, where there is no possibility of a net upward hand movement, no other relative minimum exists on the trajectories as illustrated by the bottommost curve in Fig. 2 where $t_r = 0.2$ seconds. When $v_h \geq v_r$, a negative velocity (upward) is achieved. This net upward velocity will eventually be overcome by gravity and again move in a downward direction. The hands will, however, reach an upward peak or relative minimum y_{min} before this happens as depicted in the top three trajectories. These crests occur at t_{opt} and have an elevation $y_{min} \equiv y(t_{opt})$. Both t_{opt} and y_{min} are established by applying traditional calculus procedures to Eq. (3); hence,

$$\frac{dy}{dt} = 0 = gt - v_h \qquad (6)$$

$$t_{opt} = \frac{v_h}{g} \qquad (7)$$

$$\frac{d^2y}{dt^2} = g > 0 \qquad \text{for all } t \qquad (8)$$

$$y_{min} = y(t_{opt}) = v_h\left(t_r - \frac{v_h}{2g}\right) \qquad (9)$$

Equation (8) indicates that the relative minimum y_{min} given by Eq. (9) is also the absolute minimum. Indeed, y_{min} represents the very best the bricklayer can do to elevate his hands. In order for him to achieve a net upward reach, y_{min} must be a negative. Equation (9) may be used to establish a general criterion for "falling up"; thus,

$$y_{min} = v_h\left(t_r - \frac{v_h}{2g}\right) < 0 \qquad (10)$$

or

$$t_r < \frac{v_h}{2g} \quad \text{... net upward hand motion} \qquad (11)$$

Using $v_h = 63$ in./sec., a net upward reach of zero occurs at

$$t_r = \frac{v_h}{2g} = \frac{(63/12)}{2(32.2)} = 0.08152\ sec.$$

This case is depicted in Fig. 2 where the parabola just touches the line $y = 0$. Observe that all the peaks occur at the same t_{opt} given by Eq. (7).

Observations - Free Fall

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. (11) 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. 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.

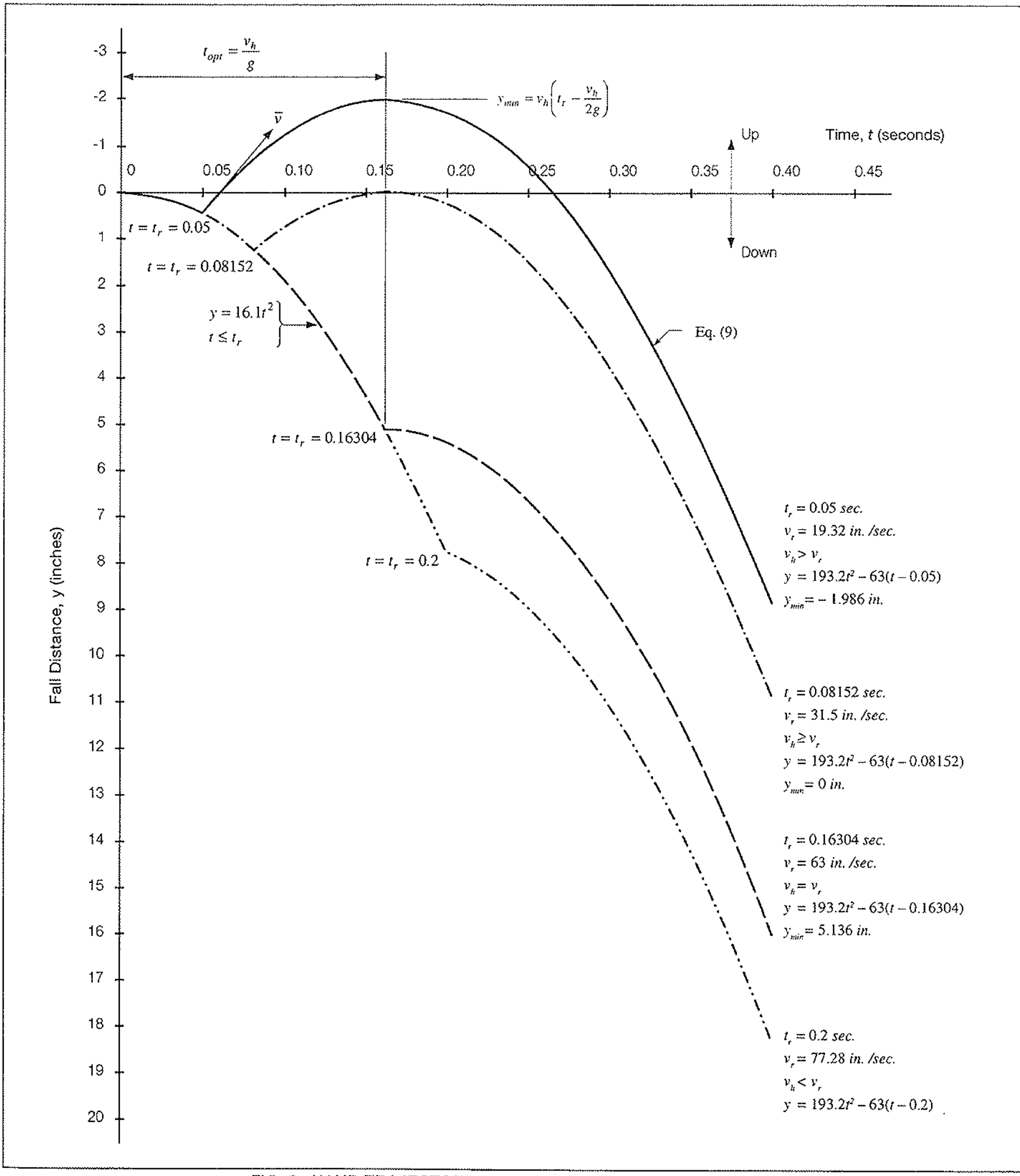

FIG. 2 HAND TRAJECTORIES (v_h = 63 IN./SEC.; t_{opt} = 0.16304 SEC.)

4. 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, $v = gt = v_h$;

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

TRIPPING

Walking proceeds by falling forward and intermittently interrupting this motion by swinging one leg forward. This process is illustrated in Fig. 3(a) where the center of gravity of the walker is located a distance $\bar{r}$ from the surface and moves at a speed v_o. The hands are located a distance S from the surface at the beginning of a tripping scenario. During this translation, the kinetic energy $(K.E.)_{tran}$ may be approximated as

$$(K.E.)_{tran} = \frac{1}{2}\left(\frac{W}{g}\right)v_o^2 \tag{12}$$

where W is the weight of the walker. When a stumbling block is encountered, as shown in Fig. 3(b), the leg may no longer swing forward and the associated "trip" converts the translation motion into rotation about the feet. The kinetic energy of translation is immediately changed into kinetic energy of rotation $(K.E.)_{rot}$ which may be approximated as

$$(K.E.)_{rot} = \frac{1}{2} I\dot{\theta}_o^2 \tag{13}$$

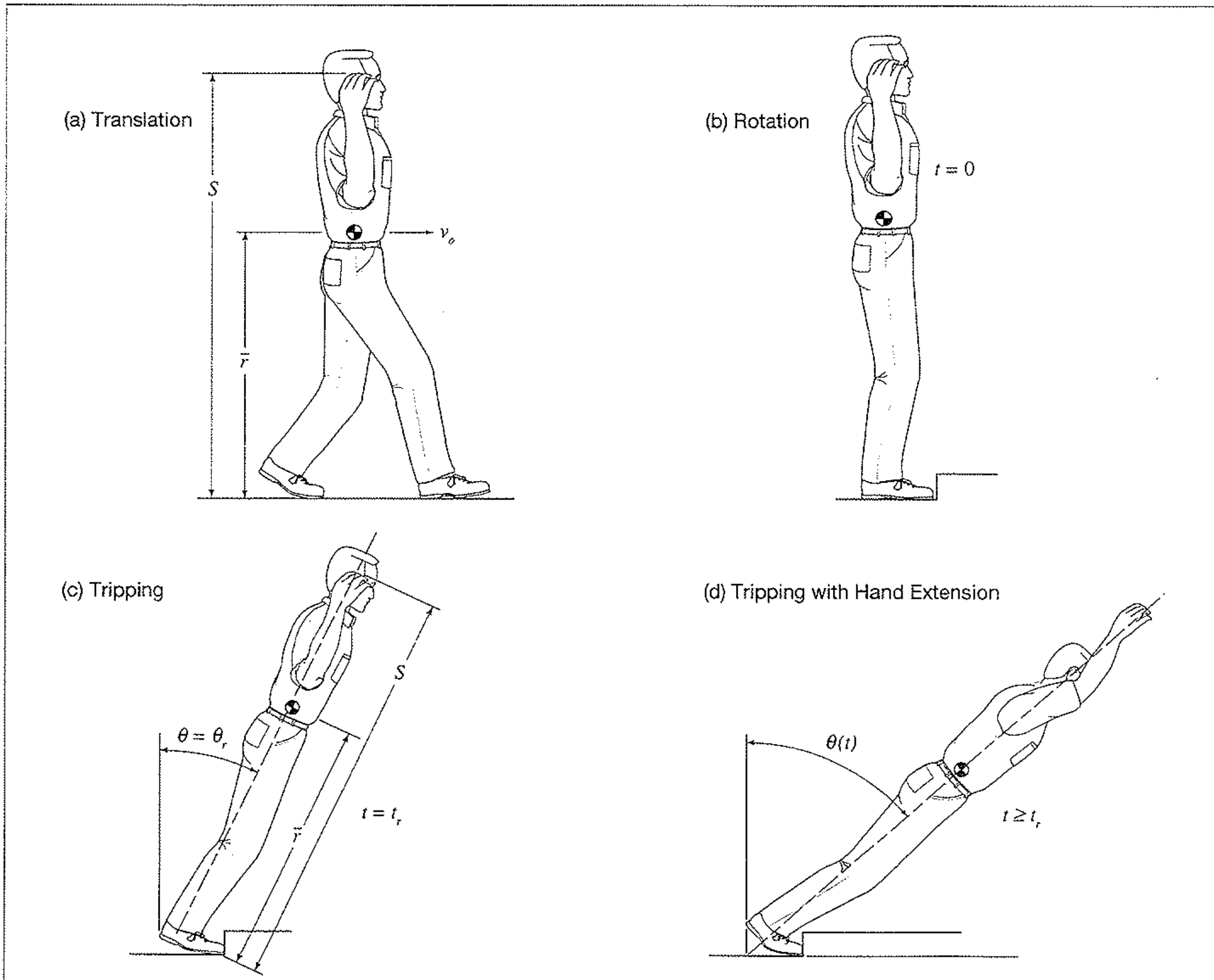

FIG. 3 TRIPPING SCENARIO

where I is the mass moment of inertia of the walker about his feet and $\dot{\theta}_o$ is the initial angular velocity of the falling man; the angle θ is measured from the vertical coordinate shown in Fig. 3(c). Here, the tripping walker is depicted as a rotating rigid body and S and $\bar{r}$ are radial coordinates; the hands are located at polar coordinates (S,θ).

At time $t = 0$ the two kinetic energies may be equated to relate the initial angular velocity of the walker to the original walking speed v_o; thus,

$$\frac{1}{2}\frac{W}{g}v_o^2 = \frac{1}{2}I\dot{\theta}_o^2$$

or,

$$\dot{\theta}_o = \sqrt{\frac{W}{Ig}}v_o \tag{14}$$

Referring to the free body diagram of the walker shown in Fig. 4, the moment M about the walker's feet is given by

$$M = W\bar{r}\sin\theta \tag{15}$$

To find an expression for $\theta(t)$, we begin by substituting this moment into the *equation of motion of a rigid body about a fixed axis*, i.e.,

$$I\ddot{\theta} = M = W\bar{r}\sin\theta \tag{16}$$

or,

$$\ddot{\theta} - \frac{W\bar{r}}{I}\theta = 0 \tag{17}$$

where $\ddot{\theta}$ is the angular acceleration and the $sin\theta$ is approximated as θ. The general solution of Eq. (17) is

$$\theta = A\cosh\sqrt{\frac{W\bar{r}}{I}}t + B\sinh\sqrt{\frac{W\bar{r}}{I}}t \tag{18}$$

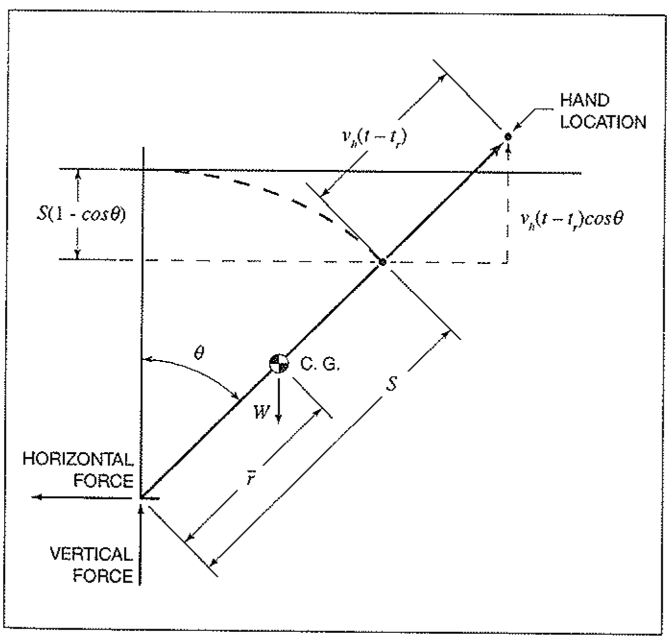

FIG. 4 FREE BODY DIAGRAM

where A and B are arbitrary constants that are determined from the problem's initial conditions;

$$t = 0, \theta = 0 \tag{19}$$

$$t = 0, \dot{\theta} = \dot{\theta}_o = \sqrt{\frac{W}{Ig}}v_o \tag{20}$$

Thus, the solution for the angular motion $\theta(t)$ becomes

$$\theta(t) = \frac{v_o}{\sqrt{g\bar{r}}}\sinh\sqrt{\frac{W\bar{r}}{I}}t \tag{21}$$

and the corresponding angular velocity $\dot{\theta}$ is

$$\dot{\theta}(t) = v_o\sqrt{\frac{W}{Ig}}\cosh\sqrt{\frac{W\bar{r}}{I}}t \tag{22}$$

The angle $\theta(t)$ describes the inclination of the falling man shown in Fig. 3(d).

During the initial phase of the tripping scenario the walker's hands move in a circular arc of radius S about his feet. The polar coordinates of the hands (S,θ) are

$$(S,\theta) = \left(S, \frac{v_o}{\sqrt{g\bar{r}}}\sinh\sqrt{\frac{W\bar{r}}{I}}t\right) \tag{23}$$

The associated vertical component $y(t)$ is given by $S(1 - cos\theta)$;

$$y(t) = S\left[1 - \cos\left(\frac{v_o}{\sqrt{g\bar{r}}}\sinh\sqrt{\frac{W\bar{r}}{I}}t\right)\right] \tag{24}$$

Equations (23) and (24) are valid until the walker begins to extend his arm parallel to the longitudinal axis of his body. This takes place after the simple reaction time t_r elapses, i.e., $t > t_r$. Thereafter, the hands will reach out a distance $v_h(t - t_r)$ from their original position. Referring to Fig. 4, the polar coordinates of the hands become

$$\left[S + v_h(t - t_r),\ \frac{v_o}{\sqrt{g\bar{r}}}\sinh\sqrt{\frac{W\bar{r}}{I}}t\right] \qquad t \geq t_r \tag{25}$$

Referring once again to Fig. 4, the vertical component of the hands is found to be

$$y(t) = S(1 - \cos\theta) - v_h(t - t_r)\cos\theta \tag{26}$$

$$= S - \left[S + v_h(t - t_r)\right]\cos\left(\frac{v_o}{\sqrt{g\bar{r}}}\sinh\sqrt{\frac{W\bar{r}}{I}}t\right) \qquad t \geq t_r \tag{27}$$

At $t = t_r$, the hands, which are moving along a circular arc at speed $\dot{\theta}S$, pick up an additional radial velocity v_h. This occurs at an angle $\theta_r = \theta(t_r)$ when the angular velocity is $\dot{\theta}_r = \dot{\theta}(t_r)$. The two velocities $\dot{\theta}S_r$ and v_h are depicted in Fig. 5 together with their horizontal and vertical components. Focusing only on the vertical velocity component $\dot{y}_r$, this is given by

$$\dot{y}_r = S\dot{\theta}_r\sin\theta_r - v_h\cos\theta_r \tag{28}$$

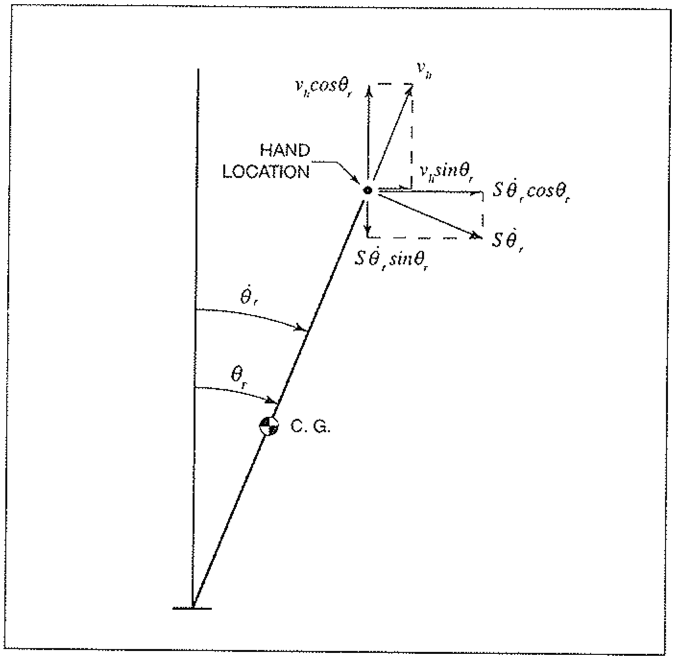

FIG. 5 HAND VELOCITY COMPONENTS AT $t = t_r$

This result may also be obtained analytically by computing the time derivative of $y(t)$ given by Eq. (26) and evaluating it at $t = t_r$; thus,

$$\frac{d}{dt}y(t) = -S\frac{d\cos\theta}{d\theta}\frac{d\theta}{dt} - v_h\cos\theta - v_h(t - t_r)\frac{d\cos\theta}{d\theta}\frac{d\theta}{dt}$$

$$\dot{y}(t) = S\dot{\theta}\sin\theta - v_h\cos\theta + v_h\dot{\theta}(t - t_r)\sin\theta$$

At $t = t_r$, we recover Eq. (28).

The last phase of tripping begins at $t = t_r$ when the walker starts to reach out. By examining his vertical hand speed we can tell if his hands begin to ascend. If $\dot{y}_r < 0$ the walker reaches upward faster than he falls downward; thus, Eq. (28) provides the following criterion:

$$v_h > S\dot{\theta}_r \tan\theta_r \quad \text{... upward motion}$$

or,

$$v_h > \left(Sv_o\sqrt{\frac{W}{Ig}}\cosh\sqrt{\frac{W\bar{r}}{I}}t_r\right)\tan\left(\frac{v_o}{\sqrt{g\bar{r}}}\sinh\sqrt{\frac{W\bar{r}}{I}}t_r\right) \tag{29}$$

No upward hand motion can ever be achieved if the hand speed constant $v_h \le S\dot{\theta}_r \tan\theta_r$.

In those cases where the walker's parameters satisfy the criterion for initial upward hand movement given by Eq. (29), a maximum upward hand position will be realized before gravity eventually dominates all motion. Consequently, if the vertical hand position $y(t)$ is plotted against time, a relative minimum (maximum upward hand position) will be obtained. These ideas can all by crystallized by considering a specific example.

Example - Uniform Body:

Approximate a walker as a prismatic rigid body of height $L = 6$ ft. moving at a speed v_o = 3mph = 4.4 ft./second. Take the hand location $S = 5$ ft. from the walking surface. Then,

$$I = \frac{WL^2}{3g} \quad \text{... mass moment of inertia} \tag{30}$$

$$\bar{r} = \frac{L}{2} \quad \text{... center of gravity} \tag{31}$$

$$\frac{v_o}{\sqrt{g\bar{r}}} = \frac{4.4}{\sqrt{(32.2)(6/2)}} = 0.4476763$$

$$\sqrt{\frac{W\bar{r}}{I}}t = \sqrt{\frac{3g}{2L}}t = \sqrt{\frac{3(32.2)}{2(6)}}t = 2.837252t$$

$$\sqrt{\frac{W}{Ig}}S = \frac{\sqrt{3}}{L}S = \frac{\sqrt{3}}{6}S = 0.2886751S$$

Equation (29) - Upward Motion Criterion:

$$v_h > \left(v_o S\sqrt{\frac{W}{Ig}}\cosh\sqrt{\frac{W\bar{r}}{I}}t_r\right)\tan\left(\frac{v_o}{\sqrt{g\bar{r}}}\sinh\sqrt{\frac{W\bar{r}}{I}}t_r\right)$$

$$v_h > \left[4.4(5)(0.28868)\cosh 2.8373t_r\right] \cdot \tan(0.44768\sinh 2.8373t_r) \tag{32}$$

Solving Eq. (32) numerically for a hand speed constant v_h = 63 in./sec. = 5.25 ft./second, we find that upward motion will take place when $t_r < 0.340343$ seconds.

Equation (24) - Vertical Displacement for $t \le t_r$:

$$y(t) = S\left[1 - \cos\left(\frac{v_o}{\sqrt{g\bar{r}}}\sinh\sqrt{\frac{W\bar{r}}{I}}t\right)\right]$$
$$= 5\left[1 - \cos(0.44768\sinh 2.8373t)\right] \tag{33}$$

This equation is plotted in Fig. 6.

Equation (27) - Vertical Displacement for $t > t_r$:

$$y(t) = S - \left[S + v_h(t - t_r)\right]\cos\left(\frac{v_o}{\sqrt{g\bar{r}}}\sinh\sqrt{\frac{W\bar{r}}{I}}t\right)$$
$$= 5 - \left[5 + 5.25(t - t_r)\right]\cos(0.44768\sinh 2.8373t) \tag{34}$$

This equation is plotted in Fig. 6 in conjunction with the corresponding curve described by Eq. (33). The resulting vertical hand elevations are shown for various values of the simple reaction time t_r.

In those instances where only maximum upward reach is of interest, it is not necessary to reveal the entire displacement history $y(t)$. Here, Eq. (27) provides a criterion for a net upward reach, i.e.,

$$y(t) < 0 \quad \text{... upward reach}$$

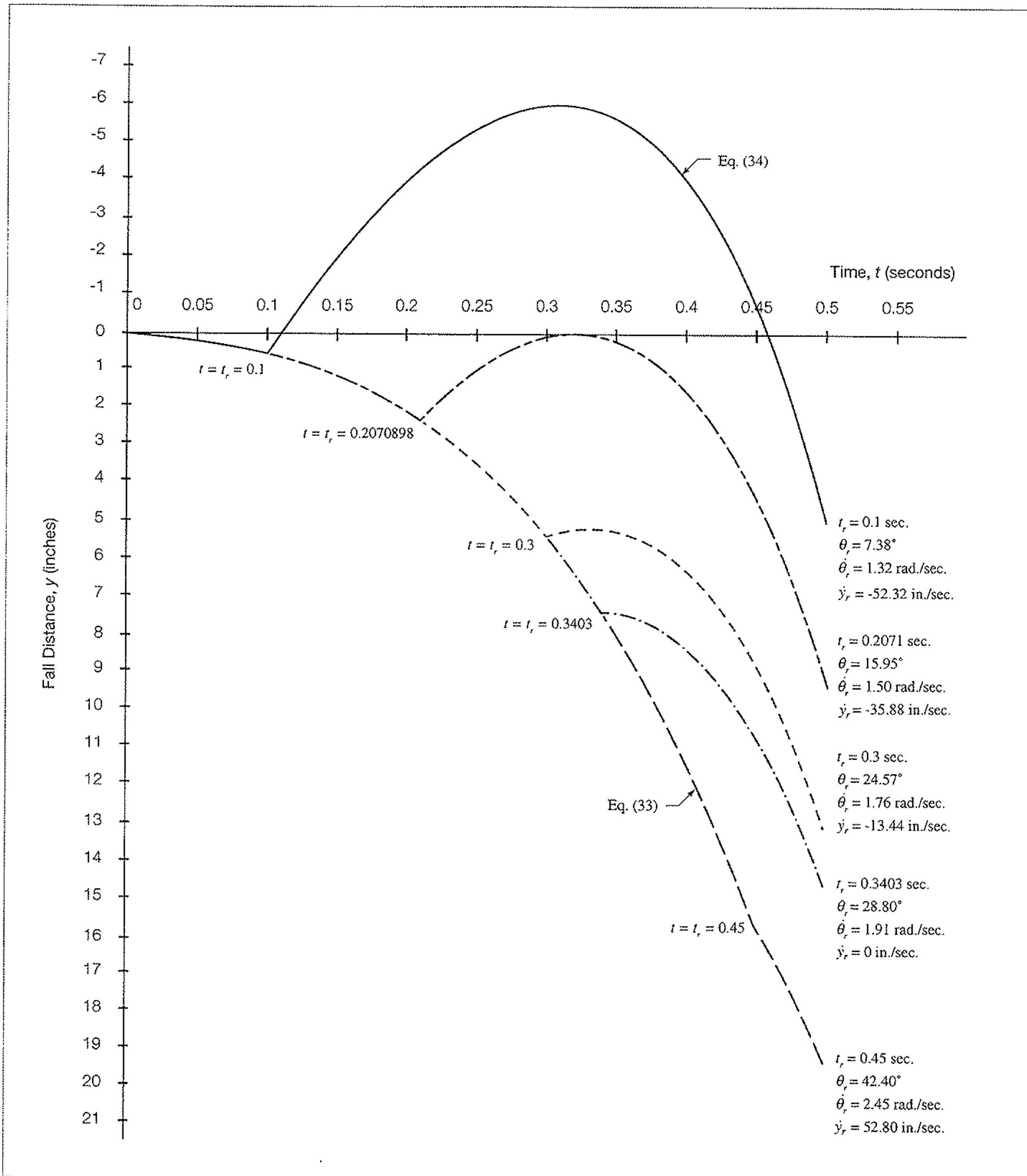

FIG. 6 HAND TRAJECTORIES UNDER TRIPPING CONDITIONS

or, after rearranging terms,

$$t_r < t + \frac{S}{v_h}\left[1 - \frac{1}{\cos\left(\frac{v_o}{\sqrt{g\bar{r}}} \sinh \sqrt{\frac{W\bar{r}}{I}} t\right)}\right] \quad (35)$$

For the example problem, Eq. (35) becomes

$$t_r < t + \left(\frac{5}{5.25}\right)\left[1 - \frac{1}{\cos(0.44768 \sinh 2.83725t)}\right] \quad (36)$$

Using an equality in Eq. (36), t_r is plotted against time in Fig. 7 for $S = 5$ feet. We observe that an upward reach may be obtained whenever $t_r < 0.2071$ seconds. A second curve is shown in Fig. 7 which corresponds to $S = 2.625$ ft. = 31.5 inches; this is roughly the height of the walker's palms when his arms are hanging down. In this case, an upward reach requires that $t_r < 0.2838$ seconds.

Equation (21) - Angle at $t = t_r$:

$$\theta_r = \frac{v_o}{\sqrt{g\bar{r}}} \sinh \sqrt{\frac{W\bar{r}}{I}} t_r \quad (37)$$

$$= 0.44768 \sinh 2.8373 t_r \quad (38)$$

The walker's inclination angle at the time he begins to reach is indicated in Fig. 6.

Equation (22) - Angular Velocity at $t = t_r$:

$$\dot{\theta}_r = v_o \sqrt{\frac{W}{Ig}} \cosh \sqrt{\frac{W\bar{r}}{I}} t_r \quad (39)$$

$$= 4.4(0.28868) \cosh 2.8373 t_r \quad (40)$$

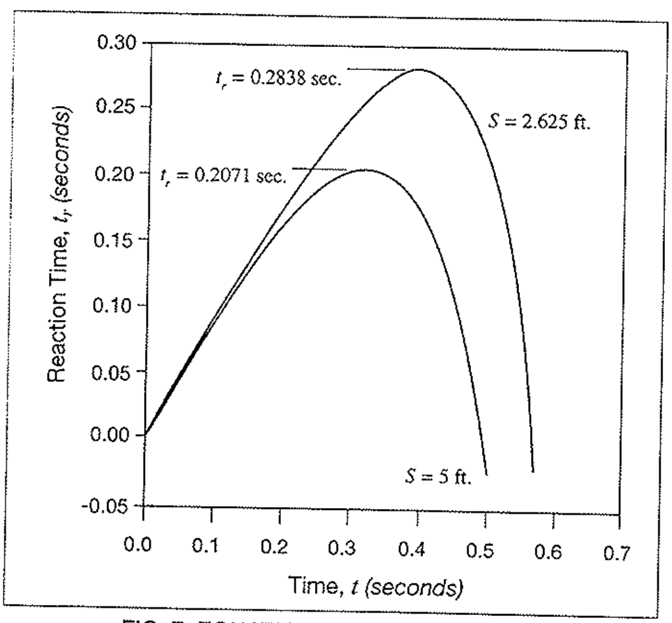

FIG. 7 EQUATION (36); v_h = 63 IN./SEC.

The walker's angular velocity at the time he begins to react is shown in Fig. 6.

Equation (28) - Vertical Hand Speed Component at $t = t_r$:

$$\dot{y}_r = S\dot{\theta}_r \sin\theta_r - v_h \cos\theta_r$$

$$= 5\dot{\theta}_r \sin\theta_r - 5.25 \cos\theta_r \quad (41)$$

Equation (41) incorporates a hand speed constant taken as v_h = 63 in./second; $\dot{y}_r$ is listed in Fig. 6.

Observations - Tripping

1. The maximum simple reaction times that enable a walker to achieve a net upward hand movement during a tripping scenario are obtained by maximizing t_r given by Eq. (36) as illustrated in the example problem. Table 1 tabulates maximum reaction time for several walking speeds and initial hand elevations. The occurrence times are also listed; these values of t maximize t_r and give the elapsed time from the onset of the trip.

TABLE 1 MAXIMUM SIMPLE REACTION TIME

Walking Speed	Initial Hand Elevation, S	Maximum Simple Reaction Time	Occurrence Time
2 mph	2.625 ft.	0.4079 sec.	0.5397 sec.
3 mph	2.625 ft.	0.2838 sec.	0.4038 sec.
4 mph	2.625 ft.	0.2061 sec.	0.3125 sec.
3 mph	5.0 ft.	0.2071 sec.	0.3230 sec.
4 mph	5.0 ft.	0.1405 sec.	0.2355 sec.

2. As shown in Table 1, shorter reaction times are required for faster walking speeds.
3. Table 1 also indicates that shorter reaction times are required as the initial hand elevation is raised.
4. Fall intervention strategies should move in the direction of slower walking speeds and lower railings and grab bars. Whenever practical, continuous hand contact with banisters and the like is advisable.
5. Vestibular senses monitor equilibrium and the awareness of body position and movement [Ref. 8]. According to Boff and Lincoln, the simple reaction time "for sensing the onset of bodily rotation is so variable that only a median of 400 msec. can be meaningfully defined" [Ref. 9]. Increasing this median value to take care of the unanticipated nature of trips, produces a reaction time that is greater than any of those listed in Table 1. This implies that no net upward movement can be expected while tripping.

Occasionally, the vestibular senses can be completely overwhelmed by information from the visual sense. Vestibular and visual sensation, together with tactile feedback from contacting the stumbling block, are available to trigger the walker's response to tripping. We currently have an impoverished understanding of the simple reaction time at which these three senses are stimulated in a tripping scenario. Indeed, this is the motivation for formulating our analysis using the simple reaction time as the only unknown.

6. Recall that Eq. (16) was simplified by taking θ as an approximation for $sin\theta$. Since $\theta \geq sin\theta$, this implied that we overestimated the overturning moment on the walker which in turn leads to a higher angular acceleration than would normally be experienced. On the other hand, we ignored the increase in $I/\bar{r}$ that occurs when the walker extends his hands and arms; this leads to a lower angular acceleration and tends to compensate for the linearization assumption. If we consider the case where the walking speed is 3 mph and the hands are elevated S =2.625 ft., the occurrence time associated with the maximum reaction time is shown in Table 1 to be $t_r = 0.4038$ seconds. Using Eq. (21) we calculate an angular position of $\theta = 36.25$ degrees = 0.6327 radians. The $sin\,0.6327 = 0.5913$; hence, the approximation is 7% too high. The exact solution of the equation of motion involves elliptic functions. Computer simulation techniques are readily available that can account for very complex dynamic situations.

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