Kai-Ping Shaw,[1,2,3] *M.D., Ph.D. and Shuh Yuan Hsu,*[4] *M.S.*

Horizontal Distance and Height Determining Falling Pattern

REFERENCE: Shaw K-P, Hsu SY. Horizontal distance and height determining falling pattern. J Forensic Sci 1998;43(4):765–771.

ABSTRACT: Falling from a height, usually from a building, occurs ordinarily in suicide, in some accidents, and sometimes as an act of homicide. The point of trajectory, the horizontal distance and the impact point are closely related to the initial velocity, angle and height. This study examines the falling pattern in order to determine the mental status of the jumper as well as the manner of death. Initial velocity is found using horizontal movement and height. A serial study of athletes performing both the running jump (long jump) and standing jump (swimmer's start jump) via biomechanical methods is described. The initial velocity of the running jump and standing jump in normal athletics is 9.15 and 2.70 m/s with initial jumping angles of 21 and 38 deg, respectively. The maximal horizontal velocity of 9.15 m/s is closely related to maximal strength of initial velocity, angle of engaged force, and height. Theoretical estimation of the initial velocity between 2.70 and 9.15 m/s is correlative with the unique initial velocity and running jump to fall from a height that is closely related to the voluntary and attempted jump. Hence, the jumping victim with an initial velocity higher than 2.70 m/s implies suicide. These results indicate that horizonal distance and height are legitimate measures to use in speculating on the falling pattern and the manner of death. A unique case of suicide involving a run and jump with initial velocity greater than 2.70 m/s is illustrated.

KEYWORDS: forensic science, forensic engineering, falling, biomechanical study, standing jump, running jump

Falling from a height can be the result of an accident, homicide, or suicide. Without a careful evaluation of the social history, scene investigation and autopsy results, it is difficult to determine the manner of death (1,2). Limited data, including toxicological studies, patterns of injury, defensive wounds and related evidence, are essential to determine an unnatural cause of death (3–6). In the case of falling from a height, the manner of death can be determined easily from the scene investigation rather than from autopsy findings (1). The jumping point to where the body strikes the ground and the height are two major factors which may indicate the motivation of the jumper. In consideration of the decedent's unique pattern, biomechanical analysis may provide crucial information for determining the manner of death (1). According to Newton's law (7), the variation of motion is proportional to the motive force, and is applied in the direction of the angle, initial velocity and the speculative computed distance of horizontal and vertical velocity (height). In spite of the environmental factors, falling from a height is well derived from the free-fall concept with constant acceleration for different objects due to constant gravity and variable initial velocity below 152 m of height (8). A study was conducted on thirteen athletic students from the Department of Physical Education, National Taiwan Normal University, Taipei, using biomechanical methods to test the difference between the running jump of athletes and the standing jump of swimmers. In order to understand the differences in biomechanical data among various types of jumps, study is confined to the horizontal velocity of the standing and running jumps. The initial velocity of the standing and running patterns of the jump is observed in athletic subjects; this will be used to compare the horizontal velocity with different types of jump at various angles. We use these biomechanical data to construct the pattern of jump, the mental status of the jumper, and to determine the unique pattern of the suicidal jump.

Materials and Methods

Biomechanical Study of Initial Velocity in Running Jump and Standing Jump

Biomechanical studies of the running and standing jumps were performed. Thirteen volunteers were divided into a swimmer's start (standing) jump group and a running jump group. Three members of the swimmer's start jump group jumped in various attitudes and ten members of the running jump group performed running starts to initiate a jump. Besides a multipurpose polygraph, a strain gage, an electrogoniometer (9), and a force platform with two steel plates measuring $60 \times 30 \times 5$ cm^3 and connected to a strain gage were applied to determine the beginning point during the velocity measurement. A Minolta 8 mm camera (cinematography), 36 pictures/second, and a coordinate scale measuring 1.8×10.8 m^2 were utilized in the measurement of various velocities and related parameters. Body gravity was measured according to Garrett et al. (10). The running jump was launched after a prerunning for 20 m. There are three types of swimmer's start jump: traditional, swinging, and grab start; they are used to measure the maximal horizontal velocity of the individual. Horizontal and vertical velocity are coordinated with the measurement of jumping time and angle. Each member was tested for three jumps after two prior trials. Mean and standard error mean were calculated for each jump.

Theoretical Prediction

The free-fall concept with constant acceleration for different objects due to constant gravitational acceleration (G) and variable

[1] Associate professor, Department of Biology & Anatomy, Department of Biomedical Engineering. Department of Pathology, National Defense Medical Center, P.O. Box 90048–502, Taipei, Taiwan, ROC.
[2] Forensic Medicine Center, Prosecutor's Office for Taiwan High Court, Ministry of Justice, 212 Chia-Hsin Street, Taipei, Taiwan, ROC.
[3] Scientific and Technical Research Center, Investigation Bureau, Ministry of Justice, Taipei, Taiwan, ROC.
[4] Professor, Department of Physical Education, National Taiwan Normal University, Taipei, Taiwan, ROC.
Received 29 Apr. 1997; and in revised form 8 Aug. 1997; accepted 31 Oct. 1997.

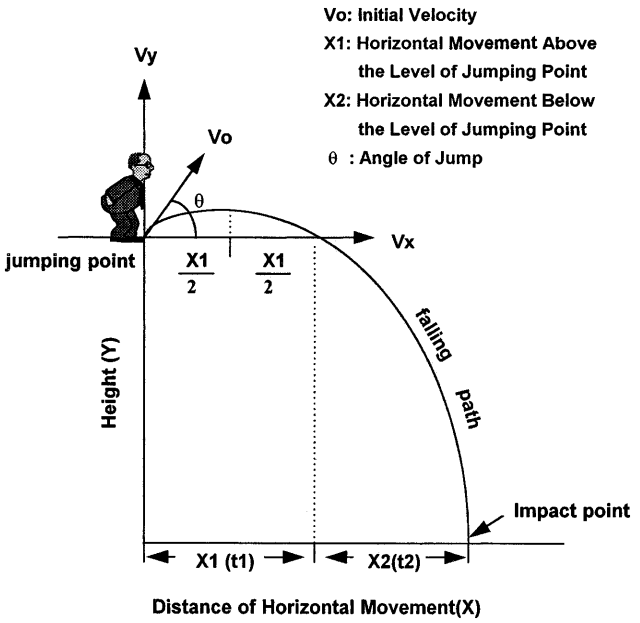

FIG. 1—*Biomechanical basis of falling from heights: Falling from (*Y*) height and horizontal distance of movement (*X*) away from the jumping point should be considered through the investigation.* t = *time of falling;* V_0 = *initial velocity.* V_x = *horizontal velocity,* V_y = *vertical velocity.*

initial velocity (V_0) at various heights (H) is applied (Fig. 1). $H = 1/2\ Gt^2$ is used as the base calculation of gravitational acceleration, H is height below the jumping point, and t is the time instant after jumping. X represents the horizontal distance of movement, including above (X_1) and below (X_2) the jumping level (Fig. 1). Maximal horizontal movement (X) can be predicted by initial velocity with the appropriate angle (Θ_{max}) of engagement. According to Newton's law (7), the change of motion is proportional to the motive force, and is applied in the direction of the initial angle of jump where the force is imposed. The derivative of the free-fall concept with the falling body is recognized as practice, with constant acceleration for different objects due to gravity and the horizontal velocity correlative with height and initial velocity. Initial velocity can be divided into horizontal velocity (V_x) and vertical velocity (V_y); therefore, the angle between 0 deg (X-axis) and 90 deg (Y-axis) (θ) should be carefully taken into account with the horizontal velocity of falling process:

$$x = (V_0 \cdot \cos\Theta) \cdot t \quad (1)$$

$$y = (V_0 \cdot \sin\Theta) \cdot t - 1/2 \cdot Gt^2 \quad (2)$$

At the point of grounding (impact point), $x = X$ (horizontal movement) and $y = -H$ (height of falling).

For a given H and V_0, the horizontal angle is Θ_{max}, where the horizontal distance will be maximum. It can be shown that

$$\Theta_{max} = \sin^{-1}\left(2\left(1 + GH/V_0^2\right)\right)^{-1/2} \quad (3)$$

Hence, maximal horizontal movement can be determined by initial velocity with the appropriate angle of engagement. The initial velocity can be derived from the height and horizontal movement in the falling case at various speculative angles as follows:

$$V_0 = \left(G \cdot X^2/(2(X \cdot \sin\theta + H \cdot \cos\theta) \cdot \cos\theta)\right)^{1/2} \quad (4)$$

The angle of initial velocity can be theoretically calculated by Eq 4 to derive the maximal horizontal movement. An Excel (Microsoft) program is used to compute the results.

Clinical Fatality of a Falling Tragedy

The decedent was collected from the Forensic Medicine Center, Prosecutor's Office, for the Taiwan High Court under a death investigation procedure which includes medicolegal autopsy, pathological, toxicological studies and biomechanical analysis. The medicolegal autopsy and the pathological observation were performed, following the standard procedure. Initial velocity (V_0) is calculated at various hypothetic angles (Θ) of jump with Eq 4 by using the height and horizontal movement.

Results and Discussion

Horizontal Velocity of Running Jump and Standing Jump

Biomechanical studies were conducted by thirteen athletes through biomechanical measurement to test the running jump and standing jump (swimmer's start jump). The initial velocity of the running jump and standing jump in normal athletes is 9.15 ±0.11 and 2.70 ±0.11 m/s with jumping angles of 21 ±0.40 and 38 ±1.33 deg, respectively. The practical measurements of horizontal velocity of the running jump and swimmer's start jump were 8.54 ±0.07 and 2.10 ±0.05 m/s and of vertical velocity, 3.88 ±0.12 and 1.59 ±0.07 m/s, respectively (Table 1). These results suggest an initial velocity between 2.70 m/s for the standing jump and 9.15 m/s for the run-up and jump that may contribute to launch the fall from a height by a voluntary (suicidal) jump. The initial velocity of 9.15 m/s can be defined as the maximal value of a normal individual engaging in a fall with a pre-running acceleration before launch.

Standing Jump—To represent the typical standing jump, without adding any running activity, selective modes of the swimmer's start jump provide unique jumping patterns that emulate the jumping activities through which the biomechanical measurements are obtained. Although many scholars have demonstrated how to find the initial velocity in sports that include a standing jump, the standing swimmer's jump represents a distinctive pattern of jump from a height that can truly emulate the jump of falling from a height. A standard standing broad jump can generate up to 3.60 m/s of initial velocity at an angle of 41.03 deg on the basis of the body gravity of normal athletic students (11). The visual adjustment and postural balance to perfectly accommodate the grounded position to a maximal horizontal movement without increasing the initial velocity should not be confused with the standing (swimmer's) jump. The swimmer's start jump, an ideal model to mimic the standing jump and falling from a height, makes it almost impossible to adjust the body position while the jumper has already left

TABLE 1—*Biomechanical studies of standing (swimmer's) jump and running (long) jump.*

Biomechanical Measurement	Swimmer's Jump (n = 9)	Long Jump (n = 30)
Initial angle, Θ	38.00 ± 1.33*	21.00 ± 0.40
Initial velocity, m/s	2.70 ± 0.11	9.15 ± 0.11
Horizontal velocity, m/s	2.10 ± 0.05	8.54 ± 0.07
Vertical velocity, m/s	1.59 ± 0.07	3.88 ± 0.12

* Data represent mean ±standard error mean.

the jumping point, and thus permits us to measure the initial velocity and other related biomechanical parameters, including both horizontal and vertical velocity as well as jumping angle. Distinct body gravities may explain the lower value of the initial velocity of the standing (swimmer's) jump while we compare the initial velocity of the standing broad jump with an adjustable gravity (11). A two-hand push of a normal individual to other individuals (70 kg of body weight) can generate an initial velocity up to only 0.4 m/s (12). An initial velocity exceeding 2.70 m/s or so becomes the criterion for the running jump that is distinguishable from being pushed or slipping before falling from a height. For instance, an initial velocity lower than 2.70 m/s cannot be distinguish between suicide, homicide or accident.

Running Jump—The running jump is a situation where there is a running start to a jump from a height when an individual is really out of his mind or has convinced himself to jump from a height. This jump is preceded by a pre-running acceleration before launching to result in an intentional fall. When an individual actually launches at maximal force, the maximal horizontal movement can reach 42% of the height (42.21 m away from the jumping point while falling from a 100 m height at an angle of 11.44 deg with an initial velocity of 9.15 m/s). A running jump initial velocity that reaches 9.15 m/s reasonably explains the maximum capability of normal athletes. An initial velocity between 2.70 and 9.15 m/s supports a jumping activity with pre-running assistance before the jump. Such data permit us to determine the pattern of fall and jump. Any initial velocity exceeding 9.15 m/s should be carefully evaluated for other reasonable explanations, including wind factor, an inaccurate jumping point, a faulty impact point, launching machine assistance, etc. It is evident that falling after a running jump is a manner of intentional jump. Therefore, the decedent's attempt to commit suicide should be considered. A falling fatality with an initial velocity exceeding 2.70 m/s should not be mistaken for accidental or homicidal cause of death.

Theoretical Estimate of Horizontal Distance with Initial Velocity and Angle of Launching at Various Heights

Deriving from the free-fall concept of constant acceleration for different objects, the initial velocity can be divided into horizontal velocity (V_x) and vertical velocity (V_y); the angle between 0 (X-axis) and 90 (Y-axis) deg (θ) should be carefully taken into account in calculating the horizontal velocity of the falling process as described earlier in the Materials and Methods section.

Falling Pattern Above the Jumping Level—The angle of maximum horizontal movement is 45 deg above the jumping surface. Accordingly, the initial velocity obtained from the standing jump and running jump is 2.70 and 9.15 m/s, respectively. The falling patterns shown in Fig. 2 imitate the jumping patterns at different angles from 0 to 50 deg with initial velocities of 2.70 m/s (Fig. 3*a*) and 9.15 m/s (Fig. 3*b*). When it iterates the falling activity (initial velocity either 2.7 and 9.15 m/s) as increasing from 0 to 50 deg of launching angle down to 0.5 m in depth, it increases the horizontal movement up to 40 deg and decreases it 50 deg simultaneously (Figs. 3*a* and 3*b*).

Falling Pattern from a Height: Emulating the Falling Pattern—The pattern is similar when theoretical iterations are up to 100 m height (Figs. 4*a* and 4*b*) with initial velocities of 2.70 and 9.15 m/s. The falling pattern with typical standing and running jumps can be postulated at various angles (Eq 3) so as to speculate on the maximal horizontal movement of the falling pattern (Fig. 5). At a height of 100 m, the horizontal movement with initial velocities of 2.70 and 9.15 m/s is classified as the peak range from 8.5 to 12.5 m and 37 to 42 m, respectively. The lower range with the angle above 40 deg is excluded because the low horizontal velocity (12) is indistinguishable from the action of being pushed or slipping/falling or accidental falling with a standing and running jump activity. It seems that any angle above 50 deg with the initial velocity either at 2.70 or 9.15 m/s is indistinguishable from minor or complete absence of jumping activity. Different heights of standing and running jump in a normal athletic individual can be iterated to obtain the horizontal movement at various heights and vice versa (Fig. 5).

Jumping Angle and Horizontal Movement—Initial angles obtained by the running and standing jump are 21.00 $\pm$0.40 and 38.00 $\pm$1.33 deg, whereas 45 deg is the best angle to generate the maximal horizontal velocity when grounding at the same level. By the time the victim falls from a height, the initial jumping angle in order to launch maximum horizontal movement becomes smaller than 45 deg (Fig. 5 and Table 2). At angles (Θ_{max}) of 11.4 and 3.48 deg, maximum horizontal movement of 42.21 and 12.22 m away from the jumping point are hypothetically estimated during a fall from 100 m height at the initial velocities of 9.15 m/s (running jump) and 2.70 m/s (standing jump), respectively. (See Fig. 6). In order to derive a theoretical estimate after iteration of the falling patterns at various initial velocities, the jumping angle should be zero so as to reach the maximum horizonal movement while falling from an infinite height (Table 2).

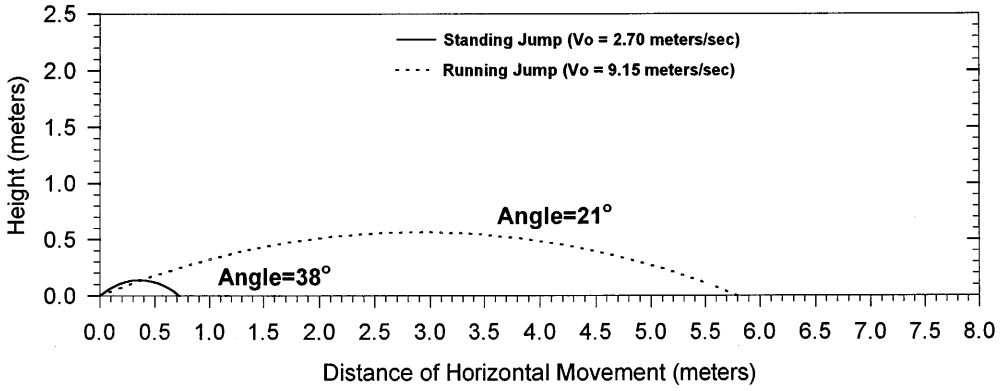

FIG. 2—*Falling patterns of standing jump and running jump above the jumping level: Running and standing jump are intimated at initial velocities of 9.15 and 2.70 m/s at initial angles of 21 and 38 deg above the jumping level.*

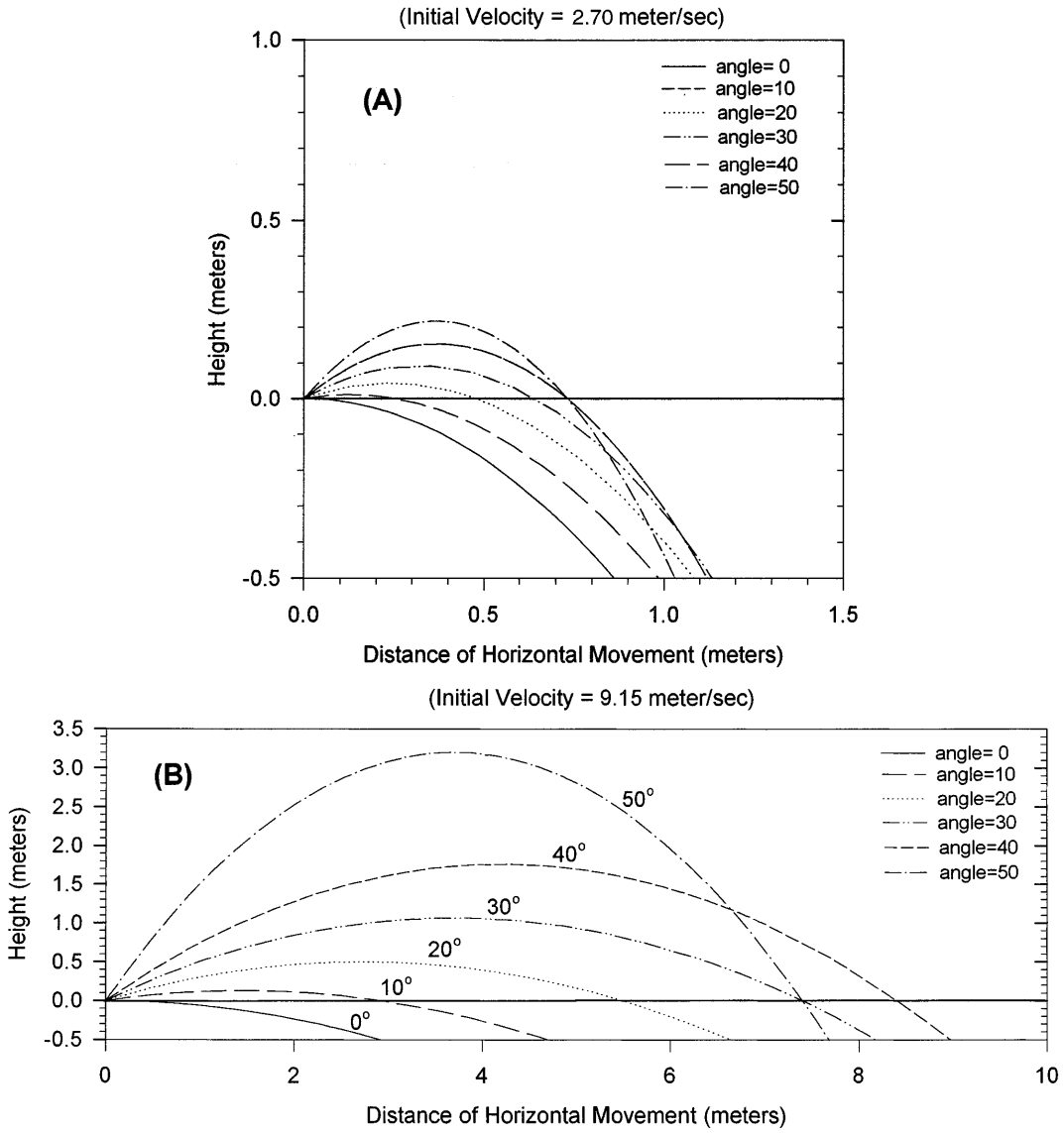

FIG. 3—*Falling patterns intimated at various angles of jump at initial velocities of 2.70 m/s (*A*) and 9.15 m/s (*B*): Maximal horizontal movement can be achieved at about 40 deg; the angle at 50 deg or over starts to minimize the horizontal movement.*

Initial Velocity and Manner of Death

Initial velocities from 2.70 to 9.15 m/s may explain the running activity before jumping as well as the conviction of intentional running and jumping. Besides, it does become the standard criterion to characterize the voluntary jump as well as the suicidal fall. The initial velocities estimated from these experiments of standing and running jumps allow us to distinguish the jumping patterns of deaths caused by high falls. The difference between the standing and running jump can be recognized as the mental status of the jumper, including the determination or hesitation of the jumper's thoughts. The results of biomechanical studies suggest that an initial velocity over 2.70 m/s is a critical point for a voluntary jump while 9.15 m/s is a cutoff point of maximal physical capability for an intentional jump. An initial velocity over 2.70 m/s in a voluntary jump, with the help of pre-running acceleration before the jump, suggests that the attempt to commit suicide is considerable. The initial velocity can be derived from the height and horizontal distance of falling at various speculative angles by using Eq 4. In conclusion, in every case, both the horizontal distance of movement and height should be used to estimate the initial velocity, to reconstruct the falling pattern, and to theorize on the manner of death so as to rule out the suicidal jump.

Case Study of Falling Victim

The decedent was a 31-year-old African American male who came to Taiwan to participate in a professional baseball team as the first-base player. The decedent was 183 cm in height, 95 kg in weight, and very athletic. On the morning of the accident, the decedent was found lying in front of an automobile beside the 14-story building (40 m high) of the suspect falling point. The victim's feet were found 10 m away from the building with massive amounts of bloody residue on the ground. He was sent to the hospital immediately and was declared dead on arrival. The decedent had lived in Taiwan for 18 months. Nine hours and thirty minutes before the falling accident, the decedent had attacked his friend while they were drinking beer together with another two friends. Thirty minutes before the accident, the janitor of his apartment saw the

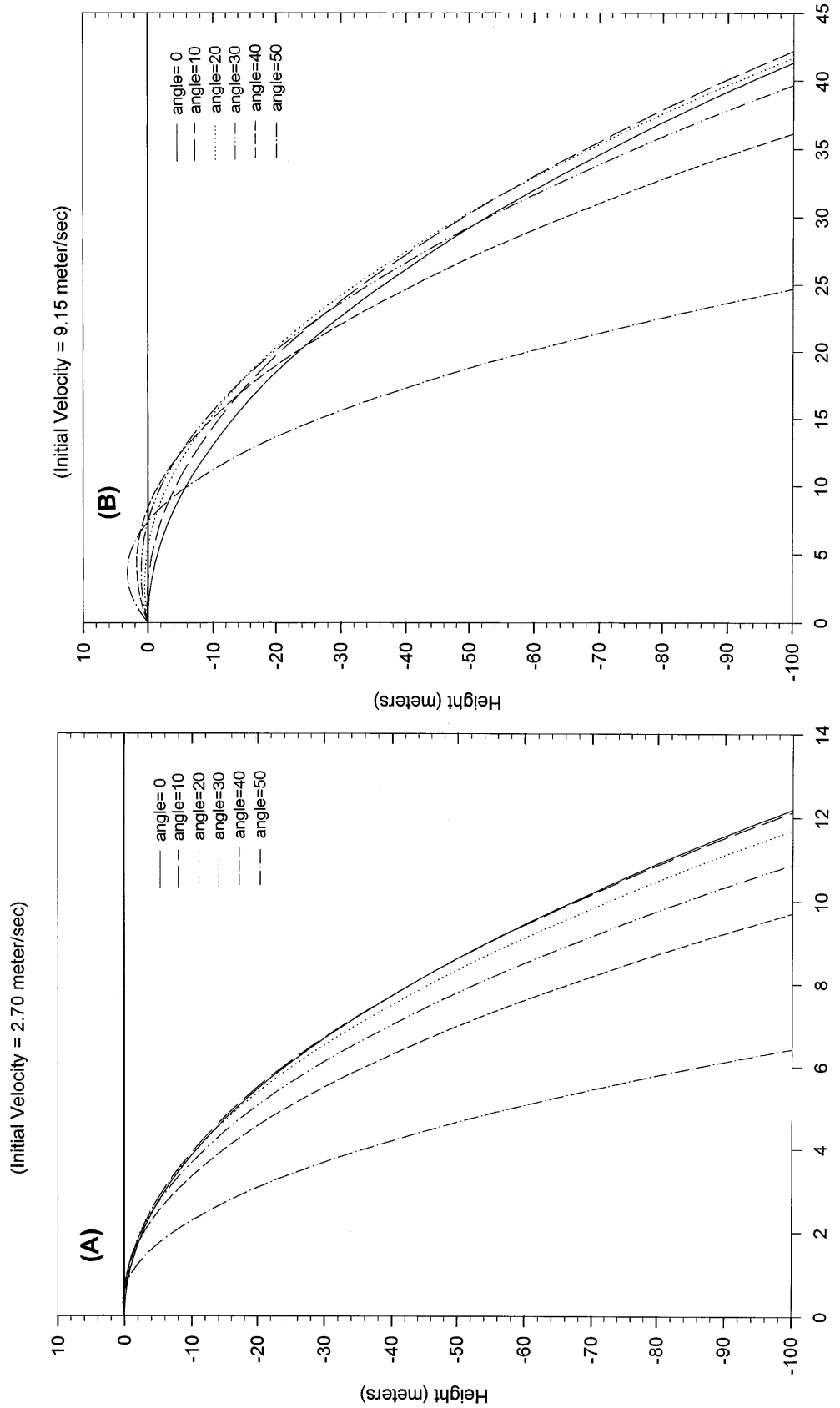

FIG. 4—*Falling patterns intimated at various angles of jump at initial velocities of 2.70 m/s* (A) *and 9.15 m/s* (B), *falling from height of 100 m.*

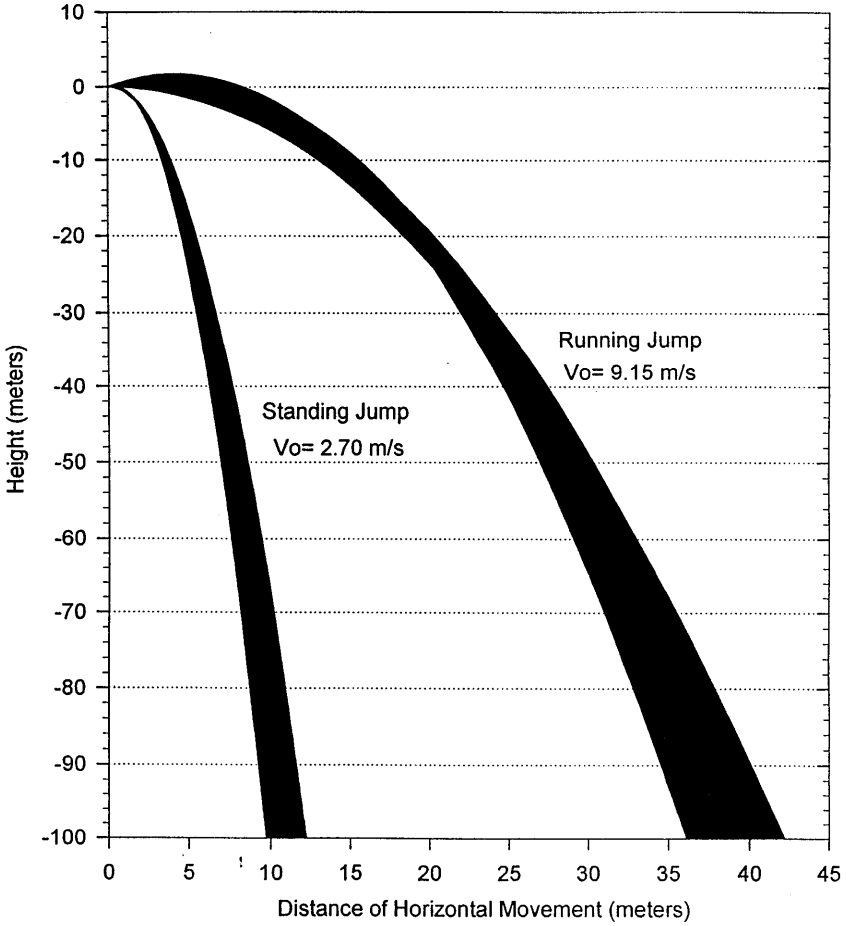

FIG. 5—*Range of maximal horizontal movement of standing jump and running jump at angles between 0 and 40 deg.*

TABLE 2—*Maximal horizontal movement and initial jumping angle varies with height at constant initial velocity of standing and running jump.*

	Standing Jump, V_0 = 2.70 m/s		Running Jump, V_0 = 9.15 m/s	
Height, m	Maximal Angle(Θ_{max})*	Horizontal Movement	Maximal Angle(Θ_{max})	Horizontal Movement
0.0	45	0.74	45	8.54
0.5	33.15	1.14	43.42	9.03
1.0	27.50	1.43	41.99	9.49
3.0	18.37	2.24	37.47	11.15
5.0	14.74	2.83	34.17	12.59
7.0	12.66	3.31	31.62	13.88
10	10.72	3.93	28.68	15.62
20	7.70	5.51	22.76	20.36
30	6.31	6.72	19.45	24.20
40	5.48	7.75	17.26	27.50
50	4.91	8.66	15.67	30.45
60	4.49	9.48	14.46	33.14
70	4.16	10.23	13.49	35.62
80	3.89	10.94	12.69	37.95
90	3.67	11.60	12.02	40.13
100	3.48	12.22	11.44	42.21

* Θ_{max} = angle of maximal horizontal movement.

decedent leaving his room. Thirty minutes later, at 10:30 A.M., he went to the 14th floor, 7 km away from his apartment, where he used to get together with his friends. The decedent had fallen from a height and had struck the hood (9.6 m to the building of the suspected falling point) of a 1992 Ford Grenada automobile parked beside the building with its rear facing the building. On the 15th floor (top of the building), there is a wide open space measuring 10 × 15 m in area with a fence measuring 1.2 m in height. It is the suspected falling place (the 12th floor) where the victim's friend lives on. Neighbors said that the victim and his friends used to enjoy the city night sights and chatting on top of the 15th floor.

Autopsy Findings

The lividity fixed on the decedent's back is light. The pupils are isometric, dilated, with bloody discharge bleeding from mouth angle, nose and both ear canals. Wave phenomenon of the decedent is noted, with the impact wound predominant over the left trunk and propagating laterization to the right side with multiple blunt and abrasion wounds in the frontal, precordial, left shoulder, left popliteal fossa, lumbar and flank region. Fracture of the left femoral head, lumbar vertebrae (L2–L3), public symphysis combined with rupture of liver, spleen, bilateral kidneys, bilateral iliac arteries skull are observed. There are bloody discharges inside the bronchus, bronchioli with 100 and 150 mL blood in the right and left pleural cavity. Rupture of the right atrium and anterior wall of the interventricular septum measuring 2 cm in length for each is

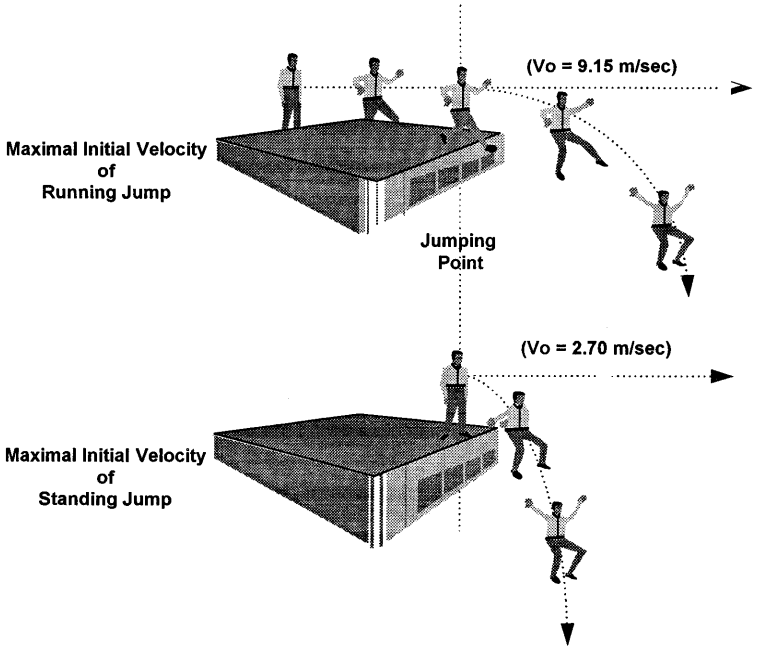

FIG. 6—*Patterns of falling: running jump and standing jump.*

observed. Abrasion wounds measuring 11 × 5 cm on right lower leg, 3 × 2 cm on left leg, and 3 × 2 cm on decedent's back are also noticeable. All organs reveal an anemic picture with multiple organ hemorrhaging that includes intracerebral, epidural, subdural, and intracerebral hemorrhages. Scene investigation of the impressions left by the head, body trunk and legs as a result of the body hitting the windshield, hood and bumper of the automobile is reconstructed.

Toxicological Findings

Screening test for amphetamine/methamphetamine by TDx and REMDi reveals positive findings in the blood, gastric content and urine: 0.27 μg/mL (in blood) and 26.22 μg/mL (in urine) of methamphetamine and 4.61 μg/mL (in urine) of amphetamine are quantified by gas chromatography/mass spectrometry (GC/MS). Blood, gastric and urine content of ethanol are 0.120%, 0.011%, and 0.044% (W/V), respectively. No opiates, marijuana, cocaine, sedatives, hypnotic or other stimulants are detected.

Biomechanical Analysis

Using Eq 4 for height (40 m) and horizontal movement (10 m) at 0, 10, 20, 30, 40, 50, and 60 deg jumping angles, the initial velocity reveals 3.50, 3.48, 3.57, 3.78, 4.15, 4.78, and 5.85 m/s, respectively. Therefore the initial velocity higher than 2.70 m/s strongly supports a conclusion of the suicidal jump of the decedent (supported by NSC 85-2331-B-016-092).

Acknowledgments

The authors gratefully acknowledge the guidance of Professor John Ming Fong and Mr. Chang-En Pu of the Scientific and Technical Research Center, Investigation Bureau, Ministry of Justice, in making these experiments available. In addition, the authors would like to express appreciation to Professor Jung-Chung Liu of National Defense Medical Center, Miss Jung-Chan Lai, Miss Ju-Hui Chung and Mrs. Wuan-Mei Chiu for their technical support and data analysis that assisted in the completion of this paper.

References

1. Knight B. Forensic Pathology: self-inflicted injury. 2nd ed. London: Arnold, 1996;231–42.
2. Snashall DC. Injury and death in the construction industry. In: Mason JK, editor. The pathology of trauma. 2nd ed. London: Hodder and Stronghton Limited, 1993;269–76.
3. Knight B. Forensic pathology: Head and spinal injuries. 2nd ed. London: Arnold, 1996;171–9.
4. Goonetilleke UKDA. Injuries caused by falls from heights. Med Sci Law 1980;20(4):262–75.
5. Thiagaraj D, Ming T, Cyn A. Patterns of injury in death due to falling from heights. Proc First Asian Pacific Cong Leg Med 1983; 399.
6. Li L, Smialek J. The investigation of fatal falls and jumps from heights in Maryland 1987–1992. Am J Forensic Med Pathol 1994; 15:295–9.
7. Halliday D, Resnick R. Fundamentals of physics. 2nd ed. New York: Wiley, 1986.
8. Balfour AJV. Aerial Sorts. In: Mason JK, editor. Pathology of trauma. 2nd ed. London: Hodder and Stronghton Limited, 1993; 256–68.
9. Klissouras V, Karopovich PV. Electrogonometer study of jumping events. R Q, 1967;38(1):41–8.
10. Garrett RE, Widule CJ, Garrett GE. Computer-aided analysis of human motion. Kinesiology Review. AAHPER, 1968;1–4.
11. Shu TM. Mechanical analysis of the standing broad jump. Bulletin of Physical Education. 1974;4(12):65–79.
12. Chen WC. A kinematic analysis of Tai Ji Chuan two-hand push. Master's Thesis. Graduate School of Physical Education. National Taiwan Normal University. Taipei, Taiwan. 1987.

Additional information and reprint requests:
Kai-Ping Shaw M.D., Ph.D.
Associate Professor
Dept. of Anatomy and Biology
National Defense Medical Center
P.O. Box 90048-502
Taipei Taiwan