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# The Influence of Behavior on Freefall Injury Patterns: Possible Implications for Forensic Anthropological Investigations*

**ABSTRACT:** Case studies of freefall injuries suggest that most falls from heights result in lower extremity, pelvic, and vertebral fractures. These injuries are largely a consequence of the fact that most falls are accidental with victims landing feet first. This study investigates whether human behavioral response affects body orientation at impact and whether the human body tends to align in a particular way as a result of physical laws. The investigation was undertaken by observing nine experimental falls of an anthropomorphic dummy from a height of 65 ft (9.8 m). In all nine falls, the dummy landed horizontally, suggesting that the human form has a tendency to align horizontally during freefall for falls greater than 50 ft (15.24 m). This has important implications for the potential use of injury patterns in the deduction of pre-fall circumstances, which are discussed here with respect to a case study of a fall victim.

**KEYWORDS:** forensic science, forensic anthropology, falls from heights, vertical deceleration injuries

Falls from heights, which result in injuries associated with rapid vertical deceleration, represent a unique form of blunt trauma. Victims of falls from heights tend to sustain a unique pattern of injury that is predictably different from injuries associated with other types of blunt trauma. Many studies have examined resulting injury patterns (particularly skeletal fractures) in attempts to reveal relationships between these patterns and various other factors, such as body position, height of the fall, nature of the impact medium, age, pre-existing medical conditions, etc. However, few have considered the possibility of an association between skeletal injury pattern and cause of the fall.

Circumstances of a fall from a height can be a key piece of information in forensic contexts, where it may be useful in assessing whether a victim's death resulted from a suicide, an accidental fall, a homicidal push, or whether death occurred prior to the fall. The patterns of skeletal injury may be of particular importance in cases where bodies are not discovered until some later time and soft tissue injuries are no longer observable, leaving a skeletal trauma analysis as one of the few means of arriving at clues regarding the manner of death.

The primary difference in these cases is the mental (and often, correspondingly, physical) state of the deceased before and during the fall and their resulting behavioral response (or lack thereof). Victims of accidental falls and homicidal pushes do not consciously want the falling action to occur and will spontaneously, as a defense mechanism, try to interfere with and manipulate the physical forces acting upon them. Fall victims will usually attempt to protect their heads from impact with the ground and/or extend appendages to brace themselves for impact. Suicidal persons, on the other hand, initiate purposeful action, resulting in less resistance to and preparation for impact (1). Snyder (1) observes that suicidal, psychotic, and inebriated individuals (whom he terms "abnormally relaxed") have a disproportionately high survival rate among freefalls of extreme distances as a result of their relaxed state. Similarly, severely incapacitated individuals or dead bodies (the most extreme cases of "abnormally relaxed" individuals) would have no defensive response to the fall and impending impact. What happens to these individuals during the course of a fall is thus dictated exclusively by the physical forces acting upon their bodies.

Unfortunately, a review of literature on falls from heights revealed few other observations about relationships between mental state and injury patterns and no empirical data. Many studies allude to the importance of psychiatric background, blood alcohol levels, and circumstances of the fall, and also indicate that a significant proportion of their data comes from both accidental and intentional falls. However, most studies pool all vertical deceleration victims into "falls" and do not separate the data in a manner that permits independent analysis of circumstances or mental state.

This study examines the effect of physical forces on the human body form in vertical freefall in the absence of interference by human behavioral response. The study involves observations of an anthropomorphic dummy, representing the "abnormally relaxed" state, dropped repeatedly (nine times total) from a height of about 65 ft (19.8 m), in an attempt to shed light on whether the orientation at impact (and resulting pattern of fractures) is associated with the mental state or physical condition of the individual at the time of the fall. The hypothesis is that "abnormally relaxed" individuals (which would consist of, for example, inebriated, suicidal, incapacitated, or dead persons) will fall in a predictably different fashion than more alert individuals due to the absence of a behavioral defense response, and that this will result in a distinct pattern of orientation at impact.

In addition, a case study of a possible suicidal jump from 100 ft (30.48 m) analyzed by the University of Tennessee Forensic

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Anthropology Center is presented here in an attempt to elucidate the possible circumstances of the fall.

### *Physical Factors*

The nature and severity of injuries sustained as a result of freefalls are governed largely by the laws of physics, meriting a brief review of how factors such as the height of the fall, impact force, impact energy, duration of impact, and distribution of force affect freefall injuries.

The height of the fall is a major determinant of injury because the velocity of impact is related to the distance of the fall. Maximum impact velocity (terminal velocity) for a human body is about 120 mph, requiring a height of about 146 m at sea level (2), but may vary depending on the orientation of the body. Force is a physical factor that changes or tends to change the state of rest or the state of uniform motion of a body and is related to the mass of the falling object and its acceleration (or, in the case of freefalls, the deceleration at impact).

Impact energy refers to the amount of energy transferred to the falling object (here, the fall victim) at impact. At the moment of impact, when the falling body undergoes deceleration, the vast majority of the kinetic energy is converted to mechanical energy, which is absorbed by the fallen object. This energy is dissipated throughout the victim's body, usually generating injuries (3). Duration of application of force (here, impact force) relates to the manner and rate of onset of the force; the slower the application of force, the greater the distance through which the body is decelerated and the slower the release of kinetic energy. The amount of stress sustained by a body is related to the impact force and the impact area. The force is determined by several of the factors described above, and the area of impact is determined largely by the orientation of the body at the time of impact. The area of application directly affects injury severity; the same force dissipated over a larger area produces less force per unit area (and less stress and therefore injury) than the same force applied over a smaller area (4).

### *Behaviorally Affected Factors*

Once falling, humans can do nothing to control height of the fall, their mass, their kinetic energy, or the nature of the material they are about to impact with, and they can do very little to control their velocity. One factor that falling humans do have some control over, however, is the orientation of the body. Behavioral responses to falling, which entail attempts to brace one's self for impact, involve changing body position in the air. Changes in body position affect the orientation of the body at the time of impact, thereby affecting the area of impact and thus the dissipation of strain.

Fractures of the skeletal system result from local stresses or strains that exceed the ultimate strength of a bone (5). The type of fracture is determined by the amount, direction, and area of force exerted on the bone, as well as mechanical properties of the bone itself, such as degree of mineralization, porosity, collagen orientation, rigidity, and anisotropy. Fractures (including those resulting from falls) tend to occur on surfaces under tension, the exception often being vertebral bodies and calcanea, which tend to fail under compressive force (6).

Use of one's joints is a means of efficiently distributing impact force in order to reduce injury (3) and is a second important factor that may be affected by behavior. While no fractures were observed in their study of voluntary jumps, Swearingen et al. (7) observed that joint pain as a result of falls was more severe when the body was more rigid (i.e., knees locked). By flexing appropriate structures at impact, deceleration forces are dissipated through the soft tissues of a joint rather than the relatively more unyielding bony structures (3). Parachutists, for example, learn how to properly cushion their falls when striking the ground in order to reduce impact injuries (8). By absorbing a portion of the deceleration forces by flexing joints and by distributing forces over a larger area, the deceleration force can be reduced by as much as 36 times (7).

Thus, while largely influenced by the laws of physics, the introduction of human behavioral response can have a significant impact on injury severity and pattern due to the effects of both orientation of the body at the time of impact as well as how relaxed the body is (and the use of joints) at the time of impact.

### *Previous Studies on Freefall Injuries*

In general, case studies indicate that the most common location of skeletal injuries in falls from heights is in the lower extremity followed by (in order of frequency) the upper extremity, head, pelvis, spine (with a preference for the thoracolumbar junction), and ribs (4,9–14). However, many of these studies did not examine relationships between these patterns and either the height of the fall or the body position.

Feet first appears to be the most common position at impact in freefalls (1,15). With respect to injuries sustained in such a position, feet-first landings result most commonly in injuries to the lower extremity, followed by fractures of the vertebrae (again, with a preference for the thoracolumbar junction), the cranium, and the forearm (1–3,16). Fractures of the skull and forearm appear to be a result of secondary impact in feet-first falls (2).

Head-first impacts appear to be the second most common in freefalls (1,15) and, not surprisingly, tend to result most commonly in cranial fractures followed by the upper extremities, ribs, and vertebrae (1,3,15). Initial impact with the buttocks is the next most common impact orientation (1,17) and results most often in fractures to the pelvis, vertebrae, upper extremities, skull, and lower extremities. Side impacts appear to occur least often (1,17) and result in upper extremity fractures followed by fractures of the ribs, pelvis, vertebrae, and skull (1,3,16).

With regard to height, there is a general tendency for victims of shorter falls to suffer more skull and forearm fractures followed by (usually cervical) vertebral injuries (16,18–21), while longer falls are associated with a decrease in skull fractures and an increase in postcranial fractures such as the pelvis, vertebrae, lower extremities, and ribs (10–13,15–16,22–23). Skull fractures, in particular, tend to peak in lower falls because, besides orientation, they are secondarily caused immediately after forearm injuries. Vertebral injuries, it has been suggested, typically result from indirect force, requiring a severe impact and therefore a higher fall (18). Despite the decrease in skull impacts at higher falls, there is an association with height of the fall and mortality since, along with cranial injuries, injuries associated with pelvic fracture also greatly increase mortality (13), with drastically higher mortality noted for falls from five or more stories (12).

Note that these studies focused primarily on impacts with the ground. Impacts with water (which are usually suicidal bridge jumpers) produce significantly different injury patterns. Many suicidal jumps (particularly fatal ones) result in horizontal impacts, producing rib fractures and massive internal injuries due to maximal deceleration (24). Although less frequent in bridge jumpers, feet-first impacts result in fewer overall fractures because of the longer deceleration experienced (24,25).

The above studies focused primarily on adults; fracture patterns in children as a result of freefalls tend to differ from the patterns seen in adults. Children tend to suffer more skull and forearm fractures as compared to adults (26–29), and fewer fractures are seen in the legs and axial skeleton (26,27,30). It has been suggested that this is likely due to the higher center of gravity in children due to relatively larger heads. As a result, children tend to pitch forward in a fall and attempt to break the fall by extending their arms (26). This pattern seems to appear regardless of the height of the fall.

As in adults, however, there does appear to be an association between height of the fall and mortality in children, with death usually resulting from head injuries (27). Interestingly, though, children tend to survive more freefalls and are typically less severely injured than adults. This may be due to their smaller mass, proportionately more cartilaginous (and therefore more flexible) skeleton, greater proportion of subcutaneous fat, and more relaxed muscle tone (1).

These data tell us much about injury tendencies of the human body in freefalls. However, since these injury patterns can be so drastically affected by human behavior and since no study thus far has empirically addressed the effect of human behavior on freefalls and injury pattern, such a study is warranted. Gupta et al. (18) suggest that there are certain body parts that are usually damaged because of the natural orientation of the body during the fall and that the orientation of the body has a relation to various heights, although no empirical data are provided to support this suggestion.

## Materials and Methods

Although case studies provide an indisputably valuable resource for the collection of data related to freefall injuries, controlled experimental data are almost always superior in terms of explanatory value and predictive power. The methods described below are intended to attempt an empirically derived answer to the question of the body's natural orientation in freefall. The human body is far too complex to represent with any model or dummy and there is, therefore, no substitute for testing actual human material if one wishes to study its physical properties or biomechanical behavior under various conditions. However, the use of human material for experiments in freefall presents both ethical and logistical problems. Some experimental work has been done with human volunteers or cadaveric materials, testing the response to and tolerance of vertical deceleration (7,31–32), and one study explored fracture patterns using complete cadavers (33), although it considered *acceleration* injuries rather than *deceleration.*

Here it was concluded that, though less desirable than using actual human cadaveric materials, an anthropomorphic dummy seemed suitable to investigate the question at issue. The dummy used was borrowed from the Rural Metro Fire Department in Knoxville, Tennessee. It was a standard "Rescue Randy" manikin that was developed for lifelike adult victim handling, transportation, and extrication training and made of vinyl and plastic-coated cables. Both the distribution of weight throughout the dummy and joint mobility are designed to resemble human bodies. This particular model was 6 ft, 1 in. (1.85 m) tall and weighed 195 lb (88.5 kg) clad in a fire fighter's suit.

In order to obtain the height needed to observe significant freefall (defined for this study as an unimpeded fall of a body from a known point to a known impaction point), the dummy was released from suspension from the top rung of a fire engine ladder (Fig. 1). The fire engine was a 1989 Simon Duplex (cabin and chassis) with an LTI ladder. At full extension and positioned at an angle of 80°, the maximum height of the ladder is 75 ft (22.86 m) above the ground. For this experiment, the ladder was angled at 77°, yielding a total height of 74 ft, 2.5 in. (22.62 m).

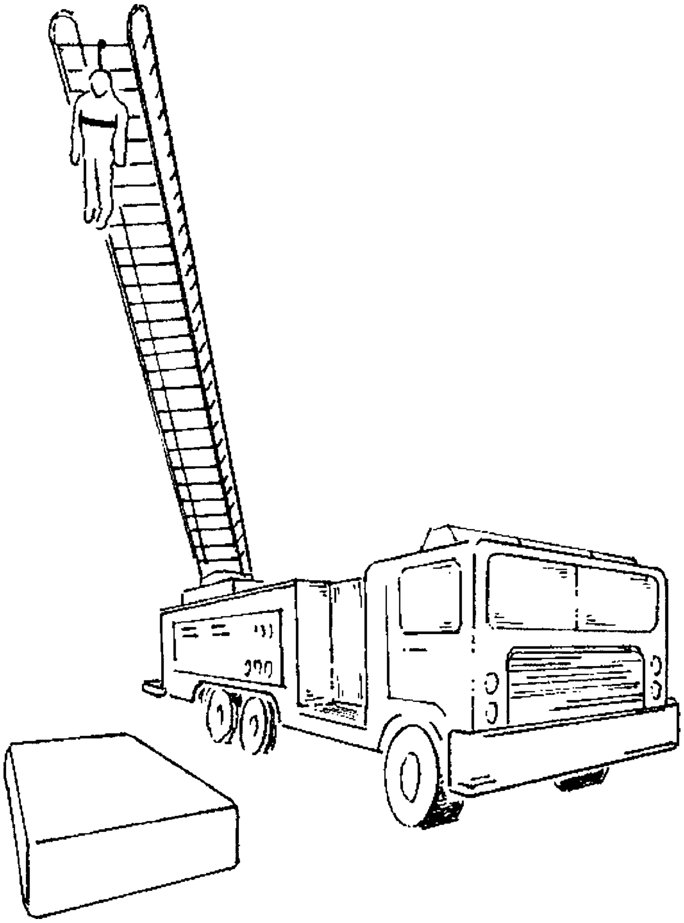

FIG. 1—*Experimental fall apparatus.*

A harness was attached to the dummy, and rope was attached to the harness. A carabiner (an oblong metal ring with a spring clip, used in mountaineering and climbing) was used to attach the other end of the rope to the top ladder rung. This attachment method enabled the dummy to start from a hanging position with no initial velocity or angular velocity and permitted easy release. The dummy (along with a fire fighter who would release the dummy) was then lifted to the maximum possible fall height by raising and extending the ladder and was released by cutting the rope with a knife. The falls, which lasted about 2 s, were captured on digital video using a Sony Digital Video Camera Recorder (model DCR-TR103/TRV110). At the bottom of the fall, the dummy was "caught" using a pole vault pit base unit (UCS brand Championship Series, 7 ft, 2 in. by 13 ft by 30 in. (2.28 by 3.96 by 0.76 m)) in order to avoid damage at impact.

A total of nine experimental falls were performed, three each from three different starting positions (Fig. 2). For the first three falls, the dummy was harnessed under the arms, producing an upright or feet-first initial body position with the arms hanging at the sides and the legs straight down. For Falls 4 through 6, the dummy was harnessed around the waist and right leg, producing an initial position that was largely horizontal, with the arms and left leg hanging below the torso. For the final three falls, the dummy was harnessed by the right ankle, producing a head-first initial position with the arms hanging behind the body and the left leg flexed toward the torso. The length of each fall was somewhat dependent on the orientation of the dummy and was approximately 65 to 66 ft (19.81 to 20.11 m)

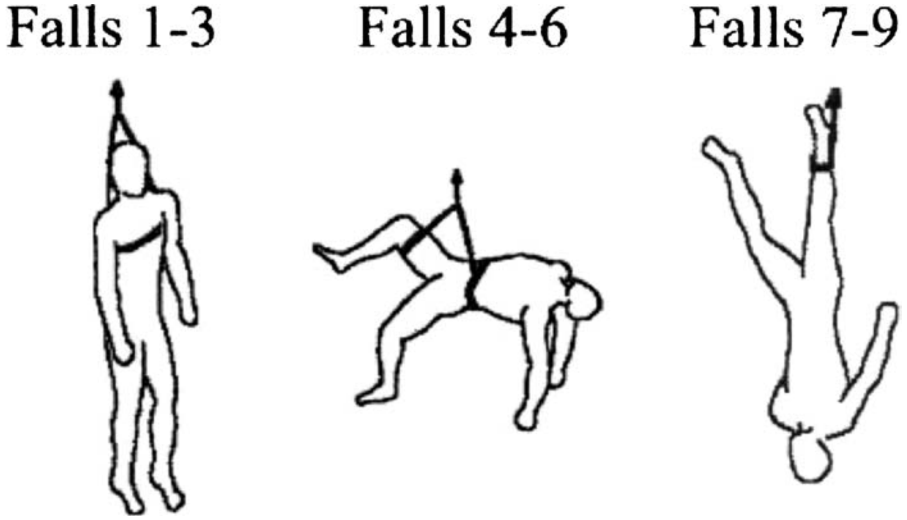

FIG. 2—*Initial body positions in experimental falls.*

(the height of the ladder minus the length of the dummy minus the height of the pole vault pit).

## Results

All nine falls resulted in impact orientations that were roughly horizontal. In the first three falls, the dummy rotated forward, landing each time in a prone position. In Falls 4 through 6, the body maintained the same basic orientation, impacting in a supine position. Falls 7 through 9 resulted in rotation to a prone position, with a tendency for the upper torso to impact slightly earlier. In Falls 1 to 3 and 7 to 9, a horizontal orientation was achieved when the dummy was10 to 15 ft (3.05 to 4.75 m) from the ground, or about 50 ft (15.24 m) into the fall.

Even over this relatively short fall, there was thus a distinct tendency for the dummy to assume a horizontal orientation during freefall. The case studies reviewed above suggest not only that falls from such heights tend to result in injuries associated with feet-first impacts, but also that side and horizontal impacts are the *least* common in freefalls. This experiment speaks toward a natural tendency toward the contrary, apparently due to the absence of a behavioral defense response.

## Discussion

### *Implications of Results*

These results indicate that there is an additional factor influencing the pattern of impact orientation in freefall case studies. The most likely explanation is a behavioral response (or lack thereof) on the part of the individual falling. The lack of behavioral response by the dummy resulted in its being at the compete mercy of physical laws, which appear to orient the body horizontally, perhaps because this is a more stable position. The pattern of feet-first injuries so pronounced in case studies must therefore be a result of the instinctive reaction of conscious humans to attempt to prepare for impact by “righting” themselves or trying to maintain an upright position.

It was also considered whether, alternatively, humans actually have fairly little control over their orientation and that a body would simply land in an orientation related to the starting position. If this were the case for individuals of all mental and physical states (i.e., if position at impact were largely dependent upon starting position regardless of behavior during the fall), this would tend to suggest that the only behavioral contribution is involved at the initiation of freefall. In other words, case reports of higher frequencies of feet-first impacts may reflect a tendency for falls from greater distances to simply be initiated feet first. However, the failure of the dummy in this experiment to land in a position representing the initial position (except in Falls 4 through 6) suggests that starting position is not the primary determinant of impact orientation.

There are a number of important limitations to keep in mind when considering the implication of these results. First, while this dummy represents the human form with respect to distribution of weight and moveability of parts, it is not clear precisely how other factors such as composition and clothing may influence freefall. Moreover, and perhaps more importantly, while releasing the dummy with zero velocity and zero angular velocity facilitated freefall initiation and minimized complicated physical factors to consider, it is not likely representative of most freefalls, which may involve some degree of initial angular velocity (as a result of the stumbling, jumping, or dumping) in order to bring about the fall. The introduction of these initial conditions may significantly affect if, how, and when the body reaches a stable orientation.

It may also be the case that, given more time and/or distance, the body would continue to rotate, resulting in other impact orientations. However, given that the falls that began in a horizontal position failed to rotate out of that position suggests that this is a relatively stable orientation. It should also be kept in mind that over 50 ft of freefall were required for the dummy to achieve a horizontal orientation (at least in those falls where the initial position was not already horizontal), and thus the implications suggested may not hold true for shorter falls.

### *Case Review*

In early spring of 2000, the University of Tennessee Forensic Anthropology Center was contacted regarding a death that had occurred in 1976 in Overton County, Tennessee. The decomposing remains of a 16-year-old female were recovered from the bottom of a 100-ft (30.48-m) cliff. An autopsy was conducted and the immediate cause of death was ruled as a “fall into an abandoned rock quarry.” However, no skeletal fractures were reported present on the remains.

The family, refused to believe that the victim could have fallen more than 100 ft into the quarry without suffering any broken bones.

TABLE 1—*Summary of perimortem fractures present on freefall victim.*

| Skeletal Element | Description of Fracture |
|---|---|
| Teeth (upper right M2, upper left M2, lower left M1, dM2, C, I2, lower right dM2) | Enamel fractures, primarily on occlusal surfaces |
| Scapulae (left and right) | Fractures of the inferior angles |
| Ribs (left ribs 2 to 12) | Fractures of the necks and shafts |
| Vertebrae (T3, 4, 6, 10, 11, L2 to 5) | Fractures of left transverse processes |
| Sacrum | Fractures of right and left alae, and the left superior articular facet |
| Os coxae (left and right) | Complete fractures of the iliopubic and ischiopubic rami |

They were also reluctant to believe that she may have committed suicide, though there was evidence to suggest that she had been severely depressed. The family suspected foul play, suggesting that the body had been placed at the bottom of the cliff after death. Confusion and disappointment plagued the family, and after 23 years they requested another examination of the remains. The Forensic Anthropology Center was asked to examine the skeletal remains for any signs of trauma that might provide a better explanation for her death.

Following exhumation, the remains were transported to the Forensic Anthropology Center in Knoxville where they were cleaned of remaining soft tissue to permit closer skeletal examination. Even during the early stages of the cleaning process, it became obvious that multiple fractures were present on the remains. While one injury to the right maxilla was clearly an antemortem healed perforating fracture, and postmortem trauma was present in the form of carnivore gnawing on the ends of several of the elements, perimortem fractures were found to be extensive. Interestingly, all trauma was limited to the axial skeleton, with no perimortem trauma observed on any element of the appendicular skeleton. Fractures of the skull were limited to enamel fractures of several teeth. Table 1 provides a more detailed list of observed perimortem fractures. It was never ascertained why the original autopsy report made no indication of fractures, despite their extensiveness at the time of our examination.

Previous observations, though largely anecdotal, indicate that the behavioral response of suicide jumpers is negligible, and they have been noted to have higher survival rates and suffer less severe injuries due to being in a relaxed state at the time of impact. Lukas et al. also noted in their 1981 study of jumpers from the Golden Gate Bridge that suicide jumpers usually impacted the water in a horizontal position (24). The falls of suicide jumpers can be expected to produce injury patterns associated with horizontally oriented impacts, as seen in the experimental dummy and in Lukas et al.'s bridge jumpers.

The victim's injuries in this case review are indicative of a horizontal impact orientation. Experimental studies on impact loading of the human pelvis indicate that iliopubic rami fractures may result from tensile stress within the bone when the force of impact is directed toward the ischial tuberosities (32); the victim displayed such injuries. Also, the extensive injuries to her left ribs and vertebrae suggest that they were subjected to a large force as well.

It seems reasonable to conclude, based on the experimental study and reexamination of the victims injuries, that she likely suffered a fall in a relaxed state involving a lack of behavioral response required to obtain or maintain an upright orientation. If we reason that she was not trying to resist the fall into the quarry, we can likely discount an accidental fall or a homicidal push as causes of her fall. Death as a result of suicide remains a likely explanation based on both the evidence presented above as well as reports of her behavior prior to her death. One scenario, however, that cannot be ruled out is that the victim was already dead or otherwise incapacitated and then dumped from the edge of the cliff. In this case, her body would be expected to fall in a way similar to that of suicidal jumpers and, presumably, result in a similar pattern of injury.

## Conclusions

Behavioral response, which is likely dependent on the circumstances of the fall and mental state of the victim, may have a notable influence on freefall injury patterns. Despite the fact that freefall case studies indicate a tendency for longer falls to result in injuries associated with feet-first impacts, experimental results obtained here using an anthropomorphic dummy suggest that there is a tendency for the human form to assume a horizontal orientation during freefall. Other studies suggest that "abnormally relaxed" individuals (including the suicidal) tend to invoke little behavioral response and have a tendency to impact in a horizontal orientation, supporting the results observed here. When applied in forensic contexts, as was done in the case reviewed here, these observations may help ascertain the circumstances preceding the initiation of freefalls and thereby aid in assessing the manner of death, particularly when skeletal fracture patterns are among the only clues.

### *Acknowledgments*

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