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Forensic Application of Computer Simulation of Falls

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ABSTRACT: The purpose of the paper is to describe a method of computer simulated fall reconstruction. Computer applications that simulate gravity and other physical parameters, such as Knowledge Revolution's Working Model®, allow for falls to be modeled and their dynamics studied. There are two prerequisites for the computer simulation of falls: the development of a dynamic computer manikin and the ability to specify the initial conditions to which the manikin is subjected. Discussion is presented on steps in the development of a two-dimensional dynamic computer manikin. Direction for the determination of initial conditions is illustrated in the context of examples that demonstrate the forensic applications of computer fall simulation.

KEYWORDS: forensic science, engineering, human factors and ergonomics, anthropometry and biomechanics, fall accident reconstruction, computer fall simulation, patterned injuries

Falls are second only to vehicle accidents as a cause of accidental injury and death (1). Human factors specialists, engineers, and other design professionals are increasingly being called upon to serve as expert witnesses in suits that claim that a fall was due to a failure to consider human characteristics and limitations in the design, operation, or maintenance of a setting or facility.

Investigators have learned that people often have poor recollections of the dynamics of how they fell or even of the sequence of events leading to their fall. This is understandable because ambulation requires little conscious intervention, and falls are typically unexpected and of brief duration. The inability to recall details of an event causing serious injury can lead some people to make inferences as to its probable causes and dynamics. Unfortunately, inference and recollection can become confounded, especially if considerable time elapses between the date of the fall and when a person is asked to provide a detailed account of the accident for the record.

Since investigators of fall accidents cannot depend on the ability of people to accurately recall details of how they fell, their task is to develop a fall model that best explains all the available data. Sources of data include the pattern of injuries, the features of the setting, ambient conditions, user characteristics and activities, and witness accounts. Since available information may be incomplete and include inaccurate recollections, there is a need for tools and methods which aid in the systematic generation and evaluation of different fall models.

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Computer Simulation of Falls

Ideally, different fall models could be evaluated through computer simulation. This would require a computer application that simulates gravity, density, velocity, acceleration, static and dynamic coefficient of friction, as well as other physical parameters. Working Model® by Knowledge Revolution is one such application (2). In fact, Working Model provides access to a virtual two-dimensional (2-D) universe in which "mass objects" can be generated and their dynamic interaction subsequently viewed and studied. The application permits the user to control the numerical algorithms used in creating the simulations. [Details of the algorithms can be obtained from the manufacturer (2).] To simulate falls using this application, it is necessary to develop a 2-D computer manikin.

Development of Dynamic Computer Manikin

Articulated 2-D drafting manikins that are based on anthropometric survey data have long been available for use in space design and layout (3,4). For computer simulation of falls, it is also necessary to have information on the mass and location of the center of gravity of each body segment, joint locations, the direction and range of segment movement and principal moments of inertia. Mannequin® is a computer program that provides, in part, such information (5). This computer application generates manikins of both genders over a wide range of percentiles, and for selected views, e.g., frontal, sagittal, transverse, and user defined. It incorporates information about the direction and extent of body segment movement. GEOBOD/MAC is another computer application that provides descriptive data of value in developing a dynamic computer manikin (6). GEOBOD/MAC is a port of program GEOBOD, written by the Calspan Corporation. The application permits the user to generate body data for adult females, adult males, and for children 2 to 19 years old. The user supplies the subject's age, weight, or height. GEOBOD/MAC provides data on body dimensions, joint locations, and the inertial properties of body segments.

A manikin can either be directly generated in Working Model or imported from another computer application, provided it is saved in a compatible file format. Working Model's graphical interface allows the user to create mass objects to represent the various body segments to scale. The mass objects are then positioned so they overlap, and are attached to one another at the locations corresponding to the hinge points in 2-D drafting manikins. The toolbar provides various means of attaching mass objects to one another to simulate articulation. For example, Working Model's slot joint tool can be used to define a path for shoulder extension.

Once the body segments are joined, it is necessary to limit the range of their movements. The toolbar provides a wide range of constraint tools. Separators and ropes, e.g., may be used to limit

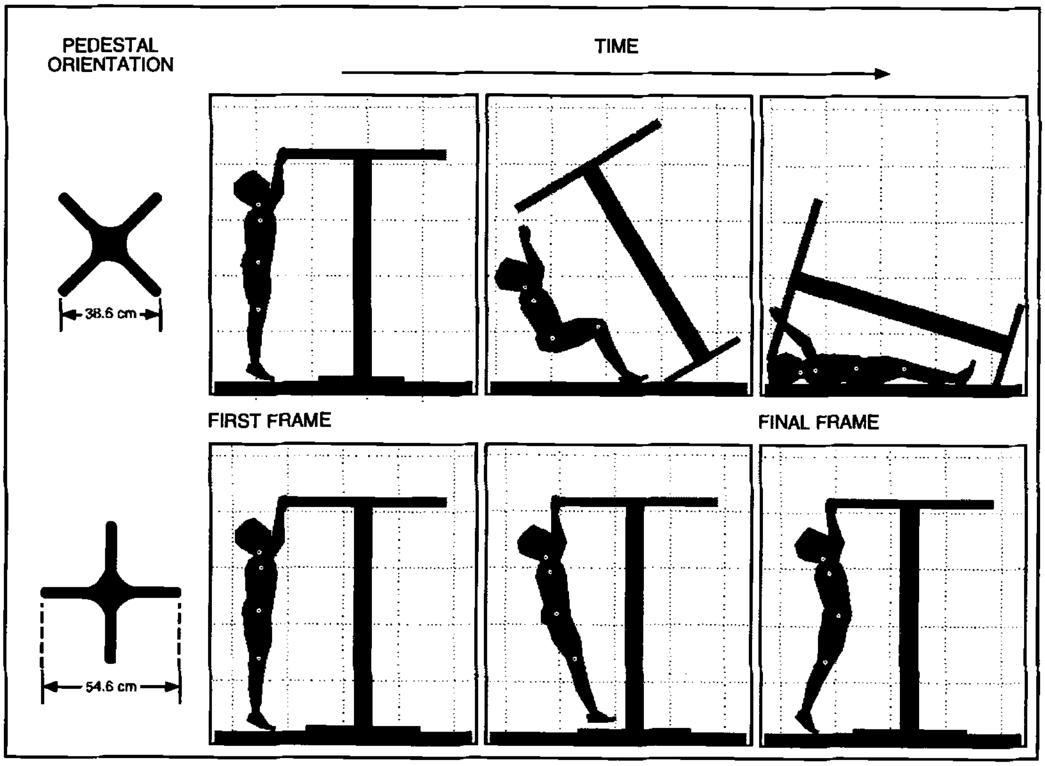

FIG. 1—*Experiment in which computer simulation was used to determine if a table would topple onto a child under two conditions of orientation for the table's pedestal base.*

the range of extension and flexion of the chest relative to the abdomen or flexion of the lower leg with respect to the thigh. Separators prevent mass objects from moving closer, and ropes, from moving further, than a specified distance.

The next step is to assign a specific mass to each body segment of the manikin. Prediction equations are available to estimate the mass of a body segment on the basis of a person's total body weight (7). The location of the center of gravity of each body segment is then examined and, if necessary, adjusted.

The last step is to test the manikin. Running the application subjects the manikin to simulated gravity. The manikin should collapse. Its body segments should neither collide with one another nor assume positions that are inconsistent with data on the functional range of movement.

Initial Conditions

Conceptually, the initial conditions in a fall simulation correspond to those that existed an instant before gravity alone became the primary factor governing the outcome of events. The initial conditions constitute frame zero of the simulation. Initial conditions include, but are not limited to, the form and location of objects in the application's window, their mass and all forces acting upon them, and the objects' initial velocities and rates of acceleration. Values for static and dynamic coefficients of friction acting among mass objects can be specified by the user. In addition, formulas may be entered for turning constraints on and off, and to govern the motion and physical properties of objects during a simulation.

Data must be obtained to establish the initial conditions. While there are sources of data on human gait (8), the literature may be of limited value for fall simulations that involve other than level surfaces or where extrapolations from the literature may be inappropriate because of the unique attributes of the setting or of the person who fell. Under such circumstances, it may be necessary for the investigator to study the accident using micromotion techniques to obtain data on which to base the formulation of the simulation's initial conditions. In addition, a range of initial conditions may be systematically explored to determine the significance of various variables on the simulation's outcome.

Forensic Applications of Computer Fall Simulation

Three examples, in order of increasing complexity, shall be presented to illustrate the forensic applications of computer fall simulation.

Case 1—The Unstable Pedestal Table

A child, who is three years old, enters a fast food restaurant in the company of his parents. While the parents go to the counter to place their order, the child walks over to a tall, 1.05-m pedestal table that is situated nearby. The table is intended for the storage of condiments. The child is too short to see what is on top of the table, and so reaches up and grasps the edge of the table top. When he attempts to pull himself up, the table tilts and topples. The child falls, and the edge of the table top strikes the child's face.

At the time of the investigation, it was observed that the table's two pedestal bases were so oriented that their four feet provided the minimum possible base of support along the table's major axes. If the pedestals had been rotated either clockwise or counterclockwise 45° further, the table would have been significantly more stable in the direction most vulnerable to tipping. However, it was not evident whether such a change in pedestal orientation would have prevented the accident. To address this issue, the table and child were modeled in Working Model. The model was then duplicated and a single modification of the initial conditions was made in the second model. The table's base of support was increased to reflect a 45° change in pedestal orientation.

The results of the simulation are shown in Fig. 1. Under exactly the same load conditions, the table with the wider base of support did not tip over although the one with the narrower base toppled and struck the child's face.

Case 2—Hole in the Floor

Ventilation and heating equipment were being installed in the second-story mechanical room of a high school gymnasium. To demonstrate how one of the air handling units would function once all the ducts were in place, a worker, 53 years old, decided to place a sheet of plywood over the unit's air intake. A 1.22 by 1.22 m sheet of plywood was lying on the floor in front of the unit. He grasped one edge of the board and walked forward as he lifted it. The worker did not realize that the board covered a hole in the floor. He stepped into the hole and fell more than 4 m onto a concrete floor.

Figure 2 presents frames from one of several computer simulations of the fall. Initial conditions were systematically altered until the manikin fell in such a way that it would account for both the pattern of injuries sustained by the worker and the testimony of witnesses who were located on the lower level. As reflected in Fig. 2, it is possible to measure and display in Working Model various parameters such as an object's velocity, acceleration, position, momentum, and the forces acting upon it.

Case 3—Fall from a Stairway

Extensive damage had been caused by an explosion and fire on an oil platform in Alaska. During the platform's reconstruction, stairs were installed without handrails. About three weeks after one such installation, a welder claimed that he fell and was injured while descending the stairs. According to the welder, he lost his balance at or near the first tread below the upper landing and landed on his knees forward of the lowest tread. He could neither account for why he lost his balance, nor provide any details of the manner in which he fell down the stairs. There were no witnesses to the accident.

The stairway, which had six risers, was metal with cleated treads. Examination of stairway geometry revealed that the run of the top tread was 24.45 cm, whereas that of the tread immediately below it, only 20 cm. The nosings of the steps did not contrast in either luminance or color with the treads.

The experts retained by the plaintiff's attorney held that the variation in run at the top of stairs increased the likelihood of a misstep occurring during descent. The lack of contrast between nosings and treads further increased the chances of a misstep since

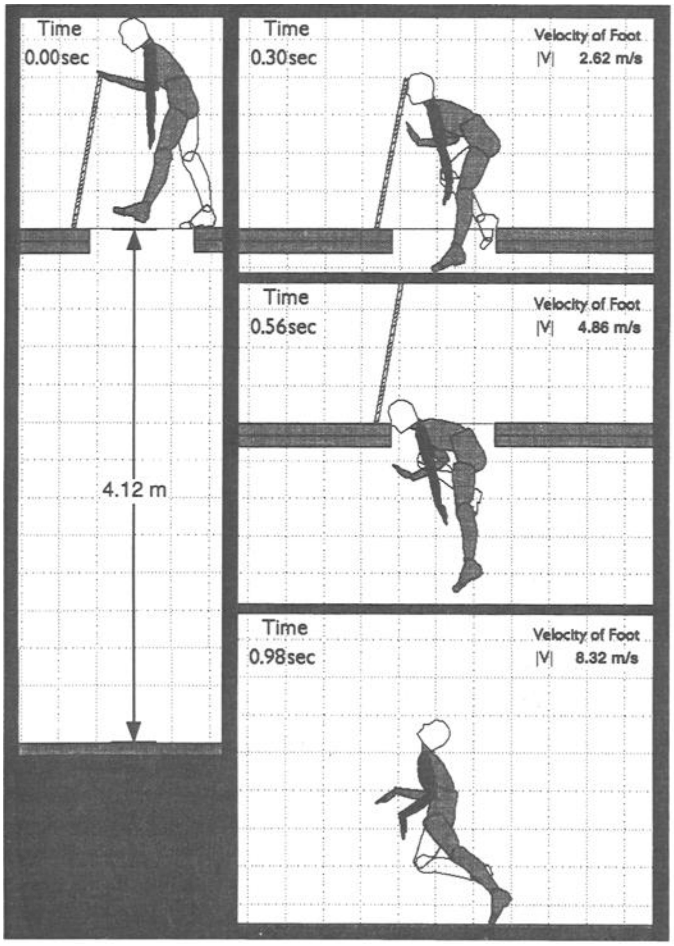

FIG. 2—*Frames from a computer simulation of a fall through a hole in the floor where the worker was lifting a board that covered the hole.*

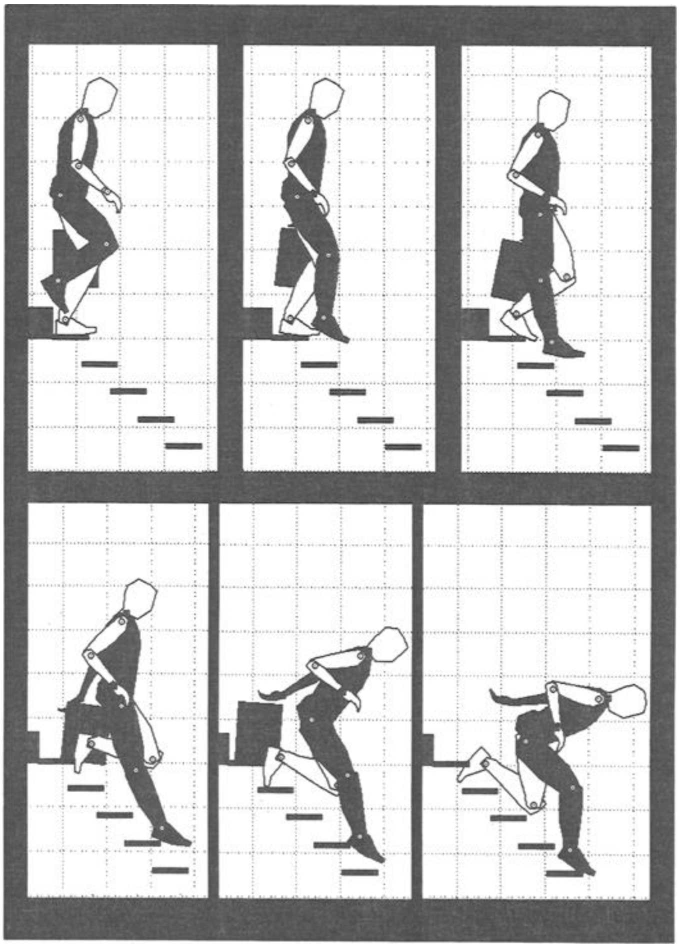

FIG. 3—*Frames from a computer simulation of a misstep near the top of a stairway in which the worker released a bucket that he was carrying.*

it was difficult to distinguish where one step ended and the next began. The absence of a handrail precluded its use as an aid in generating stabilizing forces during descent.

In response to the plaintiff experts' opinions, the defense expert opined that the accident could not have occurred in the manner reported by the welder. If the welder had lost his balance near the top of the stairway as he claimed, his body should have made contact with the cleated metal treads of one or more of the lower steps. Such contact should have left its distinctive signature in the pattern of injuries sustained by the welder. There were no abrasions on the welder's body that could be attributed to contact with the cleated metal treads.

One of the authors (JAT) determined that if the welder fell from near the top of the stairs and landed forward of the bottom tread, his center of gravity would have to move horizontally about 1.48 m and drop approximately 1.72 m. For the welder to land at the bottom of the stairs without making contact with the intervening steps, his body would have to attain an average horizontal velocity of about 1.27 m/s. With reference to human factors data, it was calculated that the average male could exert sufficient force during leg extension for his body to attain the required velocity (9).

Working independently, the other author (GDS) performed a series of computer simulations of the fall. The purpose of the simulations was to establish under which initial conditions, if any, the welder could have lost his balance near the top of the stairs without his torso subsequently striking the lower steps before coming to rest.

The stairway and a manikin that represented the welder were developed in Working Model. At the time of the accident, the welder was carrying a bucket in one hand that contained welding equipment. The total weight of the bucket and its contents was approximately 15.9 kg. The bucket was modeled and attached to one of the manikin's hands with a constraint that permitted it to rotate about its hinge point. Release of the bucket could be simulated by instructing the application to turn off the constraint at a specified time or frame.

The positions and velocities of the manikin's body segments at frame zero were established through frame-by-frame analysis of digitized videotapes and rapid sequence photographs of people descending stairs. A range of initial conditions was adopted as a result of individual differences in gait and distortions because of parallax.

Frames from one of many simulations of the fall are presented in Fig. 3. The results of the simulations supported the defense expert's opinion that if the welder fell near the top of the stairway, his body should have made contact with one or more steps before he landed at the foot of the stairs on his knees. However, the defense expert's position that the fall could not have occurred near the top of the stairway was not supported. The results of the fall simulations suggested that there were no abrasions on the welder's torso, arms, or legs that could be attributed to contact with the stairway's cleated metal treads because only the welder's shod feet came into contact with them.

Conclusion

Investigators need tools and methods to assist them in determining the likely causes of falls. One promising development in this direction are computer applications that create a virtual universe based on a translation of real world Newtonian mechanics. Eventually, it should be possible to provide such a universe with inhabitants that can walk, run, trip, and slip. For the present, there are two main challenges: first, to develop standardized 2-D dynamic computer manikins of sufficient fidelity to be useful in the simulation of fall accidents, and second, to develop standardized methods and procedures for determining the contents of frame zero of a simulation, i.e., the initial conditions. If these requirements are met, then the 2-D computer simulation of falls should prove useful in some forensic applications in which there is uncertainty as to how a fall occurred or if fraud is suspected. However, it should be appreciated that human movement occurs in three dimensions and that, in many cases, use of a 2-D model may be of limited value or inappropriate. Therefore, there is a third challenge: to know the limitations of the model and apply it only when it may yield valid and accurate information.

Acknowledgment

The figures were prepared by author (GDS) with Deneba Canvas®.

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