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Forensic Engineering Analysis of Injury Biomechanics Related to Elevator Malfunctions

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Abstract

Elevators are mechanically sophisticated devices that transport people and materials between floors in structures with two or more floors. Each year, there are numerous claims of elevator passengers sustaining injuries within the elevator car as a result of elevator malfunction. This is in spite of the numerous safety features incorporated into elevator design. In addition, the physical design of elevators simply does not allow "free fall" or any significant movement in other than the intended direction (vertical movement). In the forensic engineering analysis of passenger injury claims related to supposed elevator malfunction, it is important to include both a mechanical engineer knowledgeable in elevator design and operation and an engineer with expertise in biomedical engineering, specifically injury biomechanics. This paper will focus more on the injury biomechanics aspects of elevator incidents, although a foundation in elevator design (including safety features) will be included. The investigation should include a re-creation of the incident as much as possible. Various measurements can then be obtained in real time during the re-creation. The injury biomechanics analysis is usually straightforward. This paper will also include a case study to illustrate the main points.

Keywords

Elevator, injury biomechanics, elevator malfunction

Introduction

Elevators are transport "vehicles" that most of us use from time to time, if not frequently, to access floors within buildings, especially when the number of floors in the structure makes stairways impractical. This may involve one's personal transport between floors or the movement of materials. Elevators began to appear within buildings in the 1870s. Currently, there are over 800,000 elevators in the United States when one adds up passenger and freight installations. The number is higher when one considers residential elevators. Europe is the biggest regional market and China is the fastest growing elevator and escalator market[1]. In the United States, the average passenger elevator transports an average of 20,000 people per year. At present, four manufacturers capture a significant part of the North American elevator and escalator market: Otis, Schindler, ThyssenKrupp Elevator Systems (formerly Dover), and Kone (formerly Montgomery). Other manufacturers include U.S. Elevator Corporation and Fujitec America Inc.

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As with any other transportation device, elevator accidents leading to human injuries and death can occur. According to the U.S. Bureau of Labor Statistics and the Consumer Product Safety Commission, about 17,000 individuals are injured and 30 individuals killed in elevator or escalator incidents the United States annually[2]. Focusing on elevator workers, for the period 1992-2003, of the 173 documented fatalities, most (49%) were due to falls (down shafts), followed by "caught in/between" incidents (21%), and other causes such as being struck by a moving elevator (15%). "Caught in/between" refer to being caught within elevator machinery or between an elevator car and the shaft or another elevator car. In terms of elevator passengers, the Bureau of Labor Statistics documented 68 deaths for the time period 1992-2003, with most of these involving falls into elevator shafts. Approximately 10,000 injuries occur to general passengers annually. It has been observed that escalator injuries typically significantly outnumber elevator injuries in terms of the general user. For example, in the State of Florida for 2011, of the 408 elevator and escalator incidents reported statewide, 336 of these involved either escalators or moving walkways[3]. This is interesting when one considers that the number of operating elevators outnumbers the number of operating escalators by about 20:1[4].

General passenger injuries include trip-and-falls (usually occurs while entering or exiting a car), contact with closing elevator doors, and body forces experienced during elevator abrupt stops/accelerations/decelerations (which can lead to falls). So-called entrapments can also occur when a person (usually very thin) is trapped between the car door (gate) and the landing (outside) door. Electrical shocks can occur due to defective wiring. Most of the injuries are due to trip-and-falls. As with other mechanical devices, the causes of such incidents may reflect design issues, equipment malfunctions or failure, improper installation, improper maintenance, inappropriate use, misuse, or abuse, and a variety of external factors, including power failures and natural phenomena such as earthquakes.

Note that there are two general identifiable groups that can be involved in elevator accidents, including workers who install, repair, and maintain elevators and general passengers. For the former group of workers, most of the injuries and fatalities occur *outside* the elevator car (fatalities usually result from falling down the hoistway or shaft). For general passengers, almost all of the injuries occur *while entering or exiting* the elevator car, of which most of the injuries are due to trip-and-falls as a result of improper leveling of an elevator car with the floor. This paper focuses on general passengers and the potential injury situations that can occur within the elevator car due to sudden stops/starts. Such occurrences can lead to claims of both soft tissue and hard tissue injuries. This paper will include the presentation of an actual case analysis of sudden stops/starts, focusing on the potential impact to the passenger rather than the mechanical issues that underlie the incident.

Basics of elevator design

In the big picture, an elevator consists of an enclosed car or cab, a vertical passageway within which the elevator moves vertically (often called the hoistway), the mechanical devices that move the cab vertically, and the associated control system. For commercial applications, there are two main designs in terms of providing vertical movement: hydraulic and traction. Hydraulic designs can only be employed within buildings seven stories or less. As a result traction elevators are more commonly encountered as many commercial buildings are taller than this.

This paper focuses on commercial traction elevators since this is where many passenger injury claims arise. Most of the discussion also applies to hydraulic elevators. Other types of elevator designs, including the growing residential market, and other niche applications such as aircraft and boats will not be addressed.

Figure 1 presents a basic traction elevator design. Note that the control system and the elevator drive machine, in this case the commonly used gearless machine, is located at the top of the shaft. In some applications, such equipment may alternately be located in the basement. A number of lengths of wire cable (“hoisting ropes”) connect to the top of the car, proceed upward to the drive machine where it wraps around a device called a drive sheave, then returns downward to a counterweight system. The elevator driving machine may be based on either geared or gearless traction and incorporate a braking system, a tachometer, and a governor to insure that the maximum design speed is not exceeded.

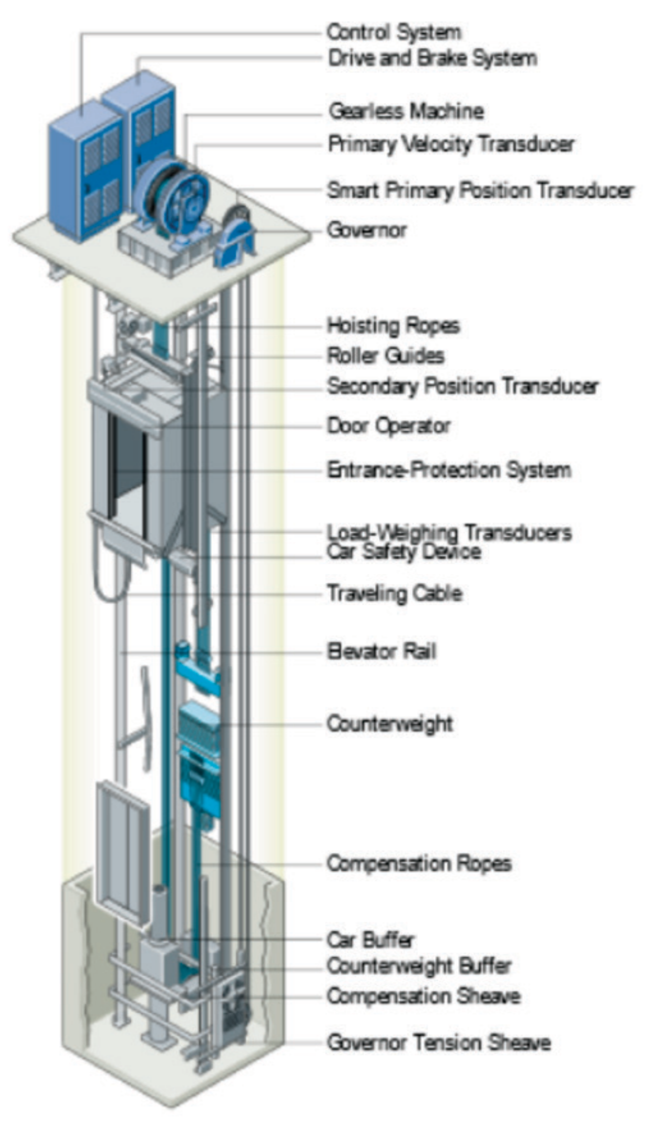

Figure 1
Diagram of a typical traction elevator design. From *About elevators moving the world – Otis Worldwide*

The cab itself includes elevator doors to protect passengers from contacting parts or surfaces outside the elevator car as the elevator moves and from falling outside the cab. These doors are in addition to the doors found at each landing or floor. The latter doors are installed to prevent persons falling into the elevator shaft and prevent person contact as an elevator car moves past the floor. Within the car itself, a control panel to allow floor selection is included along with emergency notification capabilities. Hand rails may be provided to assist in passenger standing stability. The size of an elevator car is a function of its rated carrying capacity and conforms to the national elevator standards (for example, ASME A17.1-2010[5]). The trend over the last 20-25 years has been towards larger cab sizes[6]. The cab (and also the counterweight system) moves vertically on guide rails via either roller or sliding guides. Such guide systems minimize lateral movement of the cab and otherwise establish level behavior as the cab ascends/descends.

Elevator control systems also regulate "leveling", i.e., how an elevator cab approaches a floor landing and where it stops, ideally level with the floor landing. Current standards for commercial passenger elevators require that an elevator be within 1/8 inch of the floor landing (in actual operation, most leveling is closer than this)[5]. When there is a mismatch between the cab floor and the landing level, this can constitute a tripping hazard. As noted above, such trip-and-falls are the most commonly reported elevator-related injury. The mechanical leveling process can also be a source of minor stop/start movement if the control system is not working correctly.

A number of safety features are always included in elevator system design. In addition to the governor system cited above, there are also braking systems installed on the elevator cars themselves. Various strategies will be incorporated into the control system to prevent overspeed and generally establish and maintain smooth accelerations, decelerations, and travel speeds. Also, there are devices located within the elevator pit that may include spring buffers or oil buffers in the unlikely event that the car contacts such structures while falling. More details on the safety requirements for elevator design and operation can be found in ASME A17.1-2010 *Safety Code for Elevators and Escalators* (reference 5).

Design speeds generally vary depending on the design of the system and the number of floors being serviced. Hydraulic systems generally have a design speed of 100 to 150 ft/min. Gearless traction design system speeds typically range from 500 ft/min up to 1000 ft/min. The CN Tower in Toronto (Canada) has an elevator that moves at 15 mph (1,320 ft/min). Table 1 presents standards currently accepted by the elevator industry (from references 5 and 7). In addition to speed and acceleration, "jerk" is an important variable regarding elevator operation, defined as the rate of change of acceleration. One "jerk" equals a rate change of 0.03108 g's in one second. Instruments are available to measure these variables while within a moving elevator. One example is the Maxton *SafeTach,* an elevator performance multimeter that measures speeds, rates, forces (accelerations/decelerations), and jerk[8].

Lateral movement is also important to elevator design. For traction elevators, the National Elevator Industry group that issues performance standards give a value of 30 milli-g (10^{-3} g) for lateral vibration (side-to-side and forward-backward) and vertical vibration at constant speed[7]. The same values apply to hydraulic designs. Another factor important to the analysis of door entrapment issues is the door open and door close time. The associated standards are 2 to 2.5 seconds for door opening and 3 to 3.5 seconds for door closing[7].

Variable	Drive configuration					
	1:1 Gearless		2:1 Gearless		1:1 Geared	
	Min	Max	Min	Max	Min	Max
Speed (ft/min)	400	1400	350	750	100	450
Acceleration rate (ft/s^2)	2	5	2	5	2	4
Jerk rate (ft/s^3)	4	10	4	10	5	15

Table 1
Elevator industry standards for speed, acceleration, and jerk[5,7]

Sudden or abrupt stops (or stop-starts) can be the starting point for an injury claim. In a broader sense, this can include faster than normal accelerations or decelerations. Examples of typical accelerations/decelerations for movements in this category are as follows[4]:

- stop button pressed while at full speed – less than 1 g
- sudden stop due to power failure while at full speed – less than 1 g
- car or counterweight strikes the buffer – $\geq$ 1 g
- elevator car impacts another object – several g's
  (depends on mechanical properties of the impacted object)

Passenger issues

Several factors play a role in the passenger's determination of ride quality: noise, vibration, speed sensation, and elevator car design aesthetics. Obviously the evaluation of such parameters can be very subjective. Vibration is a three-dimensional experience. It is interesting to note that most individuals will tolerate higher levels of vibration in moving environments as opposed to static environments. Side-to-side vibrational movement, often described as lateral quaking, is usually experienced during elevator car vertical movement. Passengers normally cannot detect changes on lateral quaking less than 20 milli-g or vibration in the up-down direction less than 25 milli-g[9]. For most passengers, a change in acceleration (up/down direction) becomes noticeable at about 1.3 to 1.6 m/s^2 (0.13 – 0.16 g). Also, most passengers would find an experience of a jerk value of 6.0 m/s^3 as unacceptable in terms of rider comfort[9].

While beyond the scope of this paper, psychological issues can play a very important role in a passenger's experience while riding an elevator. Indeed, some individuals have "elevator phobia", including a fear of being stuck in an elevator. However, the probability of getting stuck in a stalled elevator is about once in a lifetime[10]. Some of elevator phobia is a result of the media that has presented fictitious incidents where tragedies occurred due to elevator malfunctions, including falls. Such phobias have a lot in common with claustrophobia and the fear of falling[11, 12]. Many such individuals will have a heightened sensitivity to any elevator movements. Also, any medical factors that would influence subject equilibrium can be important to the analysis. This would include pharmaceutical drugs, alcohol, and other drugs. Finally, some individuals might experience a "panic" response during a situation involving a series of unanticipated elevator movements occurring over a short time period.

Investigating an elevator stop/start injury claim

This analysis focuses on within-the-car acceleration/deceleration incidences. It should be noted that trip-and-falls experienced while exiting or entering the elevator cab can be analyzed using the methodologies of general trip-and-falls. When an injury is claimed resulting from a within-the-car acceleration/deceleration incident, knowledge must be developed regarding several aspects of the incident:

1. What was claimed in terms of the mechanical performance of the elevator? (leading to an understanding of the acceleration/velocity/distance history)
2. Layout of the elevator car and where the person(s) was positioned
3. What supposedly happened to the claimant?
4. What injury(s) is being claimed?
5. Was a mechanism(s) established for the claimed injury(s)?

First, it is important to understand the mechanical facts of the situation, focusing on what caused the apparent acceleration/deceleration. This task is perhaps best accomplished with the assistance of a properly qualified elevator mechanical expert who understands elevator mechanics, control system operation, motor performance, etc., including associated failures. Factors to be considered include power failures, mechanical component failures, control system malfunctions, or other situations such as materials or debris (deliberate or accidental) interfering with a moving part.

Many such incidents are unwitnessed in that only the claimant was present within the elevator car at the time. The description of the elevator motions may make it difficult to determine what actually occurred. The testimony may indicate normal elevator operation before and after the incident, with the claimed incident being something of an anomaly. It should be noted that some claims of elevator motions may be viewed with skepticism. For example, a description of significant lateral quaking may be dismissed since the physical design of the elevator and the associated guide rails may make such motion virtually impossible. Following many claims of elevator malfunction, the subject elevator may be shut down temporarily following the incident while a mechanical and safety inspection is conducted; sometimes an actual mechanical issue may be documented.

It is also important to understand the layout of the elevator car and where the claimant was positioned within the car. As one actual case example, a tall male individual (6’ 7” in height) was within an elevator car equipped with a relatively low hand rail on the cab wall. The hand rail height was such that he would have to bend down to grasp it with his hand. He was standing approximately 3 feet from the wall when the elevator experienced several sudden stop/starts. He reached over to grasp the hand rail during the stop/starts, establishing an imbalance leading to a fall in the elevator and causing a knee injury. Obviously the knee injury was due to blunt trauma associated with the fall.

If a mechanical or electrical failure is identified that caused the elevator to experience accelerations/decelerations well beyond the normal range, it may be possible to re-create the incident. This may require that a technician working as part of the investigation team establish the necessary conditions outside the car (often in the control room); activities can be coordinated via phone contact. Using instruments such as the *SafeTach* described above or other accelerometer-based devices, the forensics expert can measure the forces that may have been established during the actual incident by measuring the before-during-after forces while the incident is otherwise re-created. Computer acquisition systems employ wireless accelerometers to capture data in real time. Newer smart phones or tablets have sophisticated 3-dimensional accelerometer systems that can be accessed via apps such as *Sensor Data* or *iSeismometer.* Some smart devices are now equipped with 3-dimensional gyros which can provide rotational information as well. Appropriate baseline information should be obtained in addition to the re-creation data. Another approach that provides a visual representation of the incident is to position a glass approximately half full with water on the floor or on a rigid stool and film the water level (camera perpendicular to the glass at the level of the water level) as the incident is re-created. Dying the water in conjunction with a white background material behind the glass makes it easier to see what is happening. Note that this method is sensitive to vibrations in the horizontal plane and less so regarding vertical accelerations. Another method that might be a better representation of vibrations in all dimensions employs a water-filled balloon in lieu of the half-filled glass.

Regarding the analysis of any claimed injuries, two general types of injury mechanisms must be considered: 1) blunt trauma, i.e., direct contact of some body area with some surface or object; and 2) pure acceleration/deceleration forces, i.e., no body contacts with any surfaces or objects (other than feet contact with the elevator floor). Note that vibrational forces would not be considered to be of an injurious nature due to their limited magnitude. Regarding a within-the-car incident, blunt trauma would be associated with a fall event where the individual falls to the floor or possibly contacts the elevator cab walls or the door. Occasionally, blunt trauma might be the result of contact with other passengers or objects within the car such as a push cart. Such a blunt trauma analysis would have to consider why the person fell (if a fall was involved) and what the impact forces might have been. As noted above, lateral forces are normally minimal due to the physical structure of the elevator car and the associated guide rails, so any falls would be due to other than involuntary lateral forces. Unfortunately, the surfaces within the elevator car are often “hard” (i.e., the floor, the walls, and the doors), which tends to increase the magnitude of the impact force for a given impact velocity. Otherwise, the “fall” part of the analysis can employ procedures commonly used in fall-from-height impact force incidents. Pure acceleration/deceleration incidents would follow more general analysis techniques, recognizing that the person is normally standing erect and any forces are usually applied axially. As such, differential movement across joints may be minimal. Similarly, a challenging injury on the plaintiff side would be spinal soft tissue injuries (similar to low velocity vehicular impact claims).

Case examples

A woman was working in a 30 story building and using the building service elevator (see Figure 2) to go from a high floor to a low floor during the course of her normal work routine. She was alone in the elevator when it began its descent. During the descent, the elevator experienced 2-3 sudden full stops over a very short time period. She claimed the elevator car was shaking side-to-side during the stops. She claims her body “hit all over” as she “fell down several times” and had bruises everywhere (not substantiated by the post-incident medical records except for a knee bruise). There was no loss of consciousness.

The elevator eventually reaches the ground floor where she exits with assistance. She claims injuries to her cervical and lumbar region along with bilateral shoulder issues. She would seek medical attention the following day at an acute care center. Subsequent treaters would provide a diagnosis of RSD to both the lower and upper extremities. It should be noted that her trial testimony differed significantly from her depositional statements.

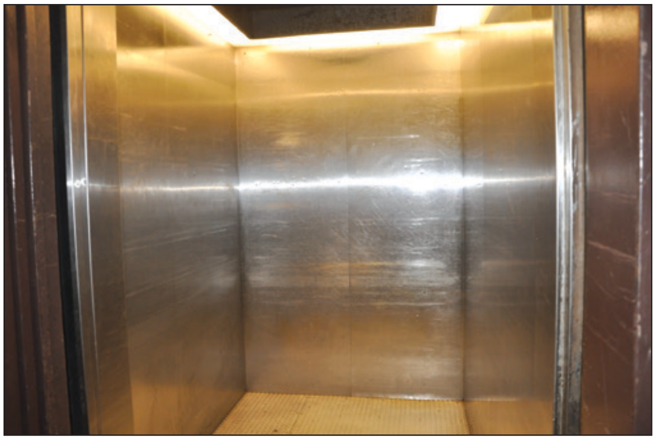

Figure 2
The actual elevator car involved in the incident (outside looking in). This was a service elevator.

Following the incident, it was determined that the elevator did experience some mechanical issues due to a malfunctioning tachometer on the elevator drive unit (see Figure 3) that was subsequently replaced. When the tachometer stopped sending a signal, the elevator would go into an emergency stop. The gearless traction elevator had a rated speed of 500 ft/min. It was determined during the discovery process that the elevator had been maintained properly prior to the incident.

With this mechanical information, the investigation team set out to re-create the incident. A technician was stationed within the control room (at the top of the hoistway) and would physically lift the tachometer (which was readily accessible) off the monitored shaft, effectively causing an emergency stop. While maintaining phone contact with two individuals in the elevator car, baseline measurements were obtained, followed by measurements during the emergency stop. An *iPhone4* and *iPad* were used to capture data (100 Hz rate), in addition to a laptop acquiring data from a MicroStrain wireless G-Link -LXRS ± 10 g accelerometer sampling at 512 Hz and a *SafeTach* unit. In addition, a glass of water half-full with water was filmed during the data acquisition, with the camera focused on the surface of the water and otherwise positioned perpendicular to glass at the level of the water surface. Several emergency stops were measured during the investigation.

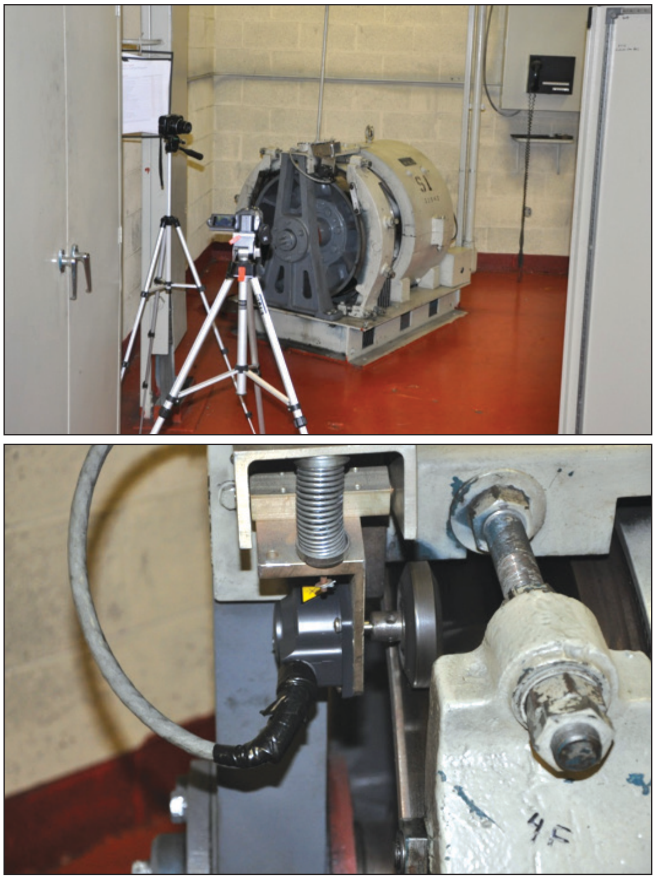

Figure 3
The elevator drive unit with the liftable tachometer (located in the control room): the overall drive unit (top) and a close-up of the tachometer (bottom).

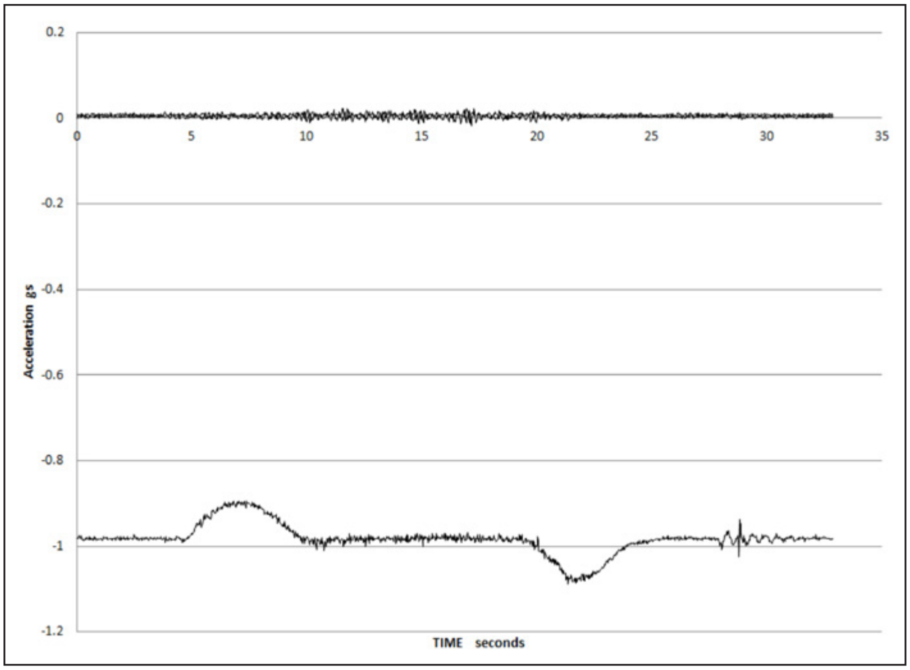

Figure 4
A normal start and stop (data from *iPad* accelerometers).

Figure 4 presents the acceleration time history for a normal start and a normal stop, with the elevator otherwise descending at 498 ft/min between the start and stop. These data were obtained using an *iPad* running *Sensor Data.* Prior to the start, data is also presented for the elevator remaining stopped. Also, the leveling process is captured following the normal stop. The elevator speed was determined by the *SafeTach* unit. A variety of information can be extracted from the plot, including:

- Acceleration in the x and y directions (the horizontal plane) is very low, fluctuating around 0 g's, even during the starts and stops. The largest variation is during the normal speed descent. These values are probably below or just at the level where a passenger might even be aware of such movement.
- The normal start has a peak change of about 0.1 g (vertical direction) with the "peak" spread out over approximately 5 seconds. The peak value of 0.1 g was also captured by the *SafeTach* unit.
- The fluctuation in the vertical accelerations during the normal speed descent is very low and comparable to that of the horizontal plane fluctuations. These fluctuations are only slightly higher than the fluctuations observed while the elevator was stopped.
- The normal stop had a peak change of about 0.1 g (vertical direction) with the "peak" spread out over approximately 4 seconds. The peak value was also captured by the *SafeTach* unit.
- Fluctuations of about 0.02 to 0.03 g were observed in the vertical direction during the leveling process following the normal stop.

Videos of the water level in the glass indicated very little disturbance of the water surface during the normal starts and stops and the associated leveling process.

Figure 5 presents the acceleration time history for a series of three emergency stops initiated by lifting the tachometer unit on the elevator drive. Data were obtained using a MicroStrain ± 10 g *G*-Link wireless accelerometer node in conjunction with the MicroStrain-provided software. These emergency stops were initiated after the elevator began descending following a normal start. A variety of information can be extracted from the plot, including:

- Acceleration in the x and y directions (the horizontal plane) fluctuated around 0.03 g's during the emergency stops, with the duration of the "upset" corresponding to the time period over which the elevator came to a stop (about 4 seconds). These values are probably below or just at the level where a passenger might even be aware of such movement.
- The peak change in the vertical accelerations during the emergency stops was approximately 0.5 g, with the peak occurring over about a 1 second time period. This was immediately followed by a 2-3 second period of fluctuating values, with the range of values being ± approximately 0-0.02 to 0.03 g's as the elevator came to a stop. The magnitude of the peak change was also observed on the *SafeTach* unit. The *iPhone, iPad, and Microstrain* accelerometer produced virtually identical results.

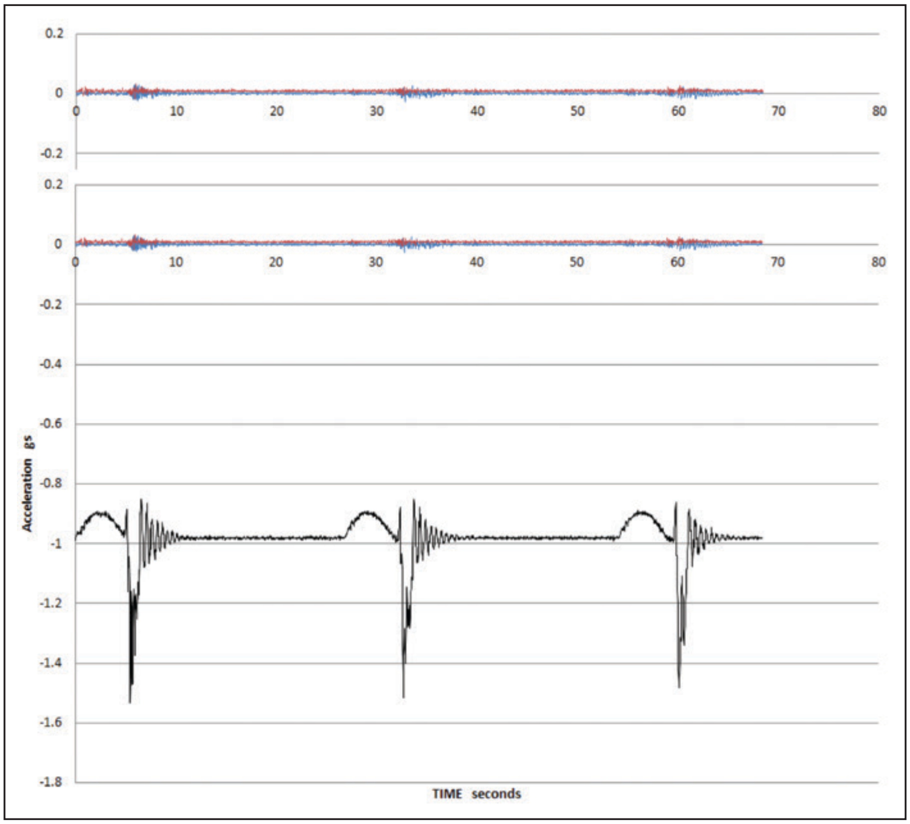

Figure 5
Three emergency stops initiated by lifting the tachometer unit. The elevator was going down before the stop was initiated for all runs. Data obtained using a *MicroStrain G-Link –LXRS* ± 10 g accelerometer

Videos of the water level in the glass indicated very little disturbance of the water level during the emergency stops.

The re-creation information indicates that a passenger would experience very little force in the horizontal plane during the emergency stops. Thus any body movements in the forwards-backwards or left-right directions would be minimal and not promoting any fall event since the body center of gravity would change very little, allowing stability to be maintained. The magnitude of the vertical forces during the sudden stops are about 0.5 g's above the force of gravity (1 g). This is a very low force and is comparable to (if not less than) the forces associated with many activities of daily living.

The plaintiff claimed that she fell several times during the sequence of events at the time of the incident. It may be possible that she fell once during the incident, possibly reflecting more of a panic reaction than as the result of body forces. However, the mechanics of the fall in terms of what hit first, what hit second, etc. is unknown. The plaintiff could offer no specifics on this. Medical records did not provide much insight into this issue; there were no documented bruising, lacerations, etc., anywhere on her body except for a knee bruise. Furthermore, there was no information to substantiate any direct head trauma during the incident. With the possible exception of the spinal injury claims (resulting from a fall), there was no obvious mechanism for any of her other injury claims established during the incident. No knee injuries were ultimately claimed. The elevator car had metal walls and a metal floor which would be important to any fall analysis. Also, the elevator car itself was rather small in size, so the possibility of contacting a wall initially as part of a fall would be significant.

Discussion

Within-the-cab acceleration/deceleration incidents are more challenging to analyze than the more straightforward trip-and-fall situations. It is very important that any injury biomechanics analysis be performed with active assistance and participation from a qualified mechanical elevator expert. This is essential when a re-creation is attempted.

An *iPhone, iPad*, a computer-based system employing a MicroStrain G-Link –LXRS ± 10g wireless accelerometer, and a *SafeTach* were all used simultaneously. For the smart devices and computer-based wireless accelerometer, all data was transferred to Excel for subsequent analysis and presentation. In all cases, the acceleration values were in agreement. However, the *SafeTach* has one disadvantage in that it captures and holds the peak values for the measured parameters. The smart device approach allows one to capture the entire acceleration/time sequence. However, parameters such as average acceleration and jerk must be determined as part of the post-run data analysis. As long as the maximum forces are less than approximately 2.5 g, the smart device approach may perform satisfactorily in such analyses. For forces greater than 2.5 g, one must employ the computer-based accelerometer units. When acceptable, the smart phone approach is certainly a cost-efficient way of performing the data collection.

After a report was rendered by the author as the Defendant's Expert, a settlement was reached based on a very nominal payment to the Plaintiff.

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