Biomechanical Evaluation of Injury Severity Associated with Patient Falls from Bed

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KEY WORDS

acceleration
falls
head injury criteria
injury prevention
hospital bed

This study investigated the severity of injuries associated with falling from bed and the effectiveness of injury-prevention strategies. Injury criteria were calculated for head- and feet-first falls from six bed heights onto a tiled surface and floor mat. These values indicated a 25% chance of experiencing a serious head injury as a result of falling feet-first from a bed height of 97.5 cm onto a tiled surface. Risk of injury increased to 40% when extrapolated for the height added by bedrails. Using a floor mat decreased this risk to less than 1% for bedrail height for feet-first falls. Calculated impact forces indicated a risk of skull fracture when hitting the tiled surface. Floor mats and height-adjustable beds positioned to the lowest height should be used to decrease the risk of injury associated with falling from bed.

Approximately one-third of people age 65 and older fall annually (Tinetti, Speechley, & Ginter, 1988; O'Loughlin, Robitaille, Boivin, & Suissa, 1993; National Center for Injury Prevention and Control [NCIPC], n.d.). According to the NCIPC, 20% of these falls occur in institutions (NCIPC) and most commonly around the bed, in the bathroom, or between the bed and bathroom (Bulat, Powell-Cope, Nelson, & Rubenstein, 2004).

Between 20% and 24% of all falls specifically are identified as falls from bed (Gurwitz, Sanchez-Cross, Eckler, & Matulis, 1994; Innes & Turman, 1983). In a study conducted by Walshe and Rosen (1979), falls from bed were found to be disproportionately associated with people older than age 65; 83% of all falls from bed were experienced by this age group, which account for only 22% of the total patient population. A high incidence of injury is associated with falls from bed; 37% of these falls result in fractures, lacerations, or hematomas (Innes & Turman). Although falling from bed is a significant problem for older adults in acute- and extended-care facilities, there are significant gaps in the research on the mechanism of injury because these events often are not observed. Furthermore, an objective assessment of injury prevention methods currently is unavailable to healthcare providers.

Objectives

The objective of this study was to determine the effect of bed height and floor surface on fall impact in a laboratory setting. Data from this study were expected to provide useful information to nurses who routinely use height-adjustable beds and floor mats to prevent injuries resulting from patients falling from bed.

Methods

Data Collection Instruments

A patient fall from bed was simulated using a Hybrid III anthropomorphic test dummy (ATD; manufactured by Denton ATD, Milan, OH). The ATD represents a 50th percentile U.S. adult male with respect to weight (76.3 kg), height (1.70m), and joint ranges of motion. To further enhance the patient simulation, the ATD was clothed in hospital scrubs.

Deceleration profiles were measured using three tri-axial accelerometers (PCB #356A02; manufactured by PCB Piezotronics, Depew, NY) internally installed in the head, thorax, and pelvis of the ATD. These deceleration profiles were measured for six fall heights (33.5 cm, 48 cm, 62.5 cm, 77 cm, 91.5 cm, and 97.5 cm) onto a vinyl composition tile (VCT)-covered concrete floor and a Posey Beveled Floor Cushion (manufactured by Posey Company, Arcadia, CA). The floor cushion measured approximately 183 cm in length, 96.5 cm in width, and 2.5 cm in thickness.

Data Collection Procedures

A sling was designed to interface with a ceiling-mounted patient-lift system to standardize the fall-from-bed event and allow the ATD to passively fall from bed. Six trials (α = .05 and β = .80) were conducted for each of the 12 configurations during two fall directions: head first and feet first.

Data Management and Data Analysis

The deceleration profiles were recorded using LabView™ (National Instruments, Austin, TX) virtual instrumentation. Mean maximum deceleration values, referenced as deceleration values, and standard

Key Practice Points

1. Injury severity correlated by injury criteria indicated a 25% chance of severe head injury during feet-first falls from bed; this risk of injury increases to 40% when height is added with bedrails.
2. A floor mat should be placed beside the bed to decrease the risk of injury associated with falling from bed.
3. A height-adjustable bed should be placed at the lowest position when the patient is not being attended.
4. The use of bedrails should be discontinued because the risk of serious head injury significantly increases due to the additional height.

deviations were calculated for each test configuration using SAS®; deceleration value equaled the mean of the peak deceleration values across six repeated trials. The deceleration values for each test configuration were analyzed in SAS using a two-way analysis of variance (ANOVA). Impact force, measured in Newtons (N), was calculated for the head during head-first falls and for the pelvis during feet-first falls, for which acceleration was based on the deceleration values ($F = m \times a$). During head-first falls, the whole body mass (76.3 kg) was assumed to impact the head and was used to calculate force. However, during feet-first falls, the mass used to calculate impact force applied at the pelvis was assumed to include all body mass minus the mass of the lower extremities (76.3 – 22.9 = 53.4 kg).

Head-injury criteria (HIC), a value used in the automotive industry to correlate acceleration with injury severity, was calculated for the deceleration profiles of the head for each trial according to Equation 1, where t = time (ms), dt = time differential, and a = acceleration (m/s^2; Mertz, 1994). Resulting values were compared to established HIC limits and analyzed in SAS using a two-way ANOVA.

Equation 1: $HIC = [1/(t2 - t1) \int a\, dt]\, 2.5\, (t2 - t1)$

Any frequency that exceeded the accelerometer's predefined frequency range caused the accelerometer to power down to prevent damage to its electronics. For this reason, deceleration profiles of the thorax were measured for only 66 trials, and profiles of the pelvis were measured for 54 trials during feet-first falls. All other test configurations were measured according to protocol.

Bedrails were not physically installed in this study. Instead, injury criteria for bedrail use were extrapolated from measured data trend lines. This extrapolation may result in conservative values, however, because bedrail use may alter fall mechanisms and injury patterns.

Results

The results presented are those of the deceleration values measured at the head, thorax, and pelvis during head-first falls followed by feet-first falls. HIC values and impact forces calculated for the head during head-first falls, and HIC values calculated for the head and impact forces calculated for the pelvis during feet-first falls, also are presented.

Head-First Falls

A head-first fall event generally followed a lateral impact sequence of head, thorax, then pelvis with rotation about the longitudinal axis occurring throughout the fall event, as illustrated in **Figure 1**.

Deceleration values recorded for the head and pelvis during head-first falls significantly increased as height increased (head: $p < .0001$, pelvis: $p = .040$) and significantly decreased when using the floor mat (head: $p < .0001$, pelvis: $p = .022$). Furthermore, the floor mat was more effective at decreasing the deceleration values measured at the head as height increased ($p = .001$). Deceleration values measured at the thorax did not vary based on the presence or absence of the mat, but deceleration values increased significantly with fall height ($p = .005$; **Table 1**).

Impact forces calculated for the head during head-first falls reached a maximum of 5,368 N at a height of 91.5 cm for falls onto the VCT-tiled surface. However, when the floor mat was used, this value was reduced to 1,641 N for a similar fall height (**Table 2**). **Figure 2** illustrates the relationship between fall height and impact force calculated for the head during head-first falls onto a VCT-tiled surface and a floor mat.

HIC values calculated for head-first falls onto a VCT-tiled surface ranged from 13.41 to 282.68, compared with 1.33 to 10.01 for falls onto the floor mat. HIC values were significantly dependent on fall height ($p = .0017$) and mat use ($p < .0001$). Also, HIC values were more effectively decreased by the mat with increasing fall height ($p = 0.0026$). When extrapolated to represent the presence of a bedrail at a height of 122.5 cm, HIC values increased to 325 for impacts onto the VCT surface.

Feet-First Falls

A feet-first fall event generally followed a posterior impact sequence of pelvis, thorax, and then head with rotation about the longitudinal axis occurring throughout the fall event. The feet and knees initiated a "crumple" effect at lower heights because the lower extremities were in contact with the floor for longer periods of time before torso impact occurred (**Figure 3**).

Deceleration values measured at the head, thorax, and pelvis during feet-first falls increased significantly with increasing fall height (head: $p = .0004$, thorax: $p < .0001$, pelvis: $p < .0001$); however, the use of the floor mat significantly decreased deceleration values for the head and thorax only (head: $p < .0001$, thorax: $p < .0001$). Furthermore, the floor mat more effectively attenuated the deceleration values of the thorax as fall height increased ($p = .010$; **Table 3**).

The maximum calculated impact force at the pelvis was 1,975 N for falls onto the VCT-tiled surface from a height of 97.5 cm (**Table 4**). Forces calculated for impacts onto the floor mat generally were lower than those onto the VCT surface and reached a maximum of 1,310 N at a similar height. **Figure 4** illustrates the relationship between fall height and calculated pelvis impact force for feet-first falls onto a VCT-tiled surface and floor mat.

HIC values calculated for feet-first fall events onto a VCT-tiled surface ranged from 486.51 to 1,234.63, compared to 3.96 to 374.35 for falls onto a floor mat. HIC values increased, though not significantly, with increasing fall height; however, HIC values were significantly decreased with floor mat use ($p = .0006$). When extrapolated to represent the presence of a bedrail at a height of 122.5 cm, HIC values increased to 1,469 for impacts onto the VCT surface.

Discussion

During a fall-from-bed event, deceleration values and HIC values were dependent upon the height from which the fall occurred and the impact surface. Statistically, these factors affected each body region differently as the direction of impact changed from head-first to feet-first falls. The variations reported in the results can be explained by the amount of body segment deflection due to rebound off the impacted surface. Deceleration values measured at the thorax during head-first falls did not increase significantly with an increase in height because of the direction of impact onto the shoulder rather than on the posterior portion of the thorax as observed during feet-first falls. The deceleration values measured at the pelvis during feet-first falls were attenuated not because of the impact site but as a result of the crumple effect caused by the preceding contact of the feet and legs.

Skull fractures have been associated with falls in general, but the specific circumstances causing those injuries are not explained in the literature (Sattin et al., 1990). Impact forces calculated during head-first falls may indicate a risk of sustaining a skull fracture, as the literature reports a range of values inclusive of the forces calculated at heights greater than 91.5 cm (Nahum, Gatts, Gadd, & Danforth, 1968; Schneider &

Figure 1. Impact of Head and Thorax During a Head-First Fall from Bed

Table 1. Deceleration Values During Head-First Falls With and Without a Floor Mat

	Means ± *SD* (g)	
Height (cm)	No Mat	Mat
Head		
33.5	34.50 ± 15.42	9.22 ± 5.56
48	47.69 ± 25.65	12.69 ± 12.74
62.5	18.60 ± 10.89	6.90 ± 1.41
77	44.19 ± 15.80	10.70 ± 2.94
91.5	70.36 ± 16.52	12.26 ± 4.19
97.5	64.02 ± 25.33	21.51 ± 7.10
Thorax		
33.5	16.85 ± 6.97	6.61 ± 3.98
48	28.55 ± 15.79	20.79 ± 19.09
62.5	29.48 ± 20.15	13.48 ± 3.94
77	30.82 ± 8.63	46.67 ± 47.78
91.5	36.14 ± 9.55	13.87 ± 2.80
97.5	48.50 ± 25.54	43.11 ± 41.31
Pelvis		
33.5	14.29 ± 8.25	8.48 ± 4.03
48	11.46 ± 7.54	13.97 ± 7.45
62.5	20.74 ± 3.85	11.31 ± 6.82
77	19.82 ± 10.67	12.44 ± 4.16
91.5	18.06 ± 5.91	20.52 ± 10.99
97.5	20.63 ± 7.33	16.32 ± 9.94

Table 2. Head Impact Forces During Head-First Falls With and Without a Floor Mat

Height (cm)	Force (N): VCT Tile	Force (N): Floor Mat
33.5	2,631.99	703.13
48.0	3,638.53	968.02
62.5	1,419.24	526.79
77.0	3,371.51	816.68
91.5	5,368.16	935.67
97.5	4,884.87	1,641.12

Figure 2. Head Impact Forces During Head-First Falls With and Without a Floor Mat

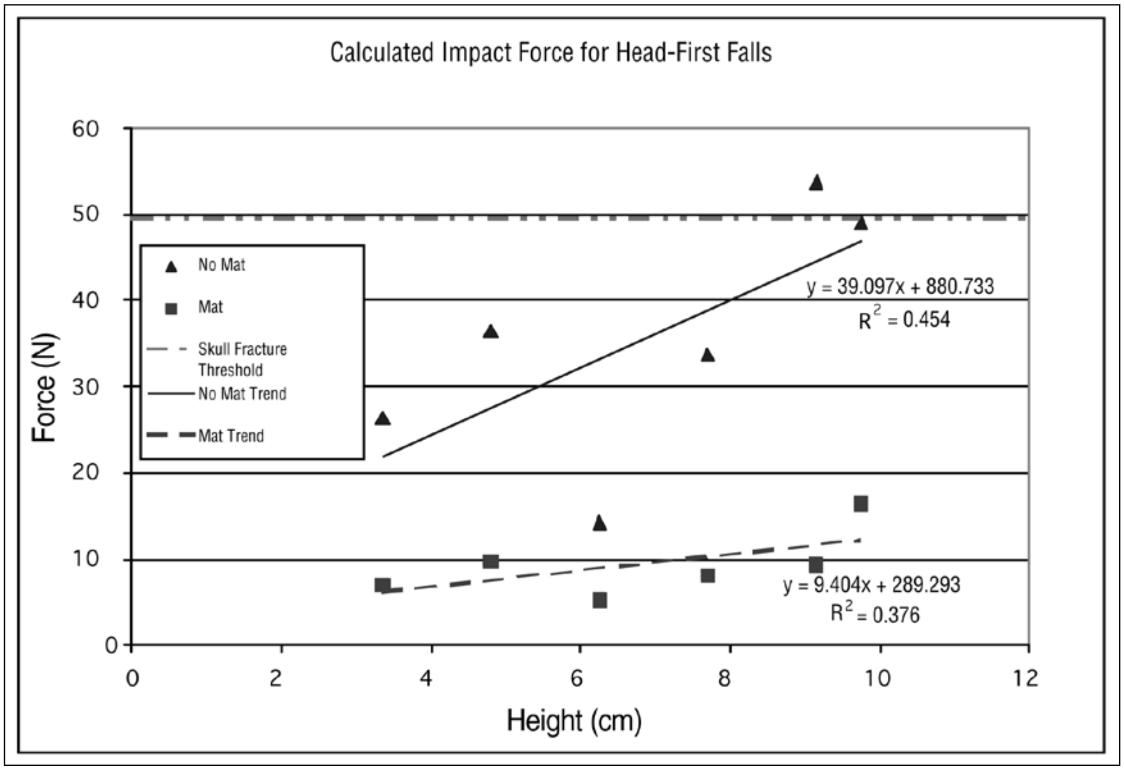


Figure 3. Initial Feet Impact During a Feet-First Fall from Bed

Nahum, 1972). Neck injuries also have been associated with falls and may be indicated, as neck deflection visually was observed during this study (Sterling, O'Connor, & Bonadies, 2001). Because the posterior region of the pelvis was first impacted during feet-first falls, risk of hip fracture was not indicated. Furthermore, calculated pelvis impact forces resulting from feet-first falls were substantially lower than the hip fracture threshold of 4,340 N (Etheridge et al., 2005). Extremity fractures specifically have been associated with falling from bed (Innes & Turman, 1983; Nevitt, Cummings, & Osteoporotic Fractures Research Group, 1993; Sterling et al.), but quantifying risk of extremity fractures is beyond the scope of this study.

Impact forces were computed for our Hybrid III crash test dummy, which represented a U. S. adult male of average weight; consequently, impact forces experienced by very small or very large patients may not be represented by our findings.

According to automotive standards, HIC values for a U.S. adult male in the 50th percentile must not exceed 700 when calculated over a 15-ms time period to minimize risk of serious head trauma. HIC values calculated for head-first falls onto the VCT-tiled flooring correlated with less than a 1% chance of experiencing a serious head injury as a result of falling out of bed, with *serious* defined as head or neck pain and possible concussion. The data extrapolated to include similar fall heights during feet-first falls indicate a 25% likelihood of experiencing a serious head injury. This risk increased to a 40% chance of injury when extrapolated to account for height added by bedrails. The relatively high risk of serious injury associated with falling out of bed feet first without a mat is not reflected in the literature because brain trauma has not specifically been associated with falls from bed. These results may indicate that patients do not commonly fall from bed feet first or that falls from bed are broken due to impact with other objects such as bedside tables, which account for the incidence of lacerations, contusions, and bruising (Lyons & Oates, 1993; Macgregor, 2000).

Although no statistical inference can be made concerning thoracic or pelvic injury based upon measured or calculated values, visual observation of the impact site may indicate a higher risk of injury to the clavicle, scapula, and hip (Sattin et al., 1990). The longitudinal rotation observed during head-first falls resulted in lateral impact upon the shoulder and pelvis (**Figure 5)**. As such, the risk of clavicle, scapula, and hip fractures may be increased because these areas have limited soft tissue to cushion an impact.

General Observations

Throughout the data-collection process, several observations were made about fall mechanics and possible resulting injury. For example, the ATD's scrubs became torn over time around the knee and shoulder impact sites and may reflect the incidence of lacerations as documented in the literature (Lyons & Oates, 1993; Macgregor, 2000). Postmeasurement inspection of the floor mat revealed permanent deformation at the head and thoracic impact sites. This information may be useful in determining mat placement and design. Although not examined in this study, adding bedrails may produce different fall mechanics because bedrails may provide an additional pivot point about which the ATD, or patient, could rotate. Particularly during feet-first falls, the ATD may complete more degrees of rotation and impact the pelvis and thorax laterally rather than on the posterior portion, as observed during this study.

Although calculated HIC values in this study suggest a 40% chance of sustaining a serious brain injury resulting from a feet-first fall, the use of a mat significantly reduced this risk. The mat also provided a protective effect for the pelvis during head-first falls and for the thorax during feet-first falls. As such, a floor mat should be used in the healthcare environment to decrease the chance of a serious injury associated with falls from beds. The coverage of the floor mat used in this study did not ensure that impact occurred on the mat, however. The ATD used in this study was designed to mimic joint range of motion and anthropomorphic dimensions, but its vinyl skin had a higher density than human soft tissue, which decreased the amount of deflection upon impact. The skin difference may have allowed the ATD to rebound off the surface more so than an actual patient. During data collection, the mat was repositioned several times because the pelvis of the ATD tended to impact more toward the foot of the bed with increasing bed height during head-first falls. Likewise, the head of the ATD tended to impact more toward the head of the bed during feet-first falls with increasing bed height. To maximize the likelihood that all falls will occur on the mat, mats should extend 15 cm beyond both the headboard and footboard. For maximum clinical performance, the width of the floor mat also should be increased by approximately 15 cm to accommodate a total approximate width of 111.5 cm.

Regardless of fall direction, the deceleration values measured at the head, thorax, and pelvis all increased significantly with increasing fall height. This suggests that lowering the bed to the lowest-available position while patients are left unattended would reduce risk of injury associated with falls from bed. The literature recommends that caregivers reposition beds to a height that is comfortable for them while they attend to patients to reduce their risk of low-back injuries. By

Table 3. Deceleration Values for Feet-First Falls With and Without a Floor Mat

	Means ± *SD* (g)	
Height (cm)	VCT Tile	Mat
Head		
33.5	74.13 ± 58.41	8.48 ± 6.66
48	152.47 ± 46.12	41.51 ± 22.40
62.5	131.81 ± 31.07	75.93 ± 26.38
77	N/A	91.58 ± 47.24
91.5	N/A	66.41 ± 38.37
97.5	N/A	54.52 ± 27.73
Thorax		
33.5	8.47 ± 5.16	3.29 ± 0.61
48	17.80 ± 6.04	7.15 ± 1.58
62.5	43.06 ± 16.00	20.26 ± 10.17
77	50.23 ± 13.64	38.30 ± 28.26
91.5	95.12 ± 43.13	38.06 ± 16.24
97.5	N/A	58.25 ± 46.01
Pelvis		
33.5	4.84 ±1.49	9.97 ± 8.90
48	8.18 ± 3.21	5.13 ± 3.13
62.5	8.88 ± 3.55	8.05 ± 3.57
77	23.46 ± 10.75	18.17 ± 7.41
91.5	32.28 ± 23.19	19.28 ± 4.52
97.5	36.97 ± 21.52	24.53 ± 8.02

Table 4. Pelvis Impact Forces During Feet-First Falls With and Without a Floor Mat

Height (cm)	Force (N): VCT Tile	Force (N): Floor Mat
33.5	258.73	532.60
48.0	437.06	273.73
62.5	474.54	430.06
77.0	1,252.80	970.41
91.5	1,724.29	1,029.64
97.5	1,974.55	1,310.10

Figure 4. Pelvis Impact Forces During Feet-First Falls With and Without a Floor Mat

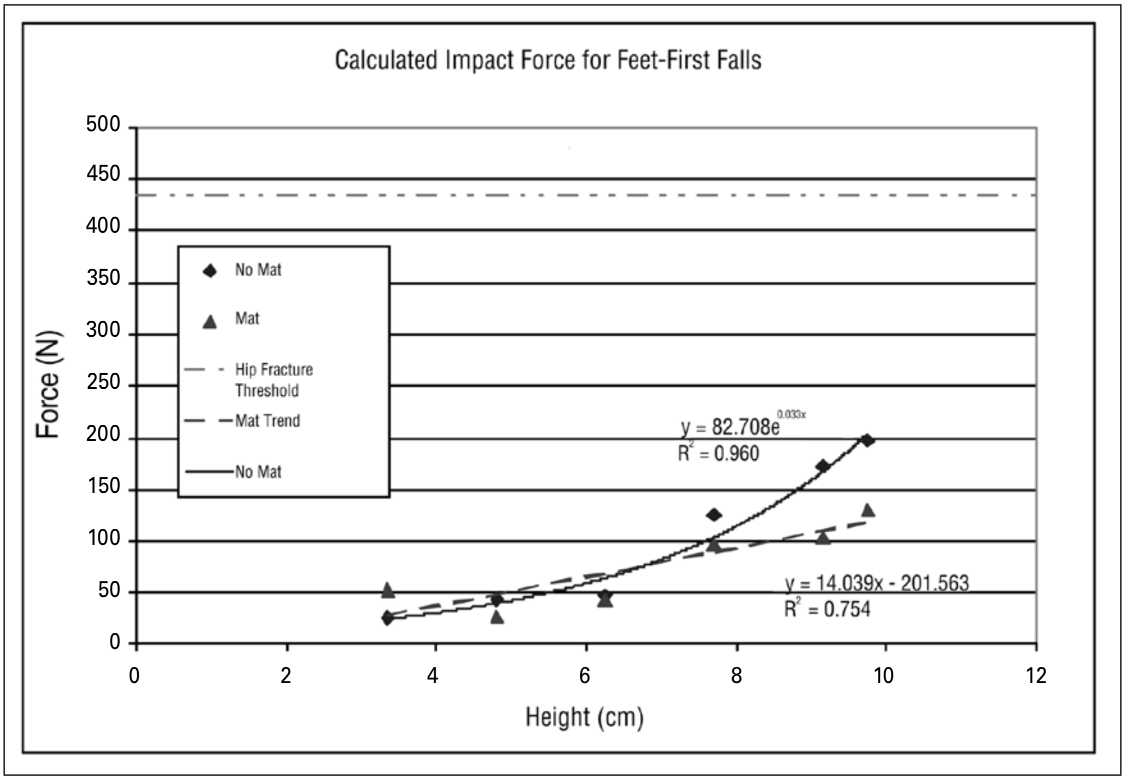
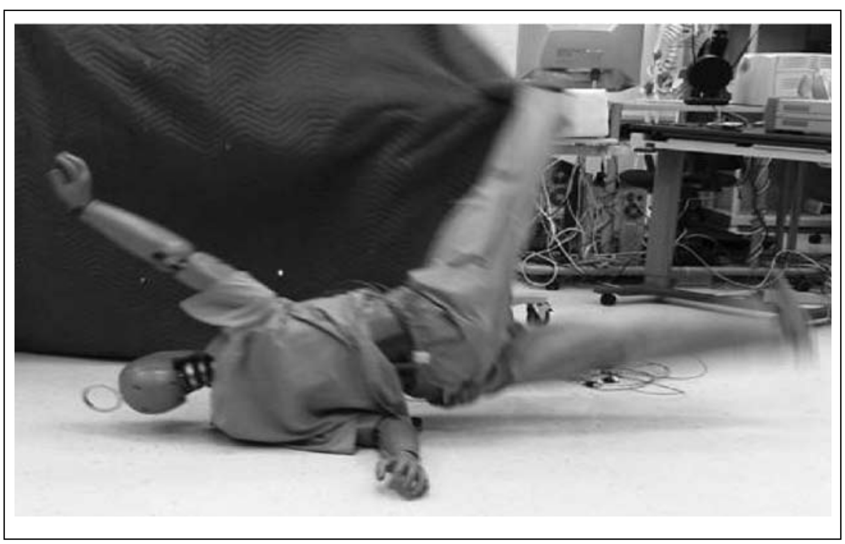


Figure 5. Shoulder Impact and Potential Upper-Extremity Dislocation During a Head-First Fall



using adjustable-height beds in clinical environments, injuries can be prevented for both patients and caregivers (de Looze et al., 1994; Caboor et al., 2000).

The use of bedrails was not included in this study because the U.S. Food and Drug Administration considers bedrails to be restraint devices. Therefore, bedrails may be used only if prescribed by an attending physician. In addition, mechanical testing of a mannequin falling over a bedrail would be difficult to simulate and could produce unreliable data. Consequently, results of this study do not directly answer the question of whether bedrails increase the risk of injury due to falls from bed. Rails add height to a fall, however, and results quantify the effects of increasing height on the force of impact. Results also support the claim that raising bedrails can increase the risk of fall-related head, thorax, or pelvic injuries regardless of bed height and provide evidence clinicians should consider when making judgments on the use of bedrails.

The results of this study demonstrate the ideal environment for preventing injuries associated with falling out of bed should include positioning the bed to the lowest-possible height, placing a floor mat of adequate length and width beside the bed, and avoiding added distance of falls due to bedrail use. By implementing these changes in the clinical environment, patients and caregivers can be assured that the highest quality care is being provided.

The effect of only one brand of floor mat was measured during this study; however, other similar devices may be more or less effective. Further research is needed to determine the effects of floor mat characteristics (e.g., foam density and thickness) on injury prevention and the effects that falling over a side rail have on the biomechanics of falls.

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