ARTICLE

Using Test Dummy Experiments to Investigate Pediatric Injury Risk in Simulated Short-Distance Falls

Gina E. Bertocci, PhD; Mary Clyde Pierce, MD; Ernest Deemer, MS; Fernando Aguel, BS; Janine E. Janosky, PhD; Ev Vogeley, MD, JD

Background: Short-distance falls, such as from a bed, are often falsely reported scenarios in child abuse. In attempting to differentiate between abusive and nonabusive injury, knowledge of factors that affect injury risk in falls could prove useful.

Objectives: To assess the biomechanics associated with simulated short-distance falls in children (one fall scenario, without attempting to maximize injury potential) and to investigate the effect of impact surface type on injury risk.

Methods: Repeatable fall experiments from bed height (0.68 m) onto different surfaces were conducted using an instrumented side-lying Hybrid II 3-year-old test dummy. Biomechanical measures assessed in falls included head acceleration, pelvis acceleration, femur loading, and head injury criteria.

Results: Fall dynamics resulted in the pelvis or legs making first contact. Biomechanical measures assessed in simulated bed falls were below known head injury criteria and lower extremity injury thresholds. The impact surface type had a significant effect on head injury risk and lower extremity loading. Playground foam proved to have the lowest associated injury risk of all the tested surfaces.

Conclusions: The biomechanics of a child falling from a short distance, such as from a bed, were investigated using an experimental laboratory mock-up and an instrumented test dummy. Despite the impact surface having an effect on injury risk, rolling from a 0.68-m (27-in) horizontal surface from a side-lying posture presented low risk of contact-type head injury and leg injury on all tested impact surfaces.

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SHORT-DISTANCE falls, such as from a bed or sofa, are one of the most common falsely reported mechanisms of injury in child-abuse cases.[1] Information aiding physicians in determining the compatibility between a specific injury and a reported fall from a bed or sofa would prove useful. Clinician guidance is needed when taking patient histories as to which factors of an injury scenario are critical to predicting injury outcome. For example, details related to a fall, such as fall height, impact surface, and landing position, have been previously shown to play a crucial role in injury outcome.[2-7] A systematic means of studying each of these factors in isolation, especially in short-distance falls, could be beneficial in attempting to determine their contributory nature toward injury risk.

To date, most retrospective bed or sofa fall studies[8-11] conclude that these falls do not lead to clinically significant injuries; however, there are some results that conflict with this conclusion.[12] Perhaps one of the most critical factors in assessing injury outcome in these studies is whether the falls have been witnessed or corroborated. Studies using a hospital setting present a unique opportunity for evaluating injury outcome following corroborated bed falls.

Helfer et al[8] studied 246 children aged 5 years and younger who had fallen from a bed. Their study found a low incidence of fracture and no serious head injuries. This study also compared corroborated falls with uncorroborated falls in terms of fracture incidence, reporting a 3.7% fracture incidence for the self-report group and a 1.2% incidence for corroborated falls. The authors conclude that physicians should be suspicious of child abuse if they examine a child with a serious head injury when the cause is reported to be a fall from a bed or sofa.

Lyons and Oates[9] conducted perhaps the most rigorous review of bed falls, studying 207 children aged 5 years and younger who had fallen from bed during a hospital stay. This study is of particular value in that it was conducted in a controlled hospital setting, where abuse could be ruled out. Among these children, there were 31 cases of injury; 29 cases resulted in contusions and small lacerations, and 2 resulted in frac-

From the Child Advocacy Center and the Centers for Disease Control and Prevention: Center for Injury Research & Control, Children's Hospital of Pittsburgh (Drs Bertocci, Pierce, and Vogeley and Messrs Deemer and Aguel), and the Departments of Pediatrics (Drs Bertocci, Pierce, Janosky, and Vogeley), Family Medicine (Dr Janosky), Rehabilitation Science and Technology (Drs Bertocci and Pierce), and Bioengineering (Dr Bertocci and Messrs Deemer and Aguel), University of Pittsburgh, Pittsburgh, Pa.

tures (clavicle and skull). Despite the head being the most common impact site, loss of consciousness was not reported in any cases. Lyons and Oates concluded from their study that falls from short heights do not typically produce clinically significant injuries.

Nimityongskul and Anderson[10] conducted another study of corroborated bed falls during hospital stays, with fall heights ranging from 0.3 to 0.9 m (1-3 ft). In 76 children, aged 16 years and younger, a very low incidence of fracture was found. Only 1 child was reported to have a skull fracture, and 1 child with osteogenesis imperfecta was found to have a tibia fracture. The authors concluded that severe head, neck, and extremity injuries are rare when children fall from beds.

Another review of children who had fallen from bunk beds found that none of the children who had fallen from the lower bed had injuries that warranted hospital admission.[11] Of 60 children who fell from a top bunk, only 6 required hospital admission for injuries, including 4 concussions, 1 skull fracture and subdural hematoma, and 1 laceration.

In contrast, a study[12] of self-reported bed and bunk bed falls in the United Kingdom reported a higher incidence of injury. However, these cases were not necessarily corroborated by anyone other than a parent or caregiver. Among injuries from upper and lower bunk beds in this retrospective review of emergency department records, 52% of self-reported cases had significant injuries. Fractures, minor head injuries, lacerations, and soft tissue injuries were reported. Because a large portion (78%) of the injuries was found in children aged 6 years and younger, the author cautioned that children younger than 6 should not be permitted to sleep in upper bunk beds.

The variation in injury outcome found across these studies highlights the need for more detailed assessments of the fall environment (such as impact surface and fall height) in corroborated or witnessed bed falls. Because the question remains as to whether bed falls can produce extremity fractures or head injuries, our study estimated injury risk through measuring femoral loading, head acceleration, and head injury criteria (HIC) in simulated bed falls, using a 3-year-old anthropomorphic test dummy (ATD). Our experiments were not designed to maximize injury potential but instead were intended to investigate a simple lateral roll from bed height. A 3-year-old child ATD was chosen for this study based on findings from our Child Advocacy Center and Centers for Disease Control and Prevention: Center for Injury Research & Control indicating that children aged 3 to 4 years are at increased risk for child abuse. In the past 12 months, our center has had 102 cases of serious physical abuse—46 of these cases involved children older than 1 year. Of the 10 child-abuse–related deaths at our center, 6 of the fatalities were children aged between 1 and 4 years. In addition, the Children's Bureau reports ongoing concern for this population, identifying 45 454 cases of maltreatment among 3-year-old children during 1999.[13]

METHODS

Repeated experiments were conducted using a pediatric test dummy to investigate falls from a side-lying posture and an elevated horizontal surface. These short-distance falls simulated one scenario of rolling off of a bed or sofa. The intent was not to maximize injury potential but instead to study one possible fall scenario—a simple lateral roll from a bed. We did not in any way cause the ATD to lead with its head. A Hybrid II 3-year-old ATD (First Technology Safety Systems, Plymouth, Mich) was used to represent the fall victim. The head and pelvis were instrumented with 3 uniaxial accelerometers, arranged with 1 accelerometer for each axis. The pelvis was modified to accommodate the mounting of 3 uniaxial accelerometers located posteriorly on the structure of the pelvis. The metal rod representing the femur was instrumented with 4 strain gauges to measure femoral strain for conversion into femoral loading. Three of the gauges were positioned to measure axial and bending load, and the fourth gauge measured torsion load. Equations that relate these strain measurements and the geometry and material properties of the rod were used to determine the loading conditions required to produce these strains.[14] These equations were verified by applying a known load to the rod in various configurations to produce bending, axial, and torsional loading.

The ATD was positioned in a side-lying posture with legs fully extended and arms extended above the head. The ATD was placed at the edge of the horizontal surface. An actuator, in contact with the posterior of the ATD's lower torso, was used to introduce a repeatable force to nudge the ATD off of the horizontal surface. As recommended by the ATD manufacturer, joints were calibrated so that the friction was sufficient to just support the weight of the limb. The orientation of each joint was measured using a goniometer, and the ATD was reset to the position at the beginning of each drop to ensure repeatability. Overall gross motion kinematics were captured during the fall using videography.

DATA ACQUISITION AND ANALYSIS

A LabVIEW program (National Instruments, Austin, Tex) was created for the purpose of data acquisition. The data were collected at a sampling rate of 1000 Hz, based on the Nyquist sampling theorem. Data were filtered using a 1.6 kHz Butterworth filter (National Instruments).

Data were analyzed to obtain the peak values of each measure, duration of loading spike, and impulse. The head acceleration data were used to calculate HIC that account for duration of acceleration exposure. The formula for the HIC is defined as

$$HIC = (t_2 - t_1)\left[\frac{1}{(t_2 - t_1)}\int_{t_1}^{t_2} a(t)dt\right]^{2.5},$$

where $a(t)$ is the acceleration; dt, the differential operator of integral; and t_1 and t_2, the start and finish times of the acceleration spike. Because proposed criteria exist for calculating HIC for 15 milliseconds (HIC_{15}) and 36 milliseconds (HIC_{36}), HIC_{15} and HIC_{36} were determined for each fall scenario. The HIC are commonly used to assess risk of head injury in motor vehicle crashes,[15] as well as to evaluate the safety of materials such as playground surfaces and motorcycle and sports helmets.[16,17]

PROCEDURES

The ATD was pushed from the horizontal surface 3 times onto each surface type (wood, padded carpet, linoleum, and playground foam) from the same initial 0.68-m height and initial position. The 0.68-m height of the fall was measured from the impact surface to the center of mass of the ATD (located at mid abdomen).

Coefficient of Friction Properties of Impact Surfaces

Impact Surface	Test Dummy Static	Test Dummy Dynamic	Shoe Static	Shoe Dynamic
Playground foam	1.23	0.97	0.71	0.70
Carpet	1.23	1.14	0.58	0.51
Linoleum	1.25	1.00	0.43	0.43
Wood	1.04	0.82	0.42	0.29

The ATD impact surfaces used in our study represented actual indoor and outdoor surfaces. Linoleum, carpet, and wood impact surfaces were adhered to a 1.83×1.83-m (6×6-ft) platform. The platform, built to standard building codes, consisted of 0.02-m (three-quarter-inch) plywood flooring covering 0.05×0.1-m (2×4-in) joists positioned 0.41 m (16 in) on center (ie, 0.41 m from the center of one joist to the center of the next).

The playground safety surface (playground foam) consisted of a series of 0.61×0.61-m (2×2-ft) tiles (0.05 m [2 in] thick) arranged to create a 1.83×1.83-m surface. No adhesive was used per manufacturer's instructions; instead, the perimeter was framed with wood to prevent tiles from slipping. Playground tiles were placed on top of a concrete subbase. Linoleum used in the study was a no-wax self-adhesive vinyl flooring. The 1.83×1.83-m wooden subfloor was covered with the vinyl flooring to create the impact surface. Carpet used in the study was open loop with padding and was installed using carpet tacks over the wooden subfloor. The wooden subfloor, without any covering, also served as an impact surface used in testing.

IMPACT SURFACE PROPERTIES

The coefficients of friction were measured between each impact surface and the ATD; the ATD head was used to represent the ATD surface properties in testing. The static and dynamic coefficients of friction were experimentally determined. The coefficient of friction results are shown in the **Table**.

The coefficient of restitution (COR) is a measure of how efficiently energy is returned to an object after impact. A COR of 1.0 is perfectly elastic, while a COR of zero is inelastic, having no rebound on impact. The COR was assessed by dropping a billiard ball from 0.91 m (36 in) onto the test surface and measuring the rebound height of the ball. Because the billiard ball deformed very little during impact, the returned energy came from the test surface. The square root of the ratio of the final and initial heights is equal to the COR. Each surface was tested 3 times. The mean COR values for the test surfaces were 0.57 for playground foam, 0.33 for carpet, 0.12 for linoleum, and 0.12 for wood.

STATISTICAL ANALYSIS

Data from each of the conditions were considered as replicates to measure variability within each. A between-condition analysis was done to assess potential differences among the 4 surface types. Following a statistically significant omnibus test, post hoc comparisons were done. Each of the outcomes (ie, HIC_{15}, HIC_{36}, head acceleration, and pelvic acceleration) was analyzed separately. Because of the violation of the necessary statistical assumptions of homogeneity of variance and normality for the parametric tests, nonparametric tests were performed; however, the statistical results of the parametric and nonparametric tests did not differ. The nonparametric results are reported. Statistical significance was defined as $P \leq .05$.

RESULTS

Fall biomechanics and the effect of impact surface were evaluated by conducting experimental short-distance falls from a constant height of 0.68 m (27 in) (measured from the ATD center of mass), which may represent a common bed, sofa, or bench height, onto various impact surfaces. The ATD dynamics during the fall onto playground foam are shown in **Figure 1**. The ATD exhibited a rolling motion about its longitudinal axis (midsagittal plane axis) during descent to the impact surface. The ATD completed approximately one half of a full rotation and impacted the playground surface on its side. In each of the fall experiments, the legs or the pelvis impacted the surface first, followed by head contact with the surface.

Significant differences were found when comparing HIC_{15} and HIC_{36} across the various impact surfaces. For HIC_{15}, significant differences ($P \leq .05$) were found when comparing carpet with linoleum, carpet with wood, and playground foam with wood. For HIC_{36}, significant differences ($P \leq .05$) were found between linoleum and playground foam, as well as between wood and playground foam. Compared with other test surfaces, playground foam resulted in the lowest HIC_{36} (mean, 55), HIC_{15} (mean, 53), and head acceleration (114*g*) (**Figure 2**). Conversely, the wood impact surface was associated with the highest HIC_{36} (mean, 418), HIC_{15} (mean, 313), and head acceleration (245*g*). No significant differences were found in head accelerations or pelvic accelerations generated in falls across different surfaces.

Axial tension in the femur (**Figure 3**) was significantly lower for falls onto playground foam compared with falls onto carpet and wood surfaces (left femur, $P = .04$). A significant difference was also found in right femoral tension associated with the effect on carpet (136 N; 31 lb_f [pound force]) vs the linoleum surface (999 N; 227 lb_f) ($P = .04$). Other modes of femoral loading (bending and torsional) did not vary significantly across the tested impact surfaces (**Figure 4** and **Figure 5**).

COMMENT

Impact surface type played a role in HIC values produced in simulated short-distance falls from a 0.68-m (27-in) height. Playground foam and padded carpet appeared to be associated with the lowest risk of head injury. Mean HIC_{36} values associated with falls onto wood were 443% higher compared with falls onto carpet and 660% higher than HIC_{36} values generated with falls onto playground foam. This suggests that falls from beds or sofas onto a wood surface are more likely to lead to direct contact–type head injury than falls onto padded carpeted floors. However, to assess whether this difference would translate to a difference in clinical outcome, it is necessary to compare experimental measures with injury thresholds or criteria. Unfortunately, little data exist related to injury tolerance in 3-year-old children.

Despite the paucity of injury criteria for children, it is possible to compare HIC values measured in this study with HIC tolerance levels recently proposed by the National Highway Traffic Safety Administration (NHTSA)

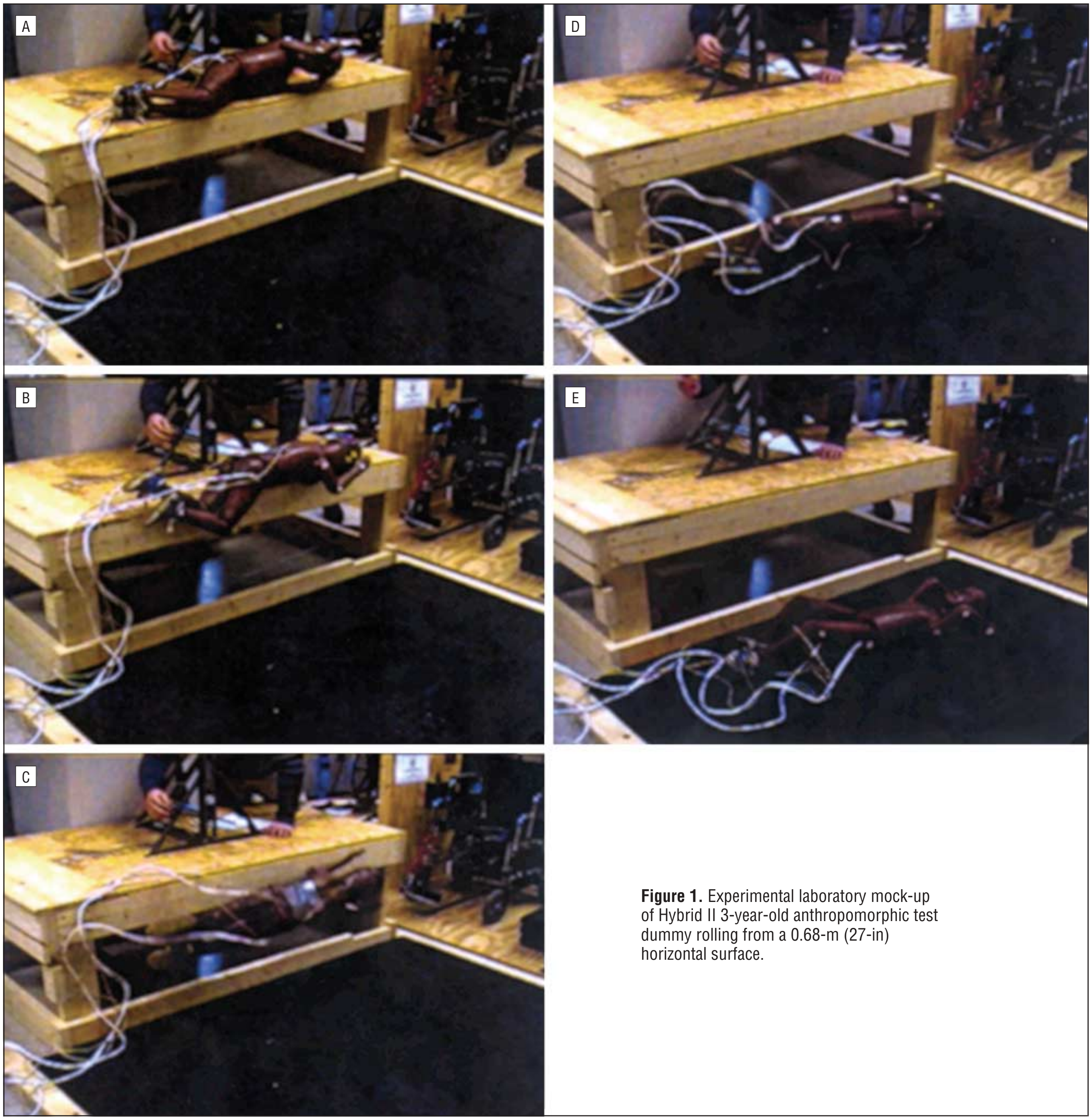

Figure 1. Experimental laboratory mock-up of Hybrid II 3-year-old anthropomorphic test dummy rolling from a 0.68-m (27-in) horizontal surface.

for the Hybrid III 3-year-old ATD.[18] The NHTSA's proposed HIC_{36} threshold of 900 is associated with a 47% probability of skull fracture in 3-year-old children. In a more recently proposed Interim Final Rule for Federal Motor Vehicle Safety Standard 208, NHTSA recommended calculating the HIC value for 15 milliseconds in lieu of the previous 36 milliseconds.[19] Using HIC_{15} as the basis to predict a head injury threshold, NHTSA established a HIC_{15} limit of 570 when using the Hybrid III 3-year-old ATD. In our study, no test scenarios produced HIC_{36} or HIC_{15} values exceeding NHTSA criteria. The highest HIC_{36} mean value, 418, was generated with impact onto a wooden surface. The highest HIC_{15} mean value, 313, was also associated with falls onto the wooden surface. Inflicted brain injury is often the result of angular accelerations of the head, which are not described in this study. Although HIC do not account for noncontact head injury mechanisms, they provide a preliminary assessment of the likelihood of contact head injuries, such as skull fractures, in short-distance falls.

Compared with known injury criteria, our findings indicate that rolling falls from surfaces such as a bed or sofa from a side-lying posture onto different surfaces have a low risk of direct contact head injury in young children. These findings are echoed through epidemiological studies[8-10,12] of falls from beds in young children. Accordingly, head injuries associated with short-distance falls, such as those from beds or sofas, should be carefully scrutinized by the clinician to assess compatibility of the presenting injury and the reported fall scenario. The plausibility of head injuries from these short-distance, side-lying posture falls rests on the caregiver

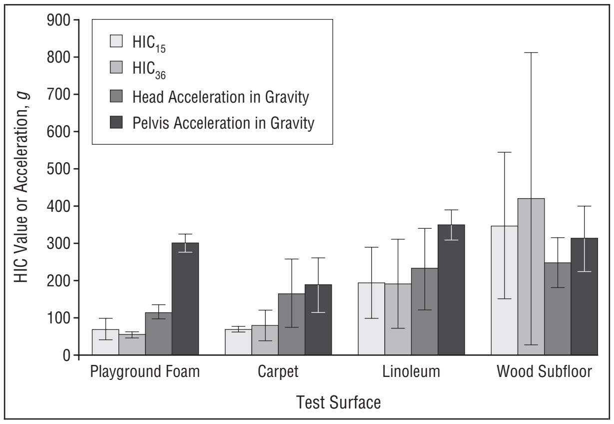

Figure 2. Head injury criteria calculated for 15 milliseconds (HIC_{15}), HIC_{36}, head acceleration, and pelvis acceleration for various test surfaces.

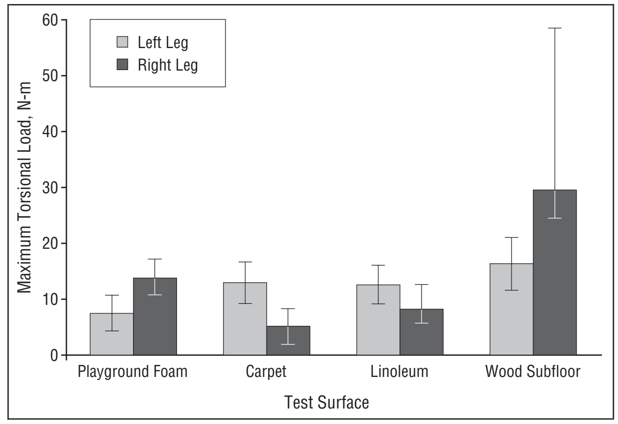

Figure 5. Right and left femur maximum torsional load for various test surfaces.

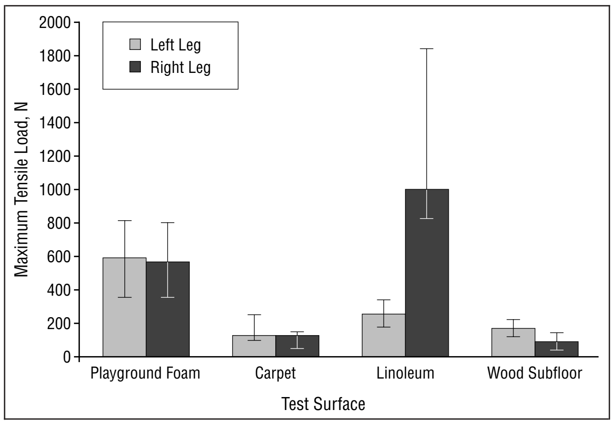

Figure 3. Right and left femur maximum tensile load for various test surfaces.

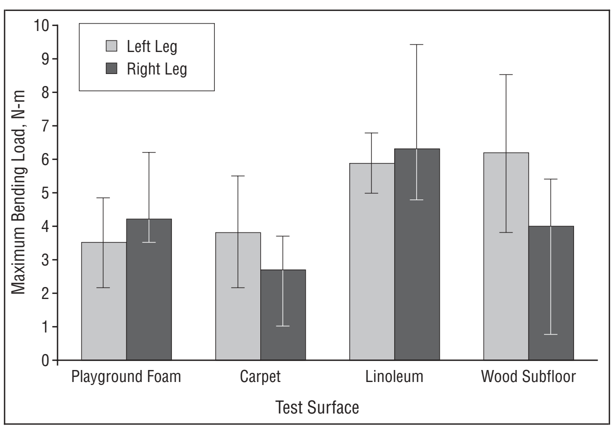

Figure 4. Right and left femur maximum bending moment for various test surfaces.

to specifically define circumstances and injury mechanisms that can explain the injuries.

Unfortunately, injury tolerance data for the femur in 3-year-old children are scarce. In quasi-static testing of a single 2½-year-old child, Martin and Atkinson[20] found a cadaveric femur threshold bending moment of 52 N-m [Newton-meter] (465 in-lb_f). None of the bending moments generated in our experimental falls approached this threshold. Among all of our experimental tests, the highest mean femoral bending was only 6.3 N-m (56 in-lb_f) (12% of threshold) and was associated with the fall onto linoleum.

Stanley[21] evaluated 17 cadaveric femurs from children aged 6 years and younger. Using data for the 3-year-old, they proposed a compressive fracture limit of 871 N (198 lb_f). The weak point under compressive loading is often the distal epiphysis of the femur. None of our experimental falls onto various test surfaces exceeded this femur compressive load limit. The highest compressive load (620 N [141 lb_f]) found in our series of experiments was associated with falling onto linoleum.

Hirsch and Evans[22] proposed a strength range of 5700 to 13 200 N/cm^2 (8358-19 355 lb_f/in^2) of the 6-month-old femur that is loaded in tension, as determined through testing of 8 cadaveric specimens. Using the cross-sectional area of the 3-year-old ATD, this converts to a tensile load limit of 11 396 to 26 400 N (2590-6000 lb_f). In our experiments, the maximum femur tension, which was likely induced through a bending moment, was much lower (999 N [227 lb_f]) than the fracture threshold and was associated with falls onto linoleum. This is reasonable because it is difficult to imagine conditions resulting from a bed fall that would lead to significant tension in the femur.

However, relative to femoral injury risk, loads measured in our study were not cadaver-based and were instead measured using a human analogue. Correlation studies between the Hybrid II ATD femur and cadaveric results would be necessary to make such a direct comparison and to validate the biofidelity of the ATD. Therefore, fracture prediction in our study provides only limited value. Although it is of interest to compare observed femur loading values with injury thresholds and to examine trends in biomechanical measures associated with various impact surfaces, it is not possible to definitively indicate the clinical outcome associated with such loading.

The sensitivity to initial position was not investigated in this study. Because landing position has been previously shown to affect injury outcome in falls[23] and because initial position affects impact position, it is reasonable to assume that initial position can have an effect on our results. For example, in our testing, first-surface contact was with the legs or pelvis. Altering the initial

What This Study Adds

Short-distance falls, such as falls from a bed or sofa, are one of the most common falsely reported mechanisms of injury in child-abuse cases. Most, but not all, existing epidemiological studies indicate that severe injuries do not result from bed falls. In a laboratory-controlled environment, our study investigated head and lower extremity injury risk associated with short-distance falls from a supine posture, using an instrumented test dummy. We also studied the effect that impact surface has on injury risk in these falls. Our study found a low risk of contact-type head injuries and lower extremity injuries associated with short-distance falls. Impact surface type affected the risk of injury. A better understanding of the likelihood of injury associated with short-distance falls could aid physicians in determining the compatibility between injury outcome and reported short-distance fall scenarios.

position may increase the contact head injury but decrease the risk of angular acceleration–derived (ie, inflicted type) brain injury and extra-axial hemorrhage. Previous experimental tests of cadaver infant (neonate to 14 months) skull fragility showed that head-first contact from an 82-cm (32.2-in) height onto stone, carpet, and linoleum led to skull fractures of the parietal bone.[24] Therefore, additional studies should explore the effect that initial position, in particular leading with the head, has on overall injury risk during a bed fall. In fact, some may believe that a head-first fall is a more likely bed fall dynamic for a child than that evaluated in our study.

This study provides preliminary biomechanical data associated with simulated short-distance fall events in 3-year-old children. This effort represents a first step toward a better understanding of injury risk associated with a short-distance fall, such as a fall from a bed. However, these measures are derived from a Hybrid II ATD, which only approximates a 3-year-old child. Because biomechanical response data on children are scarce, child ATDs are typically less biofidelic than their adult counterparts. Less than desirable scaling techniques from adult to child, based on geometry and mass, are often used in the development of smaller ATDs.[18] In addition, despite a few studies[25-27] attempting to extend the use of the Hybrid II ATD to low-energy events, the Hybrid II ATD was developed for high-energy impact events, such as motor vehicle crashes. The application of this ATD to the study of fall biomechanics should therefore be limited to investigating trends in biomechanical measures. Active muscle response and protective reflexes that may be present in 3-year-old children during a fall are also not accounted for in our ATD model. Moreover, lower extremity response to loading, assessed through the addition of strain gauges to the structure representing the ATD femur, has not been previously validated for biofidelity. Therefore, lower extremity loads described in this study should be used primarily for assessing trends in femoral loading across various fall conditions. Increased lower extremity ATD biofidelity could be achieved through cadaveric assessment of pediatric femoral biomechanical properties and duplication of these properties within the ATD.

CONCLUSIONS

This study provides a biomechanical assessment of a simulated short-distance fall, such as a bed fall, using an experimental laboratory mock-up and an instrumented 3-year-old test dummy. Impact surface type significantly affected head injury risk and lower extremity injury in side-lying posture rolling falls from 0.68 m (27 in). These findings further highlight the effect that subtle fall environment differences, such as surface type, can have on injury risk and highlight the need for detailed clinical histories when attempting to differentiate between abusive and nonabusive injuries. However, despite the effect of impact surfaces, rolling from a short distance in a side-lying posture onto all tested surfaces presented a low risk of head and lower extremity injury. These findings are consistent with those of previous retrospective case-based studies that have found that bed falls do not typically result in severe injuries in children.

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Corresponding author and reprints: Gina E. Bertocci, PhD, Department of Rehabilitation Science and Technology, University of Pittsburgh, 5044 Forbes Tower, Pittsburgh, PA 15260 (e-mail: ginaber@pitt.edu).

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Correction

Error in Figure Legend. In the Article by Clifford et al titled "Sequelae of Infant Colic: Evidence of Transient Infant Distress and Absence of Lasting Effects on Maternal Mental Health," published in the December 2002 issue of the ARCHIVES (2002;156:1183-1188), an error occurred in the legend to Figure 2 on page 1185. That legend should have read as follows: "Cry/fuss distribution at 3 months of age for 320 infants. Minutes per week represent total minutes of crying and fussing during the 12th week of life (mean, 400.5 minutes; SD, 280.6 minutes)." The journal regrets the error.