Femur Fractures Resulting From Stair Falls Among Children: An Injury Plausibility Model

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ABSTRACT. ***Background.*** **Stair falls are common among young children and are also common false histories in cases of child abuse. When a child presents with a femur fracture and a stair-fall history, a judgment of plausibility must be made. A lack of objective injury and biomechanical data makes plausibility determination more difficult. Our objective was to characterize key features associated with femur fractures from reported stair falls, to develop a model for assessing injury plausibility (IP).**

Methods. **Children 2 to 36 months of age who presented with a femur fracture from a reported stair fall were studied prospectively. Detailed history recording, examinations, fracture characterization, and injury scene analyses were conducted, and biomechanical measures associated with injury prediction were calculated. With our proposed IP model, all cases were then scored for the detail of history, biomechanical compatibility of fracture morphologic features, time to seeking care, and presence of other injuries.**

Results. **Twenty-nine children were diagnosed with a femur fracture resulting from a reported stair fall. The IP model made a clear distinction between 2 groups, designated plausible and suspicious. Significant differences were observed for the detail of history, biomechanical compatibility of fracture, time to seeking care, presence of other injuries, and total IP scores. In the plausible group, the minimal linear momentum associated with a transverse fracture was almost 10-fold greater than that for spiral or buckle fracture types.**

Conclusions. **This study adds new information to the current body of knowledge regarding injury biomechanics and fractures among children. The IP model provides an objective means of assessing plausibility of reported stair-fall–related femur fractures and identifies key characteristics to facilitate decision-making.** ***Pediatrics*** **2005; 115:1712–1722;** ***femur fracture, child abuse, stair fall, biomechanics.***

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ABBREVIATIONS. CML, classic metaphyseal lesion; IP, injury plausibility; CT, computed tomographic; HQS, history quality scale; CPT, child protection team.

Stair falls are a common occurrence among young children and are also a common false history in cases of child abuse. When a young child or infant presents with a fracture and a history of a stair fall, a determination must be made regarding the plausibility of injury. Inaccurate assessments can result in both missed cases of child abuse and over-investigations of innocent families. Repeat injury is very likely if the diagnosis of abuse is missed, with 50% to 80% of fatal or near-fatal abuse cases having evidence of prior injuries.[1–4] Conversely, Child Protective Services involvement in cases in which the injury did not result from abusive trauma can be harmful to both the family and the child and consumes limited resources.[5,6]

Among children, stair falls are common but rarely result in serious injury,[7–9] and studies specifically evaluating stair-fall injuries did not identify any femur fractures.[7,8] The prevailing opinion is that a stair fall would not generate the required forces to cause a femur fracture and that an alternative explanation, such as child abuse, should be considered. Fractures are second only to bruises as a presentation of child abuse[4] and may be an early indication of a high-risk environment in which trauma is likely to progress.[10] A recent review of 100 cases of severe inflicted trauma at Children's Hospital of Pittsburgh revealed 11 cases in which the reported cause of injury was a stair fall. In these 11 cases, all children had bruising, 9 children had fractures, 4 had permanent sequelae such as hemiparesis, and 3 died. In all 11 cases, the stair fall was deemed a false history; in most cases, the person who harmed the child confessed to fabricating the stair-fall history.

A current lack of biomechanical understanding of femoral fractures among children makes differentiation between abusive and nonabusive fractures more difficult. Because fracture type alone cannot distinguish abusive from nonabusive trauma,[11] an objective method for injury assessment is needed. No objective injury assessment tool currently exists that provides quantifiable data for evaluating plausibility of injury in the acute setting. Our study goals were to (1) conduct a prospective clinical study to characterize femur fractures associated with a stair-fall history, (2) develop an objective clinical tool to assess injury plausibility (IP) from our case-specific data, and (3) characterize more completely the biomechanics associated with femur fractures resulting from a stair fall among children.

Our study hypothesis was that quantifiable and significant differences exist between femur fractures resulting from inflicted versus noninflicted trauma. Specifically, we hypothesized that differences exist in 4 key categories: (1) history quality and detail; (2) biomechanical compatibility of the fracture morphologic features; (3) time line for seeking medical care; and (4) presence of other injuries. To test this hypothesis, we derived a measurement tool referred to as the IP model, to allow numerical scoring of each of these 4 categories.

METHODS

Study Group and Data Collection

This study was approved by the Human Rights Committee of Children's Hospital of Pittsburgh. We conducted a prospective study to evaluate cases of femur fractures associated with a history of a stair fall. Children 0 to 5 years of age who presented to Children's Hospital of Pittsburgh were eligible for the study. To avoid selection bias and circular logic, all cases of femur fractures with an associated history of a stair fall were included in the study. No assumptions of abuse were made on the basis of the fracture type and associated history of a stair fall. Detailed history recording, physical examinations, and fracture and injury scene analyses were conducted. Information collected included age, race, ethnicity, gender of the patient, witnesses to the event and their relationship to the child, description of immediate symptoms, time to seeking care, and presence and location of skin injuries such as bruising or abrasions. When possible, an alternative light source (Wood's lamp) was used to examine the skin before cast placement. Also documented were the results of any additional studies, such as skeletal surveys, computed tomographic (CT) scans, and blood work, and whether the hospital child protection team (CPT) was consulted. Each case was categorized with empirical criteria used commonly for categorizing potential abuse cases,[11–14] to rate the likelihood that the fracture was attributable to accidental/noninflicted injury. Criteria for fracture categorization were published previously[11] and were clarified by Leventhal et al.[12] According to these criteria, cases were grouped as definite or likely abuse, questionable, or definitely or likely accidental. Specifically, the category of definitely noninflicted/accidental required that the account was corroborated by noncaretaker adults or that the injury occurred in a public setting. The category of likely noninflicted/accidental required that (1) the fracture and history were consistent, (2) the story was consistent and thorough, and (3) the behavior after the injury was consistent with the type of fracture.[11,12] The definite abuse category for our study required a confession of abuse.

Our multidisciplinary research team included specialists in pediatric emergency medicine, orthopedics, radiology, child abuse injuries, biomedical engineering, and statistics. Radiographs were reviewed for detailed fracture descriptions by a pediatric orthopedic surgeon and a pediatric radiologist. Both were blinded to the history and injury details, race, presence of other injuries, results of any additional testing performed, CPT consultations and conclusions, and Leventhal criteria. The study's biomechanical engineers conducted biomechanical analyses of the injury events and provided input concerning the match of fracture morphologic conditions and loading conditions.

The IP Model

Scoring

A nonweighted ordinal scale of measurement ranging from 0 to 12, with 0 representing the most plausible score and 12 representing the least plausible score, was developed for data quantification and analysis. The IP score is a composite scoring of 4 categories: (1) history details; (2) biomechanical compatibility of the fracture morphologic features; (3) time to seeking care; and (4) other injuries. Each category scores 0 to 3 points on the basis of the case-specific findings. Specific criteria used for scoring each of the 4 categories are presented in Table 1. The proposed model was applied to our database retrospectively. Each case was scored with the IP model by 2 emergency medicine physicians (M.C.P. and S.H.) who were also trained in child abuse injuries, independent of the Leventhal criteria. IP model scoring results were then compared with results from categorization with the Leventhal criteria.

TABLE 1. IP Model Scoring Criteria

Category	0 Points	1 Point	2 Points	3 Points	IP Score
I: HQS, 3 fall components: initial position, fall dynamics, and final position	Fully describes all 3 fall components	Describes 2 of 3 fall components	Describes only 1 fall component	Unable to describe details of any of fall components or no trauma history or changing history	
II: Fracture, see Table 2 for biomechanical match criteria	History accounts for fracture mechanism and observed leg biodynamics	History accounts for fracture mechanism but leg biodynamics not observed	History does not account for fracture mechanism	History does not account for fracture mechanism and fracture is comminuted, open, or CML	
III: Time	Sought care immediately	Delay in seeking care but fracture is clinically and radiographically subtle and well aligned	Delay in seeking care and fracture is clinically and radiographically obvious	Delay in seeking care and has respiratory, cardiovascular, and/or neurologic compromise	
IV: Additional findings/injuries in initial examination	No other injuries (skin or fractures on initial radiographs)	1 additional injury	2 additional injuries	≥3 additional injuries	
					Total IP score

Category I

A history quality scale (HQS) was developed to help quantify the richness and degree of detail the caretaker was able to provide about the actual fall. The history was subdivided into 3 quantifiable components: (1) the initial position and location of the child before the fall; (2) the fall dynamics; and (3) the final position and location of the child after the fall. One point was added for each history component the caretaker was unable to describe in detail. The account was also classified on the basis of the type of observation. This classification was adapted from a Primary Caregiver Account Classification method described by Kent Hymel, MD (verbal communication, 2002). Hymel identified the type of observation made by the caretaker as follows: a direct observation if the fall was observed directly, an indirect observation if the event was heard but not observed directly, a deduction if the event was not observed directly but objective factors led to the conclusion, and a speculation if the event was not observed or heard but an assumption was made about the cause of injury.

Category II

For fracture characterization, the biomechanical analysis of the injury event, relative loading conditions, and radiographic findings were compared for compatibility and then scored. We sought to identify whether the fracture morphologic characteristics reflected the biomechanics and biodynamics described by the history.[15] Criteria used to identify a biomechanical match are presented in Table 2. Of note, 3 points were scored if the fracture load type was not accounted for by the history and the fracture type was classified as a high-risk fracture for abusive trauma (classic metaphyseal lesion [CML])[16,17] and/or a high-energy fracture (open and/or comminuted).[16–18]

Categories III and IV

Time to seeking care was defined as the time from the reported stair fall to the time of the first call to a medical professional and/or the time to presenting for medical care. Other injuries/external findings included erythematous marks, bruises, abrasions, cuts, mucosal, nasal, and scleral injuries, and soft-tissue swelling other than at the femur fracture site. It should be noted that the other injuries category scoring did not include findings of additional studies such as CT scans or skeletal surveys.

Biomechanical Fracture Analyses

A secondary goal of this study was to characterize more thoroughly the biomechanics associated with fractures among children. Biomechanical measurements, including potential energy, kinetic energy, and linear momentum, which are known to be associated with injury risk, were calculated from injury scene and child-specific data. To obtain data for biomechanical calculations, scene analyses documented the number, slope, and type of stairs, the type of covering on the stairs, whether the stairs were slippery, the type of landing, the distance fallen, and objects or parts of the stairway struck during the fall. Biomechanical measures were derived by considering the child's weight and height, the distance fallen, and, in cases in which the child was being carried, the caretaker's weight and height and the distance from the child's held position on the caretaker to the ground. The following biodynamic measures of potential energy, kinetic energy, and linear momentum were estimated for each fall, ie, potential energy = mgh, kinetic energy = $\frac{1}{2}mv^2$, and linear momentum = mv. In these equations, m is mass, g is 9.812 m/second^2 (gravitational acceleration), h is the height of the fall, and v is impact velocity. Impact velocity was calculated as an uninterrupted free fall from the center of mass of the child to the first step of impact (according to the law of conservation of energy). In cases in which a caretaker was involved, his or her mass was taken into account as appropriate for calculation of potential energy and kinetic energy; the mass of the caretaker was taken into account only if he or she impacted (landed on) the child. The center of mass of the child was assumed to be at one half the height of the child. In cases in which a caretaker was holding the child, it was assumed that the child's center of mass was at two thirds the height of the caretaker. In cases in which the height of the caretaker was unknown, it was assumed to be of the 50th percentile (male or female). In the rare cases in which the height or mass of the child was unknown, the child was assumed to be of the 50th percentile for his or her age group. In the few cases in which the step dimensions were not known, steps were assumed to meet average building code step dimensions (8-inch rise or stair height and 10-inch run or stair depth).

Data Analyses

The primary statistical comparisons involved examination of differences in the IP category scores between corroborated noninflicted cases and definite confessed abuse cases, in which the caretaker fabricated the stair-fall history in an attempt to account for the injury. For the IP categories as a continuum, either an analysis of variance or a Kruskal-Wallis test was used, depending on the meeting of the statistical assumptions. The IP category scores were also categorized into 0 or other (1–12), and these between-group differences were examined with either a χ^2 test or a Fisher's exact test. Other variables of interest, such as CPT consultations, race, fracture type, fall type, patient mass, patient age, and biomechanical measures, were analyzed with a similar data analytic approach (ie, analysis of variance for continuous outcomes and χ^2 test for categorical outcomes, where appropriate). Statistical significance was set at $P \leq .05$. The sample size used for this study provided for detection of statistically significant differences ranging from 15% to 40% for the various subgroups as well as the overall comparisons, with a nondirectional α of .05 and a statistical power ranging from 0.80 to 0.84, respectively.

RESULTS

Study Group

Between 1999 and 2002, 189 children between the ages of 0 and 5 years were diagnosed with a femur fracture; 29 cases were associated with a history of a stair fall. These 29 patients constituted the study

TABLE 2. Criteria for Determining Biomechanical and Fracture Type Compatibility (Biomechanical Match)

Biomechanical Conditions[15]	Fracture Types	Biodynamic History Examples
Torsional loading	Spiral/long oblique	Twisting or rotation of leg as child slips and leg folds underneath body
Bending load	Transverse/short oblique	Perpendicular impact of leg such as leg caught between stair and caretaker
Compressive loading	Buckle/impaction	Knee impacts along longitudinal axis of femur as child falls down stairs
Tension and/or shear loading	CML	Pulling or yanking of leg
High-energy event (any loading condition)	Open and/or comminuted	Pedestrian leg impacted by fast-moving vehicle

group; they ranged in age from 2 to 36 months, with 21 white children and 8 black children. In 17 cases, the stair fall reportedly occurred with a caretaker carrying the child; in 12 cases, the children reportedly fell by themselves. One of the individual falls was in a walker.

The IP Model

Overall Scores

A distinction was observed between those with an IP score of ≤3 ($n = 25$) and those with a score of ≥6 ($n = 4$). Table 3 provides individual category and total IP model scores, with details that include age, whether the child fell with the caretaker or alone, HQS rating, fracture morphologic features, whether a delay in seeking care occurred, a fall description, and a listing of other injuries. Table 4 provides summary results of cases with lower IP scores (≤3), designated the plausible group, and higher IP scores (≥6), designated the suspicious group. The same 25 cases that achieved lower IP scores (0–3) were also categorized independently as likely or definitely accidental according to the Leventhal criteria. Four cases were categorized as questionable, likely, or definite abuse according to the Leventhal criteria; these same 4 patients also received higher IP scores of 6, 8, 11, and 12. Figure 1 presents the number of cases with each IP model score and comparisons with categorization according to Leventhal criteria. It should be noted that 2 caretakers in the suspicious group (those with the highest IP scores of 11 and 12) later confessed to causing the child's injuries and fabricating the stair-fall event.

HQS (Category I)

In 25 (86%) of 29 cases, the details of the event were graphic, clear, and easy to recall for the caretaker providing the account of the injury event. Of these 25 cases, 22 were said to be direct observations and 3 were indirect observations, scoring 0 and 1, respectively, on the basis of the amount of detail provided. In all 25 cases, the third component (description of the final or landing position of the child) was provided readily with clear details. Of all components, this was the one the caretakers seemed to recall the best. In 4 (14%) of 29 cases, the event was said to be a direct observation but details regarding position and fall could not be provided and the third component could not be described with details of the final body position and location in relation to the stairs.

Fracture Morphologic Features and Mechanisms (Category II)

Fracture types in this study were buckle ($n = 17$), transverse ($n = 7$), spiral ($n = 4$), and CML ($n = 1$). For 25 of 29 patients, the fracture morphologic features and history were consistent with biomechanical loading conditions. Therefore, on the basis of IP criteria, these cases were considered to be biomechanical matches. For the remaining 4 cases, no biomechanical match could be ascertained. The level and type or direction of loading likely needed to cause the observed type of bone failure could not be determined from the history. Of interest, 3 of the 4 cases in the suspicious group had transverse fractures (IP scores of 6, 8, and 11). One child was reported to be walking after the fall, despite a significantly angulated, transverse, comminuted fracture. The caretaker later confessed to fabricating the information. In the plausible group, 4 of 25 cases involved a transverse fracture (IP scores of 0, 0, 0, and 1), and each resulted from the caretaker falling onto the child's leg. Figure 2 presents fracture morphologic features and associated mechanisms of injury.

Delay in Seeking Care (Category III)

Caretakers sought medical care immediately in 19 of 29 cases, with a delay occurring in 10 (34%) cases. Of the 10 patients with a delay, 7 were children with buckle fractures, good alignment, and minimal or no impaction, all in the distal one third of the femur. These children displayed little or no localizing symptoms at the time of presentation and received a category score of 1. All 7 had total IP scores of ≤3, and the time to seeking care was 6 hours ($n = 1$), 12 hours ($n = 4$), and 24 hours ($n = 2$). The remaining 3 cases were children with a transverse fracture ($n = 2$) or a CML ($n = 1$) and were noted to be in severe pain at the time of presentation. Time delays were 6 hours, 12 hours, and >24 hours, with total IP scores of 8, 11, and 12, respectively. In all 3 of these cases, care was sought because of the concerns of a person different from the one present at the time of injury.

Presence of Additional Injuries in the Initial Examination (Category IV)

Of 29 patients, 18 (62%) had no external findings, 7 (24%) had a single isolated bruise, 2 (7%) had 2 bruises, and 2 (7%) had ≥3 bruises. For children in the plausible group, only 7 (28%) of 25 patients had a bruise/abrasion at any location, no patient had >2 bruises, and the only patient with a bruise in 2 regions was the child with the walker-related injury. This is in direct contrast to the patients in the suspicious group, in which 100% of patients showed bruising ($P = .055$, Fisher's exact test) and both confessed abuse cases had ≥3 bruises.

IP Model Performance

Comparisons were made between IP model category scores of cases classified with Leventhal criteria as accidental that were corroborated by >1 adult and those classified with Leventhal criteria as definite abuse for which a confession of abuse was later obtained. Significant differences (Fisher's exact test) were present between the IP category scores for the corroborated accidental versus confessed abuse cases for category I (HQS and amount of detail provided) ($P = .002$), category II (biomechanical compatibility of the fracture with described injury mechanism) ($P = .002$), category III (time to seeking care) ($P = .005$), and category IV (additional external/skin injuries) ($P = .005$), as well as for total IP model scores ($P \leq .001$, independent t test or Mann-Whitney U test).

As noted previously, additional tests such as skeletal surveys and CT scans were not part of the IP score. Results of any additional testing were ana-

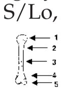
TABLE 3. Stair-Fall Categories

Age, mo	Category I		Category II, Fracture Features			Fall Dynamics	Category III, Delay	Category IV, Other Injuries	IP Score
	Fall Type	HQS, IP Score	Type, IP Score	Region	Alignment				
6	P-C	DO, 0	B/I, 0	4	G/ND	Adult fell while carrying infant in her left arm on her left hip; infant facing adult initially but during fall, infant's back arched over adult's arm, infant's leg went under her during fall	No, 0	No, 0	0
7	P-C	DO, 0	B/I, 0	4	G/ND	Adult fell while holding infant on hip; adult hit back hard on step and child hit her left leg on step at same time	Yes, 1	No, 0	1
7	P-C	DO, 0	B/I, 1	4	G/minor PD	Adult stepped on toy, fell, and slid down with child in her arms; chest to chest the entire time	No, 0	No, 0	1
7	P-C	DO, 0	B/I, 0	4	G/ND	8-y-old sibling fell and slid down on his back while carrying child; infant flipped over his arms and was caught by her legs in a jerking motion	No, 0	No, 0	0
8	P-C	DO, 0	B/I, 1	4	G/ND	9-y-old sibling slipped and fell walking down steps and dropped child	Yes, 1	Abrasion R thigh, 1	3
8	P-C	DO, 0	B/I, 0	4	G/ND	9-y-old sibling held child with arm under infant's buttocks and other arm/hand around infant; sibling slipped on coat, fell, landing on buttocks, and slid down steps while still holding infant; infant's knee hit molding	Yes, 1	Bruise line on knee,† 1	2
9	P-C	DO, 0	B/I, 1	5	G/ND	Adult tripped and fell, landing on buttocks while still holding child	No, 0	No, 0	1
10	P-C	DO, 0	B/I, 1	4	G/ND	Adult slipped, fell onto buttocks, and slid down while carrying child; heard child hit rail but unsure what part hit	No, 0	No, 0	1
10	P-C	DO, 0	B/I, 1	4	G/ND	Adult holding infant in her arms, face to face on adult's left side when she fell; adult pulled infant more on top of her as they fell; adult landed on tailbone; infant fell to the side, possibly hitting head	No, 0	No, 0	1
11	P-C	DO, 0	B/I, 1	4	G/ND	Adult fell and dropped child; child landed on third step and reportedly hit wall	Yes, 1	No, 0	2
13	P-C	DO, 0	B/I, 0	4	G/ND	Adult slipped and fell to the left; child's leg hit step	Yes, 1	No, 0	1
8	P-I	IO, 1	B/I, 0	5	G/minor PD	Child fell down steps in walker; child landed, still in walker, with head up against wall and knee resting on landing; 10 steps	No, 0	Brush burn on neck, 2 lines on knee,† 2	3
9	P-I	DO, 0	B/I, 1	4	G/ND	Child fell down stairs and was examined for head injury; infant noted to be irritable but no focal tenderness found and patient was discharged; retuned 24 h later with refusal to crawl; 12 steps	No, 0	2 cm linear bruise on forehead, 1	2
10	P-I	IO, 1	B/I, 1	4	G/Minor PD	Child fell down landing on stomach; adult at bottom of stairs but reported not hearing bouncing; found child at her feet perpendicular to stairs; 13 steps	No, 0	No, 0	2
10	P-I	DO, 0	B/I, 1	4	G/Minor PD	Child fell down head first with arms out in front landing on ceramic floor on stomach; reported child crawled to steps, leaned onto steps, and fell down without tumbling; 13 steps	Yes, 1	Swelling over vertex, 1	3
12	P-I	IO, 1	B/I, 1	2	G/ND	Child fell down and off to the side of steps; adult found child on stomach beside stairs and reported he fell off and did not roll all the way down; 14 possible steps	No, 0	Bruise over bridge of nose, linear, 1	3
17	P-I	DO, 0	B/I, 0	4	G/ND	While playing on outside porch, child and cousin fell down together; cousin was pulled down on top of child as they fell; landed on knee; 4 steps	Yes, 1	No, 0	1
31	P-C	DO, 0	S/Lo, 0	3	Complete fracture overlap	14-y-old sibling carrying infant on right hip; slipped on piece of clothing and fell backward with infant's leg between her and steps	No, 0	Small abrasion L knee, 1	1

TABLE 3. Continued

Age, mo	Category I		Category II, Fracture Features			Fall Dynamics	Category III, Delay	Category IV, Other Injuries	IP Score
	Fall Type	HQS, IP Score	Type, IP Score	Region	Alignment				
20	P-I	DO, 0	S/Lo, 0	3	Complete fracture overlap	Adult was walking down with child and child fell behind her in split position with leg caught in banister rungs; 3 steps	No, 0	No, 0	0
20	P-I	DO, 0	S/Lo, 0	3	Complete fracture overlap	Child was walking up steps, put right leg up, and slipped on wet step; child fell with right leg bent back and to the side and left leg still propped on step in split; 2 steps	No, 0	No, 0	0
30	P-I	DO, 0	S/Lo, 0	3	G/ND	Child was walking down when he overstepped with his left foot; as child fell forward, his right leg stayed back in split position; 3 steps	No, 0	No, 0	0
3	P-C	DO, 0	T/So, 0	3	Complete fracture overlap	Adult slipped and fell while carrying infant against her chest; infant arched backward, landing on adult's legs, infant facing up, with adult still holding infant's legs	No, 0	No, 0	0
9	P-C	DO, 0	T/So, 0	3	Complete fracture overlap	Adult twisted left ankle; fell backward to the right onto steps while carrying child sidesaddle on right hip; child's leg was pinned under her	No, 0	No, 0	0
10	P-C	DO, 0	T/So, 1	3	Complete fracture overlap	13-y-old cousin slipped, fell, and slid down to bottom while holding infant up to take most of fall; infant was still in her arms after fall	No, 0	No, 0	1
29	P-C	DO, 0	T/So, 0	3	Complete fracture overlap	Adult boyfriend fell backward while carrying child piggyback; child's leg was wrapped around adult's torso during fall; adult fell onto child's leg	No, 0	No, 0	0
15	S-I	DO, 2	T/So, 2	3	Complete fracture overlap	Adult reported that child fell down wooden stairs onto wooden landing; could describe stairs but could not describe fall dynamics as how child landed (language barrier; said child landed at bottom but could not describe or demonstrate details)	No, 0	Bump on head; possible rib fracture, 2	6
10	S-I	DO, 2	T/So, 2	3	Complete fracture overlap	Child was crawling up carpeted starts in front of sibling with adult following behind; said child fell backward but could not explain where she or other child was in relation to the fall or direction child ended up; said child's leg might have twisted but unable to explain; fall dynamics do not account for required fracture mechanism	Yes, 2	Small bruise on forehead; R knee bruise, 2	8
36	S-I	DO, 3	T/So, 3	4	Comminuted 45°	Adult reported that child fell down wooden steps; F*; could not describe beginning position of child, how child fell, how he landed, or how child got to the couch	Yes, 2	Bruising on face, R and L legs, back, 3	11
2	S-C	DO, 3	Bilateral CMLs: R, CML, L, CML, 3	5, 5		Adult recalled tripping and hitting infant's head on doorknob on way up stairs and then recalled dropping her; F*; could not describe how he tripped, how he was holding child, or how child hit/landed; fall dynamics do not account for required fracture mechanism	Yes, 3	Multiple bruises on face, neck, back, and ear (proximal R tibial fracture, distal L tibial fracture, skull fracture, SDH with shift, RH), 3	12

IP scores: individual category scores are shown; fall type: C, fall with caretaker; I, individual fall; P, plausible group; S, suspicious group; HQS: DO, direct observation; IO, indirect observation; type: B/I, buckle/impaction; S/Lo, spiral/long oblique; T/So, transverse/short oblique; region:
metaphyseal proximal
diaphyseal mid-shaft
metaphyseal distal



alignment: G, good alignment; ND, nondisplaced; PD, posterior displacement; fall dynamics: F*, stair fall fabricated; confessed to conflicting injuries; other injuries: SDH, subdural hematoma; RH, retinal hemorrhage. Findings in parentheses were injuries not used for IP model scoring.
† Alternative light source used for observation.

TABLE 4. Summary of Study Results

	Fall Type, no.		Median Age, mo (Range)	Reported Fall During Ascent, no. (%)	No. of Cases With Additional Studies Performed (Positive Findings)
	Caretaker ($n = 17$)	Individual ($n = 12$)			
Low IP score of <3 (plausible group)	16	9	10 (3–31)	1/25 (4)	9/25 (0/9)
High IP score of ≥6 (suspicious group)	1	3	12.5 (2–36)*	2/4 (50) ($P < .01$)†	4/4 (3/4) ($P = .024$)

* Confessed to inflicting child's injuries.
† Statistically significant.

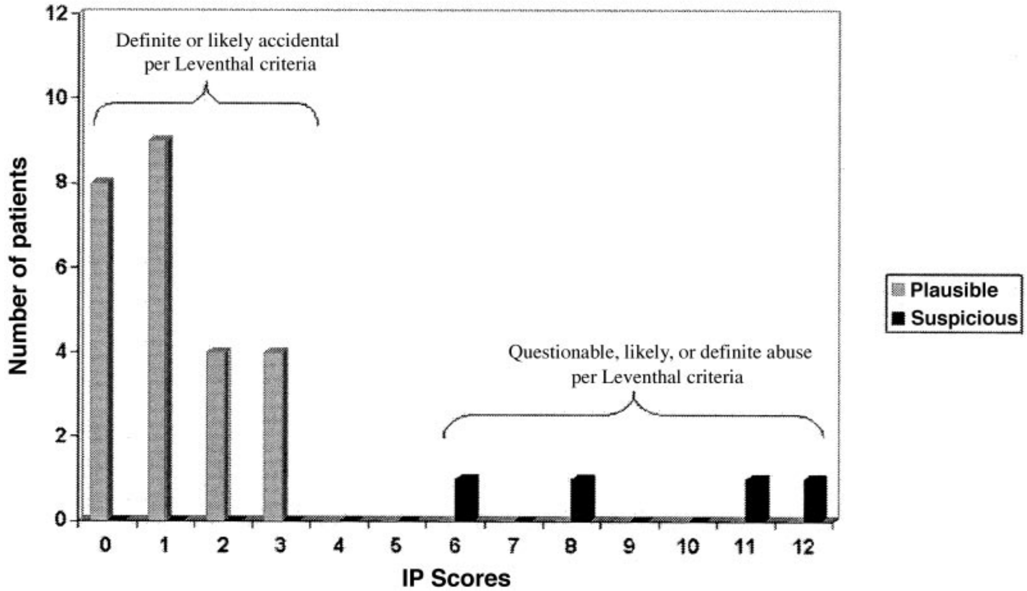


Fig 1. IP model scores, compared with categorization according to Leventhal criteria.

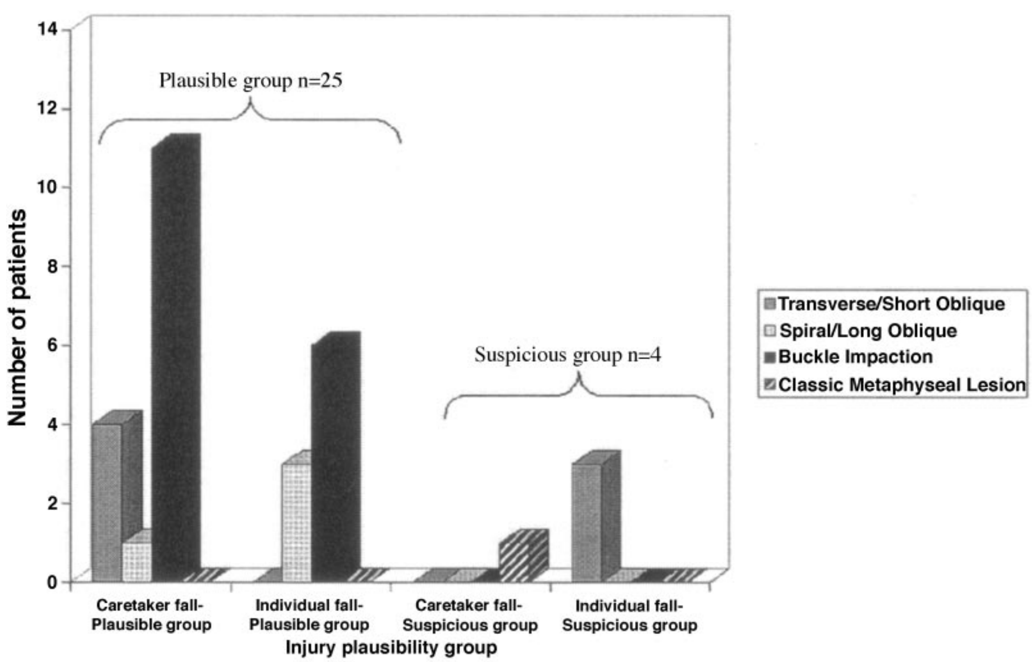


Fig 2. Number of fracture types associated with caretaker and individual falls for plausible and suspicious injury groups.

lyzed and compared with IP score results. Twelve additional studies were obtained for 9 of 25 patients in the plausible group (IP scores of ≤3), including 4 head CT scans and 4 skeletal surveys. There were no additional positive findings. All 4 patients in the suspicious group (IP scores of ≥6) received additional testing, including 4 skeletal surveys, 2 head CT scans, and 2 blood laboratory evaluations. In contrast to the plausible group, 75% of cases in the suspicious group had additional positive findings (P = .024), which included brain injury (n = 1), a skull fracture (n = 1), rib fractures (n = 2), and a liver contusion (n = 1).

Biomechanical Characterization of Fractures and Injury Events for the Plausible Group

The child's age was correlated with fracture type, with spiral fractures being more likely to occur among children >12 months of age and buckle fractures being more likely among children <12 months of age (P = .003). The number of stairs the child fell down tended to be greater when the child fell alone, ranging from 4 to 15 stairs, than when the fall occurred with the caretaker, with the stair number ranging from 1 to 8 (P = .0312). Buckle and spiral fracture types were correlated significantly with the number of steps for individual falls (P = .037), with 4 to 15 steps for buckle fractures and only 1 to 3 for spiral fractures. All individual falls resulting in either spiral or buckle fractures had lower associated energy levels than did falls with the caretaker resulting in spiral or buckle fractures. All fracture types resulting from a fall with the caretaker had greater associated biomechanical measures; therefore, there was greater injury potential as a result of falling with the adult (Fig 3). The variation in linear momentums among the cases of caretaker falls was attributable in part to the variability of the weights of the caretaker and the patient. The number of steps involved in the fall was known in all except 2 of the fall accounts in the plausible group, and the step dimensions were also known in most cases. For 23 of 25 cases in the plausible group, enough information was obtained from the history, injury scene analysis, and child examination to allow a biomechanical estimation of the fall event. For those cases, all midshaft transverse fractures with complete displacements had higher associated minimal linear momentums (250 mg/millisecond), compared with the minimal momentums for spiral (30 mg/millisecond) or buckle (10 mg/millisecond) fractures. When the child's fall also involved the caretaker, the available energy to cause injury varied, as did the fracture type, depending on the interaction of the leg with the fall environment and the caretaker. Figure 3 presents associated linear momentums categorized according to injury mechanism and type of fracture. IP model scores for each case are also included. Of note, no biomechanical estimations were performed for 2 cases in the plausible group for which the exact number of stairs involved in the fall was unknown, and for the 4 suspicious cases, because of the ambiguity of detail provided by the caretakers with respect to the fall dynamics.

All except 4 of the stairways were carpeted in the plausible group. In-home stair slopes were typically 8:8 (8 inches deep and 8 inches high), but the stair slope recommended by building codes was exceeded in 2 cases, resulting in a steeper slope. Stair surface varied from concrete to wood to carpet and did not correlate with fracture type or severity. In 2 cases, the carpeted stairs were noted to be extremely slippery because of their frequent use as an "indoor slide."

DISCUSSION

Previous Studies

When a young child presents with a significant injury such as a femur fracture and the history is a stair fall, a determination must be made regarding IP. This judgment is made more difficult by a current lack of biomechanical understanding of injury tolerance among children. Few studies exist that focus on the injury potential of stair falls. Joffe and Ludwig[8] conducted a retrospective study evaluating injuries among children who fell down stairs. In their report, they described a stair fall as 1 major fall followed by a series of smaller, low-energy falls. There were no

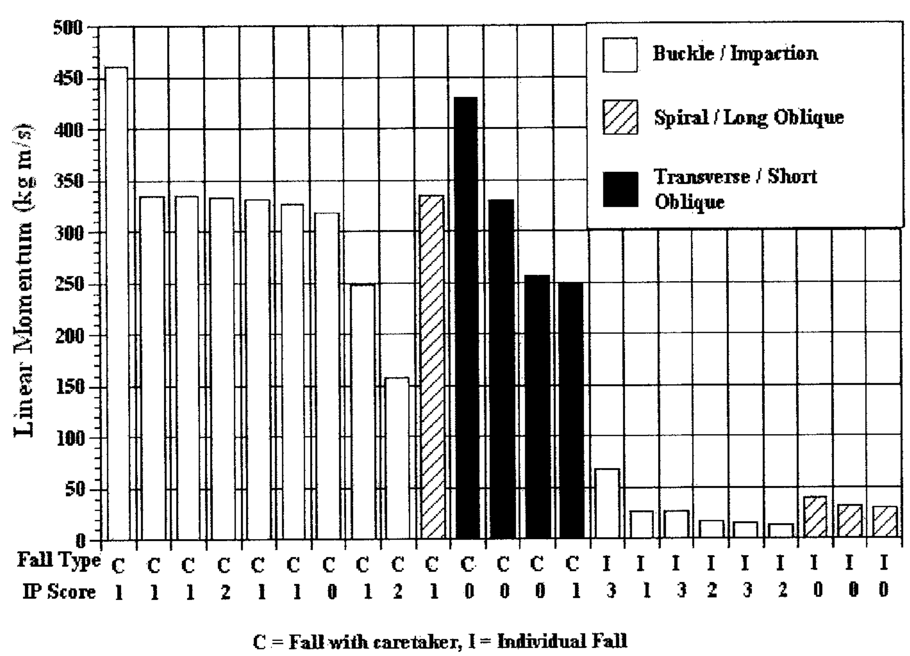


Fig 3. Plausible group biomechanical measures of linear momentum and fracture types.

cases of femoral fracture in their study of 363 cases of stair falls among children. Chiaviello et al[7] conducted a prospective study of stairway-related injuries among 69 children and also found no cases of femur fractures. Unlike in those studies, we did find cases of lower proximal extremity fractures in our series. More severe fracture types were observed when the fall involved additional weight (falling with the caretaker). Both aforementioned studies also described increased severity of injury when falls involved the caretaker.[7,8] Bertocci et al[19] conducted a study of stair falls among children by using a computer simulation model to investigate the influence of stair characteristics on injury biomechanics. That study found the number of stairs, type of stairs, and stair slope to have a significant influence on key biomechanical measures associated with injury risk. Such studies augment current knowledge, but additional work is still needed.

To our knowledge, no injury assessment tool exists that identifies objectively the factors associated with plausible versus suspicious injuries among children. Previous studies developed criteria to help categorize retrospectively abuse from accidents,[11–14] by defining criteria for definite, likely, and questionable categories for abusive trauma. Our model differs from previous criteria by providing a tool that quantifies case-specific injury data at the time of presentation. Such a tool can aid clinicians in acute treatment settings in assessing plausibility and identifying the need for additional investigation. Our study identified 25 cases of femur fractures associated with a history of a stair fall in which the history and injury details were deemed plausible and 4 cases that raised concerns regarding abusive trauma. Physicians can use data from this study to augment the current understanding of injury likelihood from stair falls.[7–9] In addition, this information can be used to aid in evaluating the likelihood of a specific fracture type occurring from a given stair-fall event and provides a database of stair-fall injuries for comparative analysis. The model does not propose to diagnose abuse or innocence but rather provides a continuum of plausibility.

History

In our study, we noted that a parent often presents with the simple history of a stair fall and additional questions, aimed at injury reconstruction, can identify factors that might contribute to the injury potential. In a few cases, these additional questions resulted in vague answers rather than an increased understanding of how the injury occurred. In the study by O'Neill et al[4] evaluating patterns of injury among abused children, 95% of initial histories were false. Leventhal et al[12] found that, in cases of abusive fractures, the caretaker histories were often vague and without detail. Hettler and Greenes[20] found that certain historical features can be highly predictive for diagnosing child abuse. Of interest in our study was the finding that the histories in the suspicious group did not seem vague initially. However the caretaker was unable to answer any specific questions about body position or location for any of the 3 components of the HQS. In all of the plausible group cases, the caretakers were able to provide precise details about the fall and especially about how the child landed and the child's final position and location relative to the steps. In the suspicious cases, details were often about the stairs or the wall, rather than about the child and the fall. Focusing on the 3 fall components may help guide biomechanical consideration of the event and likely fracture mechanisms. This may also help differentiate a fabricated story from an actual mishap.

Fractures

Our fracture analysis was based on the fact that a "specific fracture pattern results from a specific type, direction and magnitude of loading forces."[21] For the plausible group, different fracture types resulted when the child fell with the caretaker, compared with when the child fell alone (Figs 2 and 3). Typically, a buckle fracture results from failure in compression.[15] When the fall is such that the child's knee impacts the stair or molding, it is hypothesized that an axial load causes a compressive force, leading to a buckle fracture. Support is given to the knee impact theory in a study by Vogeley et al,[22] in which a bruised knee and point of impact were identified through the use of an alternative light source for a patient with a buckle femur fracture resulting from a stair fall with the caretaker. For individual falls, compressive forces may be generated in the initial larger-magnitude fall to the first step, as suggested by the stair-fall model proposed by Joffe and Ludwig,[8] or may result at the time of landing, when momentum is greatest and a sudden stop occurs.[19] For example, in 2 of our cases, caretakers reported that the children "flew off" the last 2 or 3 steps and landed on their stomachs, with knees down. Torsional loading results in spiral failure of bone.[15] In all cases in which the adult reported the dynamics of the fall as 1 leg folding or twisting underneath, the fracture type was spiral. In our stair-fall study, spiral fractures were observed only among walking patients.

When the caretaker described landing on the child's leg with the leg pinned between them and the stair, the common resultant fracture type was a displaced, midshaft, transverse or short oblique fracture. The described bending and direct impact forces resulted consistently in midshaft transverse fractures, identified as a direct biomechanical match (Table 2). With the distance of the fall and the added weight of the parent falling with the child, a load is generated that exceeds the injury threshold of the femur. In 3 cases, the fall dynamics were described as follows. The infant was being held facing the caretaker (prone), with the right hand of the adult holding the thigh of the infant and the left hand supporting the back of the child. The adult missed a step, which resulted in the adult falling backward and the child falling forward, to a position in which the child's head was toward the feet of the adult and the infant's front was facing upward (supine). In all cases, the caretakers stated that they did not let go of the infant's thigh but rather jerked the infant forward during the fall, to keep from dropping the child.

Other adult witnesses corroborated the fall dynamics. In each case, the fracture occurred in the thigh that was being held during the fall; the fractures were distal buckle fractures with posterior displacement ($n = 2$) or a midshaft, displaced, transverse fracture ($n = 1$). All 3 infants had no other injuries and no other findings to suggest abusive trauma.

Fracture Biomechanics

In the plausible group, transverse and short oblique fractures were associated with almost 10-fold higher injury biomechanical measures than the minimal measures for spiral and buckle fracture types. No transverse fractures occurred from mechanisms associated with lower energy levels, such as when the child fell alone. In 3 of the 4 suspicious cases, the fracture type was transverse. Of note, in the suspicious case in which the transverse fracture was also comminuted, the caretaker later admitted to throwing the child into an object. Scherl et al[5] reviewed 207 diaphyseal femur fractures among children ≤6 years of age that resulted from a wide range of mechanisms. Their study showed that spiral fractures were viewed as suspicious for abuse but transverse fractures were just as likely to result from abusive trauma. King et al[3] studied 429 fractures among 189 battered children and found the fracture type to be most commonly transverse (48%) and less commonly spiral (26%). In our study of femur fractures associated with a history of a stair fall, transverse fractures were more concerning for abuse than were spiral or buckle fractures. All spiral fracture cases in our study were considered to be plausible.

Time

Daley and Calvert[23] reported 3 cases of a distal buckle femur fracture that resulted from a caretaker falling on the stairs while carrying a child. They described a delay in seeking care associated with this fracture type. Our study found similar results. In the plausible group, all 7 cases of a delay in seeking care were associated with a buckle fracture that resulted from the caretaker falling with the child. In many of these cases, both the parent and the medical care provider did not realize the leg had been injured until ≥24 hours had passed. We think this delay in seeking care reflected a delay in the development of localizing symptoms and was not an indication of child abuse.

Other Injuries

A person who injures a child may sometimes fabricate a history of a stair fall as an explanation for the injuries. Previous studies documented that stair falls do not cause significant injury to >1 body region and that injuries such as proximal extremity and truncal injuries do not occur typically.[7–9] However, it is a common belief that a stair fall can cause multiple injuries, such as multiple bruises, to a child. The study by Joffe and Ludwig[8] of stairway-related injuries found that children who fell >4 steps did not have an increased likelihood of injury or injury severity, compared with those who fell <4 steps. We also did not find multiple injuries. No child in the plausible group injured >1 body region significantly; specifically, no child had a second fracture or a life-threatening brain or truncal injury in addition to his or her femur fracture. Of interest, the children in both confessed abuse cases had >3 bruises, whereas almost all of the corroborated nonabuse cases had no bruises, despite falling down multiple stairs. Our study supports the evidence that stair falls do not result in multiple injuries or even multiple bruises.

The treating physicians determined the need for additional studies and involvement of the hospital's CPT. In all cases in which the initial assessment resulted in an IP score of ≤3, no additional internal injuries were identified. In 3 of 4 cases with an IP score of ≥6, adjunct studies revealed additional findings. This supports the concept of our model functioning as a screening tool for initial assessments and aiding in distinguishing abusive from nonabusive trauma. However, not all patients in the plausible group received adjunct studies, because this was at the discretion of the attending physicians evaluating the patient. There is the possibility that other injuries would have been identified if all patients had undergone additional testing.

The limitations of our study include the possibility that we underdiagnosed abusive trauma in cases of stair falls. Apart from videotaped or public, witnessed events, there is the chance that an actual abuse case has been categorized as plausible. In an attempt to address this limitation, we included details of each case in Table 3, so that readers can better understand the reasoning behind the specific case scoring and categorization. We sought to avoid circular logic by not categorizing cases according to current assumptions about specific mechanisms or fracture types but rather assessing plausibility on the basis of specific measures in 4 categories. In addition, for IP model analysis, corroborated nonabuse cases were compared with confessed abuse cases. We do not imply that this or any model is a diagnostic test for abuse. We sought to identify factors that would help define plausible and suspicious cases of injury. Our study aim was to quantify categories that rely traditionally on more qualitative injury assessments. By quantifying these factors into a summary score, this model allows for the constellation of findings to be incorporated into a single assessment tool. The intent of such a model is to provide examining clinicians with a more objective decision-making tool concerning the need for additional investigations, such as a skeletal survey, or involvement of Child Protective Services. A second limitation is related to the biomechanical analyses of the injury mechanisms. Assumptions were made in each case for calculation of biomechanical measures. Injury scene analyses and investigations and child-specific anthropometric measurements were obtained to improve the accuracy of data for biomechanical calculations. The calculations were still, however, only estimations of the biomechanical measures associated with each injury event. A third limitation is our small study cohort. We chose to study a focused type of injury and mechanism, to compare and to characterize more effectively key features associated with

IP. This resulted in a much smaller number of patients. Larger numbers might very well result in different injury patterns and fracture types. Additional studies with larger sample sizes are warranted to continue to improve our understanding of injuries among children.

CONCLUSIONS

This study adds new information regarding fractures and injury biomechanics among children. Femur fractures can result from a stair fall among young children, and several important points were identified in this study. More severe fracture forms can occur when the caregiver falls with the child. Transverse and short oblique fractures should raise concerns if extenuating historical circumstances that could add to the potential energy of the stair fall do not exist. Spiral fractures occurred only among walking children with an associated history of the leg twisting underneath them during the fall.

This study identified key characteristics for assessing IP of stair-fall–related femur fractures in the acute setting. The richness of the history and the caretaker's ability to describe the final position of the child were key distinguishing features for identification of a fabricated history. A delay in seeking care can occur with well-aligned buckle fractures and in these cases does not necessarily indicate abuse. Even a single additional injury should alert physicians to the possibility of abusive trauma, as should the occurrence of complex fracture types such as comminuted fractures or corner/classic metaphyseal fractures.

Additional research is needed to develop and test this model and similar models that provide more objective injury assessment and differentiation between abusive and noninflicted trauma. Identification and clarification of distinguishing characteristics would provide critical data for model input, development, and validation. Because violence associated with child abuse is a progressive escalating form of trauma, an objective tool that improves our ability to identify such trauma early could potentially improve outcomes for this vulnerable population. In addition, improved accuracy might decrease unnecessary investigations of innocent families and caretakers.

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