ARTICLE

Computer Simulation of Stair Falls to Investigate Scenarios in Child Abuse

Gina E. Bertocci, PhD; Mary Clyde Pierce, MD; Ernest Deemer, MS; Fernando Aguel, BS

Objectives: To demonstrate the usefulness of computer simulation techniques in the investigation of pediatric stair falls. Since stair falls are a common falsely reported injury scenario in child abuse, our specific aim was to investigate the influence of stair characteristics on injury biomechanics of pediatric stair falls by using a computer simulation model. Our long-term goal is to use knowledge of biomechanics to aid in distinguishing between accidents and abuse.

Methods: A computer simulation model of a 3-year-old child falling down stairs was developed using commercially available simulation software. This model was used to investigate the influence that stair characteristics have on biomechanical measures associated with injury risk. Since femur fractures occur in unintentional and abuse scenarios, biomechanical measures were focused on the lower extremities.

Results: The number and slope of steps and stair surface friction and elasticity were found to affect biomechanical measures associated with injury risk.

Conclusions: Computer simulation techniques are useful for investigating the biomechanics of stair falls. Using our simulation model, we determined that stair characteristics have an effect on potential for lower extremity injuries. Although absolute values of biomechanical measures should not be relied on in an unvalidated model such as this, relationships between accident-environment factors and biomechanical measures can be studied through simulation. Future efforts will focus on model validation.

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Editor's Note: With this article by Bertocci and colleagues, we take advantage of the current capabilities of information technology. Computer modeling was used to simulate children falling down stairs—the consequences of which are commonly seen in our emergency departments. The effect of the number of stairs and the steepness of them was examined in a series of computer simulations. Go to our Web site at http://archpediatrics.com and click on the electronic version of the article to see these computer simulations. It is a dramatic example of how technology can be used to shed new light on an age-old problem. We welcome other such creative uses of information technology for articles published in ARCHIVES.

Frederick P. Rivara, MD, MPH

From the Departments of Bioengineering (Dr Bertocci and Mssrs Deemer and Aguel), Rehabilitation Science and Technology (Dr Bertocci and Mssrs Deemer and Aguel), and Pediatrics (Drs Bertocci and Pierce), Childrens' Hospital of Pittsburgh, University of Pittsburgh, Pittsburgh, Pa.

IN CHILD abuse cases, caregivers often falsely report common fall scenarios such as stair falls as the underlying cause of injury. Unfortunately, it is often difficult to determine the validity of caregiver-stated scenarios, since so little is known regarding pediatric biomechanics and injury risk associated with these relatively common falls. A better understanding of the influence that specific fall-environment factors have on injury biomechanics in children is needed. We propose that computer simulation can be used in evaluating the effect that the fall environment has on biomechanical measures associated with injury. With the use of computer simulation, a single characteristic of the fall environment, eg, the type or construction of steps, can be altered to investigate its influence on injury biomechanics and therefore injury potential. In our study, we used computer simulation modeling to investigate the effect of various stair characteristics on injury risk measures.

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Studies such as those conducted by Lyons and Oates[1] using case-specific biomechanical measures to evaluate injuries in children who have fallen from a bed are needed to begin scientifically distinguishing between unintentional and abusive injuries. In their study, injuries of 207 children who had fallen from beds or horizontal surfaces were classified by body re-

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MATERIALS AND METHODS

SIMULATION SOFTWARE

General-purpose mechanical computer simulation software (Working Model 3D; MSC.Working Knowledge, San Mateo, Calif) was used to develop a model of a 3-year-old child stair fall. This rigid-body software is commonly used to study the motion and interaction of mechanical linkages. Various 3-D geometric shapes, joints, and mechanical constraints, eg, springs and dampers, are available in the software to construct body segments or the fall environment. Inertial properties of each model segment, eg, mass, center of gravity, and mass distribution, can also be prescribed. Surface characteristics, including friction and elasticity, which influence the contact between segments and the fall environment, also can be specified in the model. Forces and torques of specified magnitude and direction can be applied to the model segments and are used to establish initial conditions of various body segments. These parameters, with the specified inertial properties of the model segments and their surface characteristics that influence interaction with the fall environment, dictate the motion and response of the model. Simulations are controlled through equations of motion defined by principles of physics and are not constrained by animation. Measurements of force, rotational acceleration, linear acceleration, velocity, and self-defined parameters can be measured and recorded for each segment throughout the simulation event.

DEVELOPMENT OF FALL ENVIRONMENT AND 3-YEAR-OLD CHILD MODEL

Using various geometric shapes, stairs with a pitch (slope) of 8:8 (rise-run or stair-height–depth) were constructed in the model (**Figure 1**). Stair-surface friction and elasticity variables were also prescribed. The 3-year-old child model was constructed using ellipsoid segments with mass and inertial properties matching that of the Hybrid III 3-year-old anthropometric test dummy (ATD). This ATD has been developed for use in motor vehicle crash analysis and provides an approximation of a 50th-percentile 3-year-old child. In addition, the matching of model specifications to the existing physical ATD will allow for future experimental validation of the model. Anatomically equivalent joints with prescribed ranges of motion were used for the hips, neck, shoulders, elbows, and knees. The ATD was placed at the edge of the stairs in a crawling position, and gravity initiated the forward movement.

SENSITIVITY ANALYSIS

Computer simulations are useful in evaluating the effects of the fall environment on biomechanics or other injury outcomes through a process known as parametric sensitivity analysis.[18,19,21] Such an analysis varies by only 1 factor at a time while maintaining all others constant, allowing us to study the effects of each separate parameter on fall biomechanics. For example, the influence that the type of flooring may have on fall biomechanics or injury outcome in a given fall can be investigated by stepwise variation of floor surface stiffness while maintaining all other model parameters constant.

The contact interface between the sole of a shoe and flooring or stair surface can be characterized by resilience and friction properties of both materials in contact. Friction, or slip resistance, between 2 contact surfaces can be represented by the coefficient of friction (COF). Frictional properties are also highly dependent on surface conditions (wet vs dry). For example, hard rubber-soled shoes on a dry vinyl tile floor have a COF of near 1, whereas the same shoe on a more slippery oil-coated surface has a COF of approximately 0.1.[22] The resiliency or elasticity (stiffness) of the shoe-surface interface can be defined by the coefficient of restitution (COR). The COR can be further defined as the amount of energy that is absorbed when 2 objects collide or come into contact. Shoe-surface contacts that are resilient will have CORs that approach 1. Materials that absorb energy on impact typically have low COR values. Examples of material COR values include the following: wood, 0.50; rubber, 0.95; rock, 0.20; and clay, 0.02.[23]

The baseline stair-fall model was defined as 7 steps with a slope of 8:8 and midrange surface friction (COF = 0.5) and stair elasticity (COR = 0.50). To determine the sensitivity of ATD fall biomechanics to various environment parameters, simulations were run in which 1 of the following parameters was varied while all others were held constant: number of steps, slope of stairs, stair-surface friction, and stair-surface elasticity. Starting with the baseline model, simulations were conducted for 3, 7, 11, and 15 steps while maintaining midrange stair friction and elasticity and an 8:8 stair slope. Simulations were also run for a series of stair-surface frictions (defined by the COF) ranging from a very slippery surface (COF = 0) to a nonslip surface (COF = 0.9) using the 7-step model and maintaining midrange surface elasticity. Next, using the 7-step, 8:8 slope model with constant stair-surface friction, simulations were conducted for varying stair elasticity (defined by the COR), ranging from a soft, "bouncy" surface (COR = 1.00) to a hard, more rigid surface (COR = 0). Finally, using the 7-step model with midrange surface friction and elasticity, the slope of stairs was decreased from the baseline 8:8 to 8:10 and 8:12. (Most building codes permit a stair slope of ≤8:12.) For all simulations, biomechanical measures associated with upper leg injury risk were evaluated. These measures included upper leg impact velocity with the steps, energy, and momentum. All measures were made at the center of gravity of the upper leg. Peak values of each variable were extracted for analysis.

gion and correlated to momentum (child mass × fall velocity) of the child during the fall. Similar studies investigating the relationships between types of injuries and the biophysics of pediatric free falls are also available in the literature.[2-4] Joffe and Ludwig[5] evaluated 363 stair falls in children aged 1 month to 19 years in an effort to better describe injuries resulting from stair falls. Although a limited number of studies describing relationships between the biophysics of a particular fall and associated injuries in children exist, additional studies are greatly needed to advance the forensic science to detect child abuse.

Femoral fractures are one of the most common fracture types associated with child abuse in children 5 years

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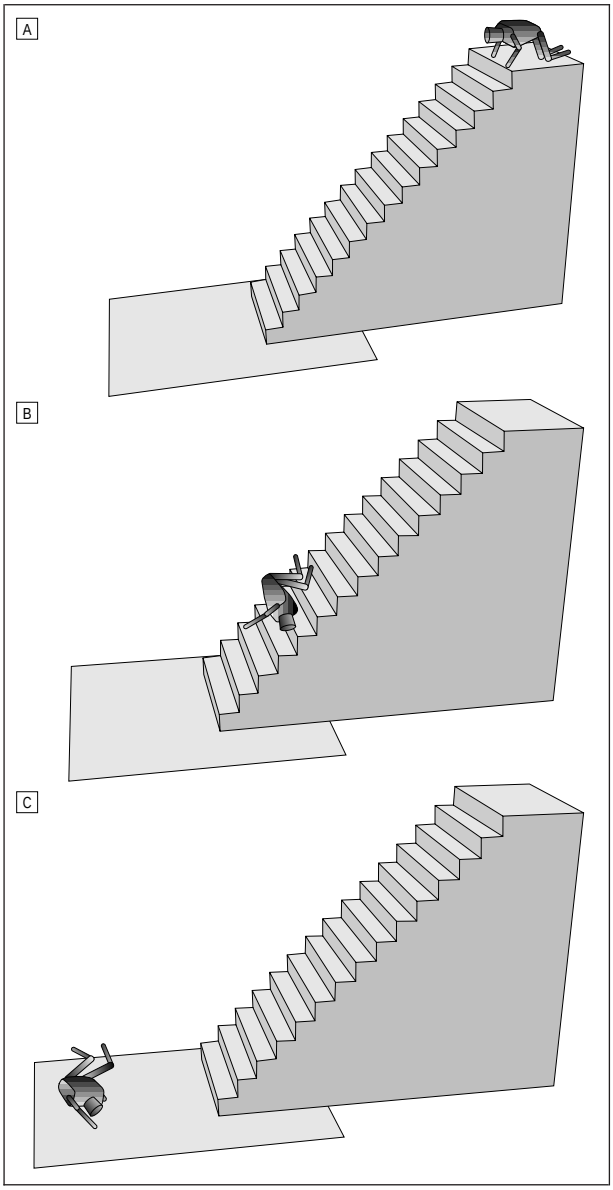

Figure 1. Simulation model of a stair fall by a 3-year-old child. A, initial position; B, midfall; and C, final resting position.

and younger.[6-13] However, femoral fractures can also result from falls in young children, making differentiation between abuse and unintentional injury mechanisms difficult for clinicians. To begin developing a foundation to aid in delineating between unintentional and abusive femur fractures, we propose using computer simulation to investigate pediatric biomechanics associated with common falls. Since femur fractures are common fractures associated with child abuse, and stair falls are a common scenario falsely reported in child abuse, our study is focused on the biomechanics of the upper leg during stair falls.

Fall characteristics and environment factors such as height of fall and impact surface properties have been shown to influence injury risk in pediatric and adult falls.[2,14-17] Mott et al[16] reported that children sustained significant increases in injuries on playgrounds with concrete surfaces as opposed to those with bark or rubber surfaces. Studies have also documented height of falls from playground equipment as having significant influence on injury risk and fracture incidence.[14] The study by Joffe and Ludwig[5] of pediatric injuries in stair falls found that falls involving fewer than 4 steps had a similar incidence and severity of injury to those involving more than 4 steps. Case-based studies such as these are needed to define relationships between characteristics of the fall environment and corresponding injuries. Unfortunately, reconstruction of the victim, the initial condition, and the fall environment are often difficult to capture retrospectively. Computer simulation and modeling techniques offer tools that can aid in the investigation of falls when data from real-world scenarios are limited.

Computer simulation techniques have been used extensively in the prediction of injury risk, particularly in motor vehicle crash analysis.[18,19] Recently, the Institute of Medicine has recommended an increase in the use of computer simulation techniques to study injury mechanisms and to predict injury risk.[20] Computer simulation has allowed engineers to economically study the influence of various factors on the risk of injury in a given scenario. Once an experimentally validated simulation model has been developed, savings can be realized through reduction in the number of costly experimental tests needed to investigate slight permutations. In our study, we used computer simulation to investigate the effects of number of steps, stair-surface friction, stair-surface elasticity, and slope of steps on key biomechanical measures of the upper leg that are associated with injury risk.

RESULTS

Without experimental validation, results of simulations can only be used to study relationships and trends among variables. Since our model has not been experimentally validated, absolute values of biomechanical measures will not be presented; instead only relationships between biomechanical measures and fall-environment factors will be described. Figure 1 characterizes the initial and final conditions of the child and the total body kinematics during the stair fall. Observation of the fall dynamics showed that the upper leg may hit the steps several times during a stair fall, with increasing contacts associated with falls involving more steps. Our model also demonstrated a slightly asymmetrical fall pattern, which can lead to differences in biomechanical measures associated with the right and left legs.

NUMBER OF STEPS

All biomechanical measures were influenced by changes in the number of steps. The impact velocity of the upper leg (speed with which the leg impacts the steps) increased as the number of steps was increased in the model (**Figure 2**). When a 3-step fall was compared with a 15-step fall, impact velocity of the upper leg increased 3-fold. As much as a 7-fold increase was observed in the peak kinetic energy of the upper leg when a 3-step fall was compared with a 15-step fall (**Figure 3**). Since momentum

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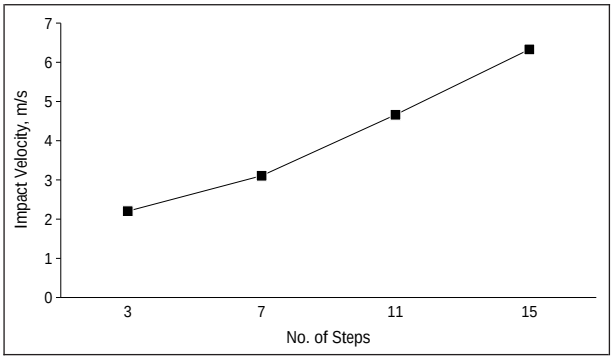

Figure 2. Impact velocity of upper leg vs number of steps.

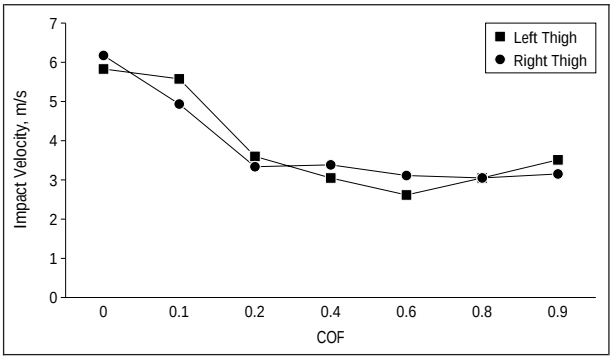

Figure 5. Impact velocity of upper leg vs coefficient of friction (COF).

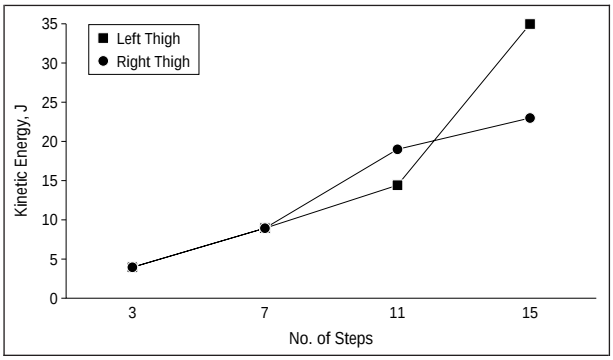

Figure 3. Kinetic energy of upper leg vs number of steps.

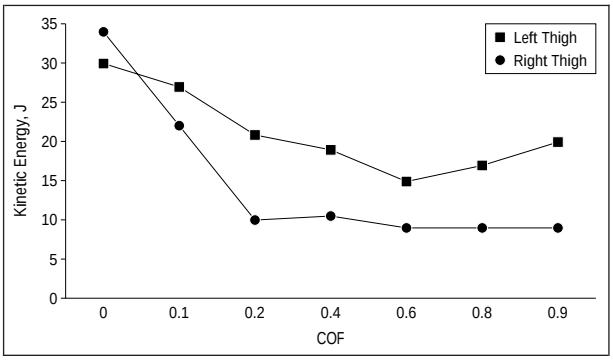

Figure 6. Kinetic energy of upper leg vs coefficient of friction (COF).

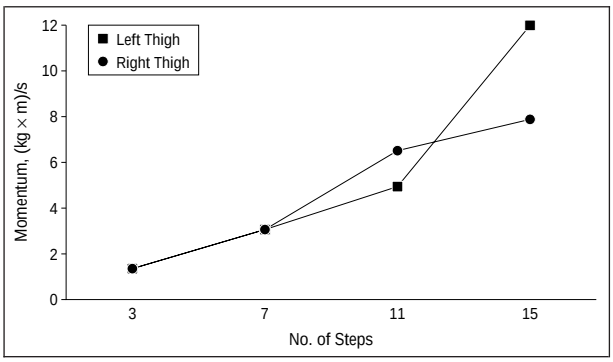

Figure 4. Momentum of upper leg vs number of steps.

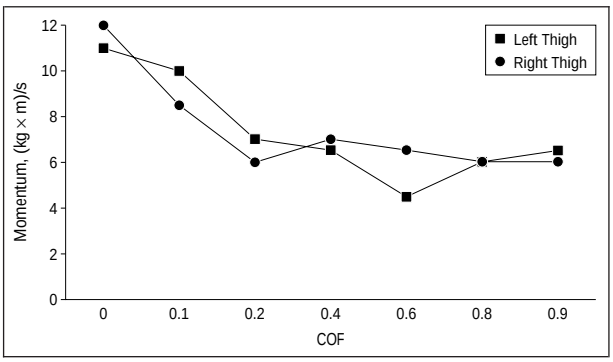

Figure 7. Momentum of upper leg vs coefficient of friction (COF).

is a function of velocity, similar increases in momentum are seen with increasing numbers of steps (**Figure 4**). Momentum of the upper leg is nearly 3 times greater in the 15-step fall compared with the 3-step fall. These findings suggest that potential for upper leg injury increases with increased number of steps.

STAIR FRICTION

All biomechanical measures decreased with increases in stair friction. Stair falls with a step COF of 0, representing a slippery surface, had higher upper leg impact velocity, kinetic energy, and momentum compared with nonslip stair surfaces (represented by a COF approaching 1). A step COF of 0 (slippery surface) in a 7-step fall generated a peak impact velocity of the upper leg that doubled the velocity found in the same fall with a nonslip surface (COF=0.9) (**Figure 5**). Kinetic energy associated with the fall on a slippery surface (COF=0) was 2 to 3.5 times higher than that associated with a less slippery or nonslip surface (COF=0.9) (**Figure 6**). Similarly, momentum was nearly doubled for slippery stair surfaces (COF=0) compared with surfaces with only slightly greater friction (COF≥0.2) in the 7-step fall (**Figure 7**). These findings suggest that slippery stair surfaces tend to increase potential for upper leg injury in a stair fall.

STAIR ELASTICITY

The elasticity (COR) or stiffness of the stairs was found to influence biomechanical measures. Kinetic energy decreased nearly 4-fold as COR was increased from 0 to 1.00 (**Figure 8**). Impact velocity and momentum also de-

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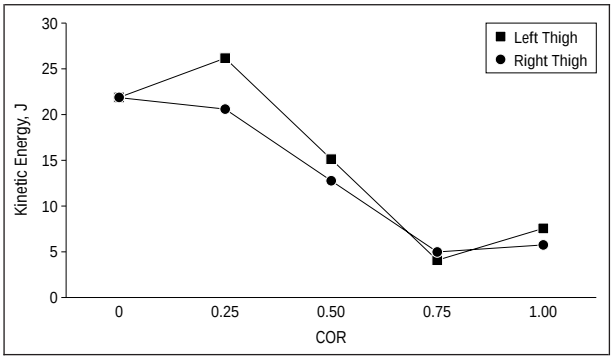

Figure 8. Kinetic energy of upper leg vs coefficient of restitution (COR) (elasticity).

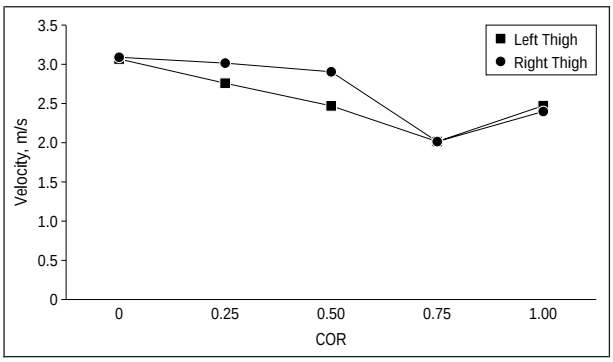

Figure 9. Impact velocity of upper leg vs coefficient of restitution (COR) (elasticity).

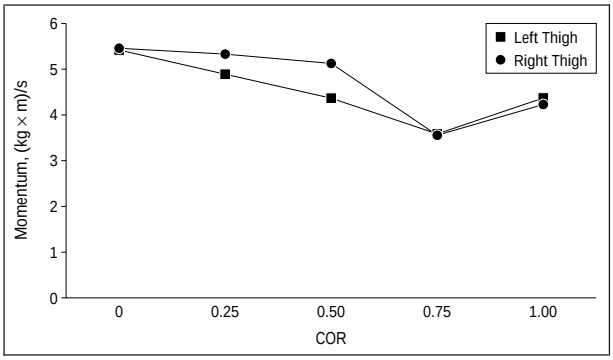

Figure 10. Momentum of upper leg vs coefficient of restitution (COR) (elasticity).

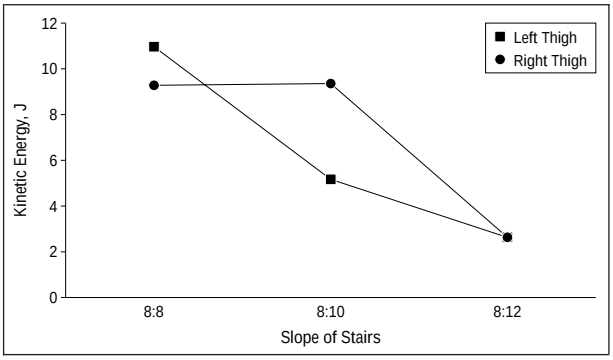

Figure 11. Kinetic energy of upper leg vs slope of stairs (rise-run).

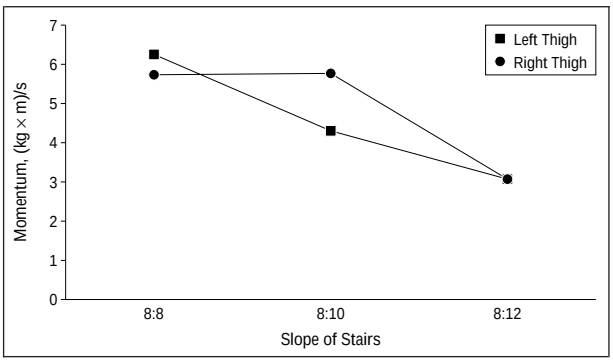

Figure 12. Momentum of upper leg vs slope of stairs (rise-run).

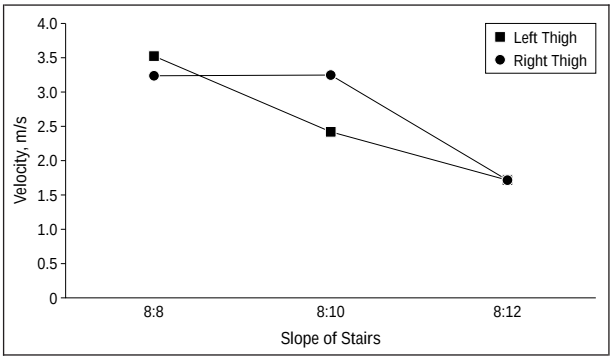

Figure 13. Impact velocity of upper leg vs slope of stairs (rise-run).

creased slightly with increasing values of COR (**Figure 9** and **Figure 10**). These findings suggest that stairs constructed of highly elastic materials tend to decrease risk for upper leg injuries in a stair fall.

SLOPE OF STAIRS

The slope of the stairs was also found to influence all biomechanical measures. In general, increases in the slope of stairs led to increases in biomechanical measures. Kinetic energy increased nearly 4-fold as the stair slope was increased from 8:12 to 8:8 (**Figure 11**). Momentum and velocity increased 2-fold with the same increase in slope (**Figure 12** and **Figure 13**). These findings suggest that steeper stairs tend to increase injury risk of the upper leg in a stair fall.

COMMENT

Using computer simulation models of a 3-year-old pediatric stair fall, we investigated the relationships between potential for upper leg injury and various fall-environment factors. Findings indicate that stair characteristics and the number of steps influence biomechanical outcome measures, and thus injury potential. Simulations revealed that increasing the number of steps, reducing stair friction (eg, slippery surface), decreasing stair stiffness (eg, concrete stairs), or increasing stair slope tended to elevate biomechanical measures increasing the potential for upper leg injury.

Our findings further suggest that characteristics of the fall environment can play a key role in predicting likelihood of injury. In other words, one stair fall is not the

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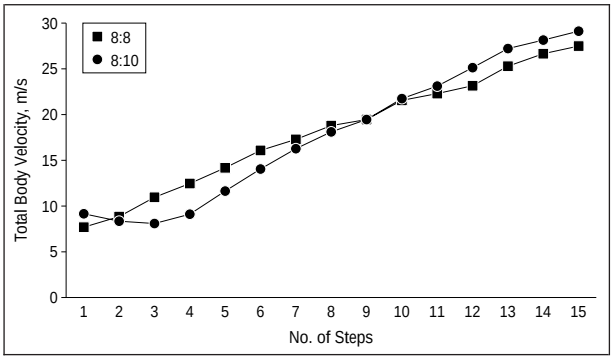

Figure 14. Total body velocity vs number of steps for varying slopes (rise-run).

same as another, although they may have involved the same number of steps. This concept illustrates the need for more detailed investigation of fall scenes, especially when attempting to distinguish between unintentional and abusive cases. Also, similar detail is needed when conducting and reporting case-based epidemiological studies to correlate injuries to particular fall types. For example, although the study by Joffe and Ludwig[5] relates the number of steps to the incidence and severity of pediatric injury, additional details of the fall environment and stair characteristics are needed to build an accurate database of stair fall injuries. (Joffe and Ludwig indicate that injury risk and severity were similar in stair falls involving more than 4 steps and stair falls involving fewer than 4 steps, without specification of stair characteristics.) Details of the victim's initial position and stair characteristics, such as those investigated in this study (surface friction, surface elasticity, and stair slope), must also be documented to make definitive statements related to injuries resulting from particular types of falls. As shown through simulations, characteristics of the fall environment affect biomechanics and the potential for injury. That is, a 7-step stair fall with a slippery or icy stair surface may have a higher potential for producing injury than a 7-step stair fall with steps that have a nonslip surface. Substantiating our findings, a report by Ellis[24] proposes that stair-surface characteristics are 1 of 3 primary factors contributing to stair falls.

Unfortunately, few studies correlate fall-environment characteristics to injury type and severity that can be used as the basis for a pediatric stair fall injury risk model. However, the study by Joffe and Ludwig[5] proposes an injury mechanism model that suggests "that stairway falls consist of an initial mild to moderately severe impact followed by a series of low-energy non-injurious falls." They further state that "there is no correlation between severity and number of steps fallen down" and that "the absence of severe or numerous injuries in falling down a greater number of steps is predicted by this model." Our simulation results do not agree with such findings and are in conflict with a stair fall injury risk model that is independent of the number of steps. Using our simulation model, we have further shown that overall body injury potential would likely increase with more steps, since total body velocity increases with the number of steps (**Figure 14**). Our simulation results support a model that reflects dependency of injury risk on the number of steps and other stair characteristics (surface materials and slope). We speculate that differences between our simulation-based model and the case-based model of Joffe and Ludwig may be due in part to undocumented variations in stair characteristics, eg, surface friction, surface elasticity, and stair slope. However, our model predicts injury risk or the likelihood of injury, whereas the model by Joffe and Ludwig was based on actual injury incidence. Our predictions of increased injury risk, implied through changes in biomechanical measures, may still be below injury tolerance levels and would not have been associated with injury incidence. In other words, predicted increases in injury risk may not reflect the difference between the absence or presence of injury or differences in injury severity. Discrepancies in these limited studies further justify the need for additional investigation in the area of stair fall biomechanics and injury incidence in the development of a pediatric stair fall injury model.

Since community and government policies often dictate the design of playgrounds, injury epidemiology studies of playground falls have been motivated to document key environment details such as impact surface characteristics and heights of playground equipment.[14,16] This type of detailed fall information and the associated injuries, occurring in a controlled playground environment, have provided a foundation for correlating playground injuries to the fall environment. These studies of playground injuries, like our computer simulation stair fall study, document the importance that subtle changes in the fall environment can have on injury potential.

The stair fall simulation model used in this study has not been experimentally validated. Future plans for our study include conducting experimental trials of stair falls for use in validating our model. Without experimental validation, absolute values of biomechanical measures should not be relied on and simulation results should only be used to study relationships between model parameters and outcome measures.

What This Study Adds

In child abuse cases, caregivers often falsely report common fall scenarios such as stair falls as the underlying cause of injury. Unfortunately, it is often difficult to determine the validity of caregiver-stated scenarios, since so little is known regarding pediatric biomechanics and injury risk associated with these relatively common falls. A better understanding of the influence that specific fall environment factors have on injury biomechanics in children is needed. Our long-term goal is to use knowledge of biomechanics to aid in distinguishing between accidents and abuse. Our study demonstrated the usefulness of computer simulation techniques for investigating the biomechanics of stair falls. Using our simulation model, we determined that stair characteristics have an effect on lower extremity injury potential.

CONCLUSIONS

This study illustrated the usefulness of computer simulation techniques to investigate the influence of stair char-

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acteristics on pediatric injury potential associated with a stair fall. Although a number of factors must be considered when attempting to distinguish between injuries that have resulted from unintentional actions or abuse, knowledge of the relationships between the fall environment and injury potential is key to providing clinicians a scientific basis for judgment. Findings of our study documented that stair characteristics, eg, surface materials and slope, can play an important role in the likelihood of upper leg injury risk. Such findings further highlight the need to carefully document the details of the fall environment when conducting pediatric injury epidemiology studies. Validated fall simulations, leveraged with case-based injury studies, ultimately will aid in developing an empirical injury model for use by clinicians in detecting child abuse.

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This work is dedicated to Frances Pierce, August 3, 1919, to December 21, 2000, Dr Pierce's mom and life inspiration.

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

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