Injury Biomechanics and Child Abuse

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Abstract

Child abuse is a leading cause of morbidity and mortality in young children and infants in the United States. Medical care providers, social services, and legal systems make critical decisions regarding injury and history plausibility daily. Injury plausibility judgments rely on evidence-based medicine, individualized experiences, and empirical data. A poor outcome may result if abuse is missed or an innocent family is accused, therefore evidence and science-based injury assessments are required. Although research in biomechanics has improved clinical understanding of injuries in children, much work is still required to develop a more scientific, rigorous approach to assessing injury causation. This article reviews key issues in child abuse and how injury biomechanics research may help improve accuracy in differentiating abuse from accidental events. Case-based biomechanical investigations, human surrogate, and computer modeling biomechanics research applied to child abuse injury are discussed. The goal of this paper is to provide an overview of key research studies rather than on review or commentary articles. Limitations and future research needs are also reviewed.

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INTRODUCTION

In an instant, a caregiver's anger and loss of control can result in serious, life-threatening injuries to a young child or infant. In fact, in the United States, child abuse is the leading cause of trauma-related death in children under 4 years of age; approximately 1200–5000 children die each year, and 150,000 sustain serious injuries (1, 2). Many of these children present for medical care with earlier warning signs of maltreatment where the diagnosis of abuse is missed, or the significance of the injury is not recognized. Repeat injury is very likely, with 50%–80% of fatal or near-fatal abuse cases having evidence of prior injuries (3–6). This missed opportunity to intervene results, in part, from a lack of scientific understanding of injuries in the young child and infant. The field of injury biomechanics in pediatrics is an integral part of the solution in properly assessing and improving outcomes for these abused children—a problem traditionally seen as a social issue.

Every year in the United States more than 3 million children are referred to social services to be evaluated for possible abuse and neglect, and approximately 1 million of these cases are substantiated (1). Many of these referrals are for physical abuse and result from a decision by a medical care provider that the injury and its described cause are inconsistent with one another. Most injury histories are provided by the caregiver because the child or infant may be too young, afraid, or injured to describe the cause. Owing to a paucity of scientific knowledge regarding the biomechanics of common household falls and injury thresholds in young children, injury assessments are based on current evidence-based medicine and clinical experience. Some objectivity is provided by empirical data from clinical studies, but further development of injury science in pediatrics may help improve the accuracy of assessments.

Injury threshold: level above which injury occurs to biological structure. Usually determined using a combination of experimental techniques (e.g., human volunteer testing, cadaveric testing, mathematical modeling)

Objective, science-based injury assessment tools could potentially improve the clinician's ability to differentiate abusive from accidental injury causation. This is important because inaccuracies in decision-making may have significant consequences, including (*a*) fatal or near-fatal injuries in children where abuse is missed and the child is placed back into the same environment; (*b*) underestimation of the violence causing the injuries in abuse cases, leading to underestimation of the intervention required to ensure patient safety; (*c*) referral of innocent families to social services for a child abuse investigation; and (*d*) legal ramifications such as loss of child custody, loss of job, and incarceration when an inaccurate conclusion of abuse is drawn. Additionally, many of these cases are debated in the legal arena in both civil and criminal courts. Expert opinions regarding how injuries occur in children are sometimes in direct conflict. These differing opinions generate confusion and can result in wrongful legal actions. The development of objective injury assessment tools may help to resolve some of these conflicts. Such tools are attainable through collaborations between medicine and bioengineering. These tools are needed to advance the current injury assessment methods with far-reaching impact for the medical, social, and legal communities.

In this review, we bring to the forefront challenges in child abuse diagnosis and demonstrate methods by which biomechanical engineering has addressed, and can continue to address, this often hidden, but ubiquitous, problem. This review focuses on current and developing bioengineering tools being utilized to research injuries in children and child abuse. A discussion of the case-based, experimental, and computational research studies aimed at better defining injury risk associated with accidental and abusive injury scenarios is included. Controversial topics, important limitations associated with current methodologies and tools, and future directions are also discussed.

Injury mechanism: description of method by which biological structures are injured or damaged

Exposure: the state of being subjected to an effect, influence, or condition, e.g., acceleration, force

CML: classic metaphyseal lesion

CHILD ABUSE INJURIES AND COMMON FALSE-CASE HISTORIES

To assess plausibility of injury and history, a scientific understanding of both injury mechanism and potential could prove beneficial. Specifically, a more accurate determination of the plausibility of injury and history when assessing potential child abuse cases can be made by (*a*) understanding the injury potential associated with common childhood injury events and (*b*) understanding the mechanism and exposure required to produce certain injuries.

False-Case Histories in Child Abuse

When an abused child is brought to medical attention, the caretaker most often cloaks the injuries as accidental in nature with intent to deceive (7). A history is provided that may have elements of the truth, but the nature and extent of trauma is not disclosed. The most common false-case histories include short-distance falls, such as falling off the couch or bed, and stair falls. Rigorous studies of short-distance falls in children can provide insight due to the fact that children often fall from short distances as they advance developmentally, learning to climb, jump, and play. In some cases, no history of injury is provided. Biomechanical techniques and approaches can improve our understanding of the mechanistic causes of specific injuries, injury potential of commonly described events, and the ways in which environmental factors influence injury risk.

Child Abuse Injuries

Certain injuries are relatively common in cases of child abuse and controversial as to their mechanistic cause and, therefore, require further biomechanical analysis (8–10). Three such injuries include subdural hematomas, retinal hemorrhaging, and a fracture termed the classic metaphyseal lesion (CML). Subdural hematomas and hemorrhaging in the retinas are common findings in infants identified as victims of abusive head trauma. The CML occurs most often in the developing bone of infants diagnosed with abusive trauma and is frequently identified in fatal cases of infant abuse (11–13). Critical questions remain regarding the degree and type of force required to produce such injuries. Additional knowledge is central to understanding the characteristics of the exposure (forces, acceleration, torque, etc.) to which a child has been subjected. This understanding is critical both for diagnostic purposes as well as designing safety intervention plans for families where abuse has been substantiated. Understanding the mechanism required to produce certain injuries can make a more accurate determination of plausibility of injury and history.

BIOMECHANICS RESEARCH AND CHILD ABUSE

Biomechanics research utilizing case-based biomechanical investigations, anthropomorphic test dummies as human surrogates, and computer simulations have helped to provide a better understanding of injury in children and are discussed in the following sections (**Figure 1**). These research methodologies allow forward progress in the field of injury science and may improve our accuracy in differentiating child abuse from accidental trauma. Animal models and cadaveric tissue testing have also contributed to the understanding of injury mechanisms and thresholds but are beyond the scope of this review.

Case-Based Biomechanical Investigations

Case-based biomechanical investigations entail conducting a detailed objective examination and/or reconstruction of an injury-producing event for the purposes of event visualization and/or determination of key biomechanical measures.

Overview. Visualization of the event aids in understanding injury mechanism, as well as the exposure of the victim, including direction(s) of impact and location(s) of impact. Visualizing the dynamics of the stated cause and assuring that it maps with the presenting injuries and/or contact points (e.g., bruises) on the body is useful when determining whether an injury is compatible with a stated cause. A detailed history of the event when witnessed should be used to piece together the sequence of the event(s). Investigative analysis may also include a dynamic and/or kinetic analysis of the event, estimating forces, momentum, impact velocity, acceleration, and energy to

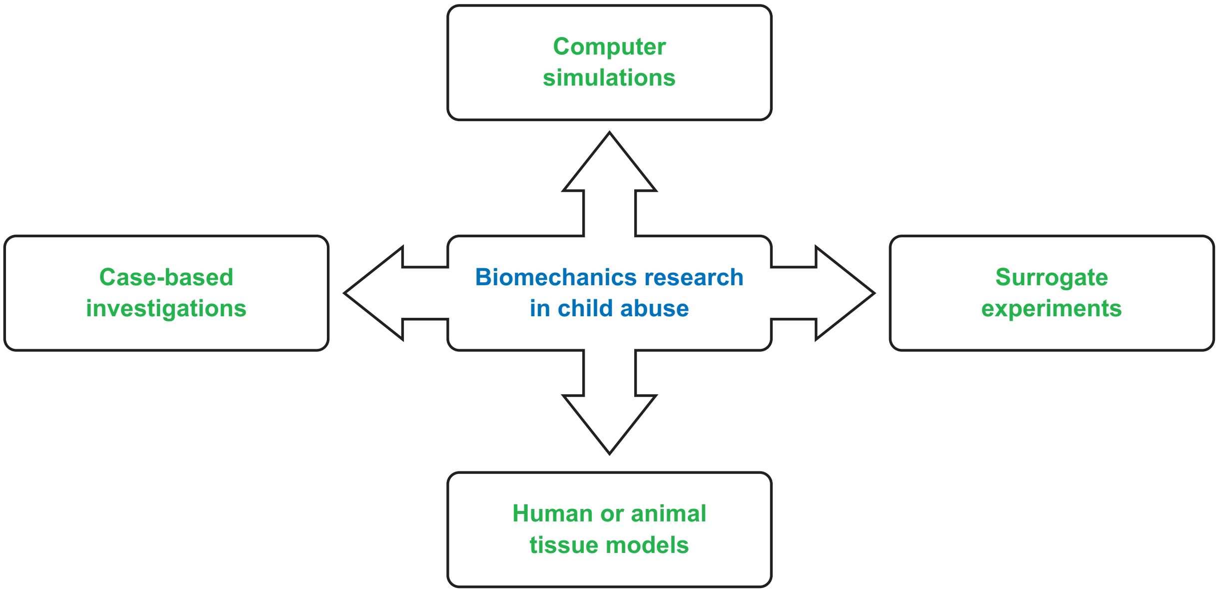

Figure 1
Classification of biomechanics research methods contributing to the delineation of abusive and accidental injuries.

characterize the victim's exposure. These key biomechanical measures in some cases may correlate with the potential to cause injury and can be particularly useful when comparing various types of injurious events. To determine these measures, details of the victim (e.g., mass, initial position), the event (e.g., fall height), and the event scene (e.g., impact surface) must be obtained as a part of the investigation. Characterization of events by their biomechanical measures and their corresponding injuries can potentially be useful in determining the compatibility between a stated cause and associated injuries. For example, low-energy events would not typically be compatible with serious, life-threatening injuries. Biomechanical measures can also be useful in categorizing different types of events (e.g., short-distance falls, stair falls) and their correlation with resulting injuries.

Anthropomorphic test device (ATD): mechanical model of the human body used as a surrogate for testing. Provides the opportunity to measure physical parameters (e.g., acceleration, force) usually for the assessment of injury risk

Case-based biomechanical investigations research used in the study of pediatric injury and child abuse. The case-based biomechanical investigational approach has been used in a small number of studies focusing on pediatric injury. This approach has primarily been used in an effort to determine injury potential of short-distance falls. When an infant or young child presents with a brain, bone, or abdominal injury, or multiple injuries that are life threatening, a short fall is often offered as the explanation. Short-distance falls of less than 3 feet are a common false-case history provided by caregivers who abuse their children (14). Short falls are also extremely common events in young children as they learn to roll over during infancy or to climb as ambulation begins. The injury potential of short falls in young children and infants is a question often debated in the courts; a question that still requires rigorous injury science research to provide more objective answers. Several key studies have combined clinical and biomechanical analysis to address questions related to injury potential and falls.

Key case-based biomechanical investigational studies. Mohan et al. (15) conducted a study on free-fall events in children and adults. This study focused on fall dynamics and incorporated scene data for injury reconstruction and analysis. Scene investigations, case-specific data, manual biodynamic calculations, anthropomorphic test devices (ATDs), and two-dimensional (2-D) computer simulations were used investigate key biomechanical measures. Injury patterns were analyzed, as were associations between biomechanical measures and injury potential and severity. This study concluded that children sustained less-severe injures than adults when exposed to similar conditions. For head-first falls, a fall distance of 4–10 feet was determined to be the threshold for skull fracture in children 18 months of age and younger (15).

Lyons & Oats (16) studied 207 children who fell out of bed to determine the likelihood of injuries. From the estimated height of the fall and the weight of the child, the momentum of impact was calculated. Momentums were then compared between injured and noninjured children. This study concluded short falls are highly unlikely to result in a serious injury and the reliability of the history should be questioned when serious injury does occur from a short fall (16). Additional work with a similar approach combining clinical and bioengineering is critical to allow real-world analysis and scientific understanding of injury potential.

Fractures are the second most common presentation of child abuse (5). Studies regarding fractures in young children for the most part are limited to descriptive studies that provide helpful information for the types of mechanisms that can result in fractures and those that are less likely to cause fracture. A clearer understanding of the required loading mechanism to produce specific types of bone failure in immature bone and the magnitude of forces necessary to cause failure in immature bone will allow clinical assessments that include both observational and experimental data for medical decision-making. It is critical for experiments to parallel real-world events to understand scientifically how these injuries in children are occurring—or how they are not occurring, in cases where a false history is provided. As previously mentioned, CMLs are highly suspicious for abuse (11–13), but their specific cause is not well defined. The mechanistic cause of CMLs is thought to occur during violent shaking events or when an extremity is grabbed and twisted. A series of cases reporting a possible nonabuse cause of CMLs was published, describing this unique fracture occurring after children underwent multiple operative repairs for clubfoot (17). This review offers some insight into mechanism, but biomechanical analysis of this unique fracture type is still required.

Injury plausibility: the level of compatibility between the stated cause of injury and the actual resulting injuries

Hymel & Jenny published a case report providing a careful biodynamic account of a spiral fracture of the humerus occurring accidentally in an infant (18). The event was captured on a family video as an older sibling was rolling the infant over. Such case reports are helpful by providing insight as to how injuries can occur. As certainty regarding mechanistic knowledge is increased, as in this case, innocent families are less likely to be investigated for abuse.

Pierce et al. (19) conducted a study of femur fractures in young children where the reported mechanism of injury was a stair fall. Biodynamics were assessed to better define the plausibility of injury. Data obtained from injury scene investigations, histories and physical exams, and X-rays were incorporated to develop an injury plausibility model in an attempt to better differentiate accidental from abusive trauma. Biodynamic measures were calculated and grouped based on their associated fracture types as well as stair fall type. Specific types of fractures were found to occur consistently with specific types of stair fall events. The details of the history of how the child fell, including the dynamics of the fall and the details of the fracture morphology, aided in determining history and injury plausibility. Certain fracture types were found to occur more commonly in younger versus older children. Additionally, higher linear momentums were associated with transverse versus other types of femur fractures. Prospective studies such as this can help clinicians identify which details of a fall event are important in assessing compatibility between fracture morphology and stated history.

Although these case-based biomechanical investigations can aid in understanding injury causation and potential, challenges remain in most studies given that descriptions of fall events are dependent on witnesses being present. Assuming that witnesses were present during the fall event, accurate description of the event depends on recollection of the witness and their ability to effectively convey details of the event. In studies where witnesses are not present to describe the event and the event is reconstructed based on circumstances and assumptions, these limitations may prevent accurate assessment and lead to incorrect conclusions. Much additional work is needed to better understand injury potential from commonly described fall events, such as short-distance falls and stair falls. Definitions of injury thresholds for various biological tissues, such as bone, in the pediatric patient are also required to predict injury potential from a given fall event. Such assessments require accounting for patient-specific data, including immaturity state and age, nutritional status, and the presence of any chronic or predisposing diseases. As medical diagnostic abilities move from generalized injury assessments to a more customized, patient-specific analysis, objective consideration can be given to the injury potential of the specific described event, as well as variables such as bone health status, when assessing fractures. Inconsistencies in the resultant injury and history provided will be determined with greater objectivity and less speculation. Through the collaborative efforts of medicine and bioengineering, objective injury assessment tools can be developed, improving the accuracy of medical decision-making.

Human Surrogate (Anthropomorphic Test Device) Experiments

ATDs, commonly referred to as test dummies, are human surrogates that have been used for many years in automotive crash-protection studies to represent motor vehicle occupants. ATDs provide opportunities to measure mechanical quantities, such as forces, velocities, and accelerations during exposure to impact or other potentially injurious events, using on-board instrumentation (e.g., accelerometers, force sensors). These measurements can then be compared with established injury criteria to provide an indication of the level of injury probability to a specific body region.

Injury criteria: correlates physical measures assessed using human surrogates with probability of injury to a particular body region

Biofidelity: degree to which pertinent physical characteristics and biomechanical response are incorporated into human surrogate designs

Overview. Test dummies are a mechanical analog of a human and often are constructed of metal or plastic elements that represent the skeleton, including mechanical joints. The surrogate skeleton is typically covered with foam or plastic representing the soft tissue, which in turn is covered with a more rigid plastic casing representing the skin. Surrogates can represent the complete human body or they may represent a specific body segment or region. Test dummies must be designed to represent the anthropometrics (dimensions and shape), mass, and mass distribution of each segment of the target human; they must be biofidelic (human like) in their response to impact, acceleration, or exposure to other physical phenomena; and they must be durable and repeatable in their response to given conditions for which they are intended. Currently, there are approximately 16 different commonly used ATDs representing infants and children (**Supplemental Figure 1**, follow the **Supplemental Material link** from the Annual Reviews home page at **http://www.annualreviews.org**) that are commercially available (20). This number can be expected to grow in the future as the desire to better understand the biomechanical response of a child under various conditions increases. However, given the paucity of data regarding the biomechanical properties of children, development of biofidelic pediatric ATDs remains a challenge.

Commercial ATDs have primarily been developed for, and their biofidelity is most suitable for, the purposes of high-speed crash investigation. Many of the child ATDs have been developed based on extrapolations from adult biomechanical properties (21, 22). The biofidelity of these surrogates may be questioned when they are used for the study of lower-energy events, such as falls. Therefore, an area of great need in the investigation of abusive and nonabusive injury events in children is the development of child-specific biofidelic surrogates. Such child-specific surrogates would allow for more realistic assessments of the type and severity of injuries that may occur in a given event, providing clinicians and the judiciary system with knowledge that will better equip them to assess whether a specific injury or constellation of injuries could result from a stated cause.

Human surrogate experimental research in the study of pediatric injury and child abuse. Although ATDs have been primarily used in the automotive crash safety area, more recently, efforts to investigate noncrash events, such as falls and shaking, have relied on human surrogates to gain a better understanding of injury potential and factors that influence injury risk. In the study of abusive and nonabusive events, research has been conducted using commercially available ATDs as well as customized surrogates. These types of studies have laid the foundation toward building a knowledge base of injury risk associated with specific events, including falls, shaking, and inflicted impacts, leading to a better understanding of the types of injuries that may result from a specific event. Key studies utilizing child surrogates are described below.

Key human surrogate experimental studies. One of the earliest studies utilizing a child surrogate was conducted by Duhaime et al. (23) to investigate shaking. In this study, a doll was modified to represent a 1-month-old infant and instrumented with a head accelerometer. The study investigated the effect of different neck designs that were constructed of either a resistance-free hinge or rubber. Volunteers were asked to shake the infant surrogate in one series of experiments, followed by another series that included impacting the surrogate head onto various surfaces. Shaking generated mean peak tangential head accelerations of 9.29 g, whereas impacts led to 428 g. Impact accelerations were 50 times greater than those associated with shaking. Mean angular acceleration measured for shaking events was 1139 rad s^{-2} with a mean angular velocity of 61 rad s^{-1}, whereas impacts led to a mean angular acceleration of 52,476 rad s^{-2} with a mean angular velocity of 549 rad s^{-1}. The more flexible hinged neck was associated with higher angular accelerations in shaking experiments. In addition to the magnitude of angular acceleration, duration of exposure to acceleration is also an important factor in predicting risk of brain injury (24). The authors reported mean angular acceleration pulse durations of 20.9 ms for impacts, and 106.6 ms for shaking events. When comparing head angular accelerations with tolerances scaled from animal models (23), Duhaime and colleagues concluded that shaking alone would not lead to fatal head injury, but direct impacts were found to be associated with angular accelerations and velocities indicative of concussion, subdural hemorrhaging, and diffuse axonal injury. Duhaime et al. suggested that "although shaking may, in fact, be part of the process, it is likely that such infants suffer blunt impact" when referring to abused children (23).

Cory & Jones (26) sought to reconstruct the original shaking experiments conducted by Duhaime et al. in 1987 (23). The Duhaime study implied that shaking alone could not cause fatal head injuries, and these findings have been used extensively in litigation to defend against shaken baby allegations. A replica surrogate with the ability to adjust key parameters was used in the Cory shaking experiments. The authors found that some modes of shaking produced impact between the chin-to-chest and occiput-to-posterior torso—a possible mechanism of injury in abusive head trauma (27). Investigators found that certain parameter changes, such as neck joint design, torso design, and mass distribution of the surrogate, produced angular head accelerations with shaking that exceeded those derived in the Duhaime study and also exceeded concussion thresholds (21, 28). Cory & Jones (26) measured peak angular head accelerations as high as 10,216 rad s^{-2} with angular velocities of 61 rad s^{-1} and peak tangential head accelerations of 1737 m s^{-2} ($\sim$177 g) during shaking events when surrogate parameters were adjusted to produce worst-case conditions. Surrogate neck design, center of gravity location, and torso construction were found to greatly affect outcome measures. The substantial differences in findings when comparing this study to the Duhaime et al. study (23) strongly emphasize the sensitivity of outcomes to surrogate design and the need for accuracy in the biofidelity of any surrogate used to represent an infant in studies investigating shaking or any other potential injury causing event. Cory also cited existing pediatric injury thresholds being based primarily on primate studies as a limitation in the prediction of pediatric injury outcome (26, 27), and highlighted the need for more accurate biologically based pediatric injury thresholds.

Prange et al. (30) also revisited the original Duhaime shaking study using a custom-built anthropomorphic surrogate representing a 1.5-month-old infant to investigate inflicted and noninflicted head injury risk. The surrogate consisted of a torso, head, and neck represented by a single resistance-free hinged joint located at the C5-C6 level, allowing neck flexion and extension in the sagittal plane. The weight of the surrogate head and representative body were matched to those of a 50th percentile 1.5-month-old infant. As a part of the surrogate development, care was taken to appropriately represent the scalp and skull properties of an infant using polypropylene for the skull and latex rubber for the scalp. Fall experiments were conducted and consisted of placing the surrogate in a supine position and dropping it from 1-foot, 3-foot, and 5-foot heights, with the head in a slightly lower position than the body to assure head-first impact. The impact surface was varied at each height and included crib mattress foam, carpet padding, and concrete. The effects of vigorous shaking and directly impacting the surrogate head onto different surfaces were also investigated in this study. The authors found that inflicted impacts onto a hard surface led to peak angular accelerations and peak changes in angular velocities that were significantly greater than those generated through fall scenarios. Furthermore, inflicted impacts onto hard surfaces led to peak angular accelerations 39 times greater and peak changes in angular velocity 3 times greater than those generated through shaking. However, authors caution that direct comparison of measured rotational responses to existing injury thresholds to determine whether injuries would be present can be misleading. The authors cite that "regional tissue thresholds specific to the infant would be required to predict injury on the basis of local intracranial stresses and strains produced by the rapid rotations." In lieu of direct comparison with published injury thresholds, the authors provide a qualitative comparison of their findings to cadaver, primate, and animal experiments with documented biomechanical responses and clinical outcomes. Using this approach, the authors concluded that inflicted impacts onto hard surfaces are more likely to lead to inertial head injuries than shaking or 5-foot falls from a supine posture with the head in a leading position. Additionally, they concluded that experimental evidence does not exist to suggest that shaking is sufficient to cause subdural hematomas (SDHs) of the brain or primary axonal injury in infants. In a follow-up letter to the editor, clarification was provided from the authors regarding the results of the Duhaime et al. study previously mentioned (23) and this study by Prange et al. (30):

CRABI: child restraint air bag interaction

> "In both papers we measure relatively small rotational velocities and/or accelerations during vigorous shaking, and low height falls are below the thresholds for severe primary brain injuries. At these levels, however, there is a paucity of data in humans, animals, and cadavers, and therefore we cannot postulate whether brain injury would be associated with these events. To summarize, new research is needed to determine if injuries can occur in the brain, cervicomedullary junction, or cervical spinal cord as a result of a single or series of head rotations at these low magnitudes, and if these injuries are primary or secondary in nature. Therefore, we cannot yet answer if shaking can cause intracranial injury in infants, and use of terminology that includes this mechanism should be avoided" (31).

Jenny et al. (32) recently investigated head injury risk in a number of different events using three different ATDs. The ATDs used represented a 5.5-lb infant, a 7.7-lb infant, and a 17.2-lb (6-month-old) infant, all of which represent children that are at high risk for abuse. The 6-month-old child restraint air bag interaction (CRABI) ATD used in this study is commercially available and commonly used in automotive crash testing, whereas the Aprica 5.5-lb and Aprica 7.7-lb ATDs were developed as a part of the authors' research. The ATDs were instrumented to measure linear and angular head accelerations, as well as neck loading during experiments. In this study, the various ATDs were shaken, thrown, bounced, and dropped in a series of experiments. Experimental results demonstrated that mass of the child surrogate and characteristics of the neck-head region influenced biomechanical outcome measures associated with injury risk. The authors also concluded that the lower-mass ATDs experienced higher angular head accelerations for a given exposure to shaking.

Bertocci and colleagues (33–35) conducted a number of ATD experimental studies focused on investigating falls in children with the goal of describing injury risk associated with common events that are often falsely reported in child abuse. One of the studies assessed head and lower extremity injury risk associated with bed falls onto various impact surfaces using an instrumented Hybrid II 3-year-old ATD (33). This study assessed linear head acceleration as well as head injury criteria (HIC) (21) values during bed falls (33). The highest mean HIC values were obtained during impacts onto a wood surface ($HIC_{36} = 418$), whereas the lowest mean HIC values were generated in bed falls onto playground foam ($HIC_{36} = 55$). However, all HIC values were below the National Highway Traffic Safety Administration (NHTSA) proposed HIC_{36} threshold of 900 for the Hybrid III 3-year-old ATD. Bending, torsion, and compressive loading of the femur were also measured because long-bone fractures are a common injury in child abuse (33). The investigators found that impact surface had an effect on outcome measures; however, there was a low risk of contact-type head injury and a low risk of lower extremity fractures from bed falls onto evaluated surfaces. Limitations of this study include the biofidelity of the ATD, the evaluation of only one initial posture that may not maximize injury risk, and the absence of assessing angular acceleration of the head. Failing to consider angular acceleration could lead to an underrepresentation of head injury risk. However, in a fall from a sofa, such as that simulated in this study, where the initial posture is supine and the torso and head remain at a similar horizontal level, linear head acceleration dominates the fall dynamics. In the absence of more biofidelic surrogates for low-energy events, this study provided a first step toward assessing injury risk during a bed fall in a controlled laboratory setting.

Studies using human surrogates and biomechanical investigation have also been conducted specifically with the intent of investigating events presented in child abuse litigation. For example, Jones et al. (36) investigated the plausibility of sustaining subdural hemorrhaging when an infant is vigorously rocked in a baby rocker. In this study, a customized surrogate of a 5-week-old infant was developed and instrumented to measure head injury. The surrogate included a head, hinged neck, torso, and legs. The surrogate was placed in a baby rocker and experiments duplicating the described scenario of caregivers rocking the child were conducted. The authors concluded that vigorous rocking produced experimental values (angular acceleration of 197 rad s^{-2}, angular velocity of 33 rad s^{-1}, and linear acceleration of 16 g during violent rocking) that were substantially lower than threshold values for head injury (−37–39), specifically cerebral concussion and subdural hemorrhage (23, 25). Therefore, the stated cause of injury was determined to be incompatible with the child's injuries. This study illustrates how a biomechanical investigation using a human surrogate can be useful in judiciary system investigations by evaluating a particular stated cause of injury.

Computer Modeling/Simulation

Computer modeling is widely used to simulate a myriad of physical events and is a useful tool in engineering analysis and design.

Overview. Computer modeling has been used extensively in the study of automotive crash safety, in particular, to investigate injury risk and to evaluate the effectiveness of safety devices. For example, Winston et al. (40) demonstrated that computer modeling can aid in identifying risks to children in crashes when limited real-world data are present. The Institute of Medicine has recognized the value of computer simulation and has recommended an increased use of computer simulation in the study of injury causation (41). Computer modeling can also serve as a valuable tool in the investigation of noncrash events to better understand how injuries occur, how the human body responds, and which factors may influence injury risk. Computer modeling is also particularly useful in exploring how changes in a specific variable (e.g., fall height, impact surface) can affect injury risk, reducing the need to conduct possibly more costly physical experiments and providing answers to questions that might otherwise be unattainable. Studies investigating the influence of a factor or parameter are referred to as parametric sensitivity analyses.

Multibody modeling, which is most widely used, relies on a system of rigid and flexible bodies with a defined mass, geometry, and mass distribution to represent human body segments. Models can be developed as 2-D or 3-D systems. Geometric segments representing body segments, often defined as ellipsoids, are connected by joints that control the relative motion between two adjoining segments. Different types of joints and their properties can be defined in the model to prescribe joint response and motion. For example, a joint used to represent the knee should move and respond differently than a joint(s) used to describe the neck. Once the human body and environment are developed in the model, the system of joined segments representing the human body is then subjected to external forces or acceleration. Collisions between body segments or segments and the environment are often defined by describing the elasticity, rigidity, force deformation, and/or energy-absorbing properties of the specific contact. To accurately define these collision or contact properties, often component or material testing must be conducted to provide input to the model.

The motion or response of the human body model is governed by the laws of physics. If the motion of the model is instead prescribed by the modeler, it is referred to as an animation. However, animations that prescribe motion are not necessarily realistic representations of real-world events and should not be confused with modeling or simulations that are governed by the laws of physics.

Of key importance to developing reliable computer models is the need for a robust validation process. That is, the model must be shown to correlate well with a physical experiment(s) first, before being used to predict the outcome(s) of a similar event. The validation process is often the most challenging aspect of computer modeling and remains crucial to the success of the model. A rigorous statistical analysis verifying that the model is predictive of physical experiments is necessary to assure proper validation (42, 43). A poorly conducted validation process will lead to a reduction in the predictive power of the model. At best, such models can only be used for qualitative comparisons.

Modeling can be done using self-developed computer code or commercial computer software programs. Given the computational intensity necessary to develop 3-D models and simulate an event, numerous software programs have been developed and are commercially available. However, even with the aid of software, building and properly validating a human body model require a substantial time commitment. Examples of modeling software include MADYMO (TNO Automotive, Delft, Holland), Dynaman (Gesac, Boonsboro, MD), Adams (MSC Software, Santa Anna, CA), and Nastran (MSC Software, Santa Anna, CA). These software programs allow for the prediction of outcome measures such as body segment acceleration, velocity, and force during a simulated event that can be used to evaluate injury risk. Most commercial modeling software is equipped with visualization capabilities. Some software programs also offer the capability of finite element analysis, in which case a single body segment or region is treated as a series of small elements, allowing for a more detailed analysis but requiring significant increases in computational time. An advantage of finite element modeling is that it allows for the description of localized deformation and stresses.

Along with concerns related to validation, limitations in computer modeling can also be due to inaccurate representation of a body region, environment, and/or event. To be able to develop and execute a model using a computer, one must represent the event in a discrete form allowing for digital processing. That is, models are an approximation of a real-world event; their ability to predict an outcome is largely dependent on the model's capability of representing the real-world scenario with a high level of certainty. A goal in model development should be to minimize approximation error (44).

Despite limitations, computer modeling offers an opportunity to gain insight into injury risk in real-world events. Additionally, appropriately developed models are highly useful for studying the effects of various parameters on injury-related outcomes or injury risk. In particular, computer models can be used to extend the limited biofidelity of current ATDs (dummies). For example, a model may be used to investigate the influence of neck stiffness, a parameter that plays a key role in head injury outcome, for a given event. However, one of the major challenges that remain in the development of human body models, particularly models of children, is the accurate description of tissue properties and human tissue response. The usefulness of a model will largely depend on the ability to accurately describe these tissue properties.

Computer modeling and simulation research used in the study of pediatric injury and child abuse. In the delineation of abusive versus nonabusive injuries, there is great need to gain an understanding of the types and severity of injuries that may result from scenarios reported as false histories. These scenarios may include shaking, falls from a bed or sofa, stair falls, etc. Although few studies have been undertaken, computer modeling can provide insight toward a better understanding of injury mechanisms, injury risk, and injury outcome in these commonly falsely reported scenarios of child abuse. However, because the following studies were largely undertaken to gain an understanding of factors affecting injury risk and most models were not validated, only qualitative findings of these studies will be presented.

Key computer modeling and simulation studies. As early as 1979, Mohan et al. (15) utilized computer modeling to study pediatric falls and associated injury outcome. Mohan et al. examined the details of head-first falls of children 10 years of age and younger. In six cases where computer simulation was used to reconstruct the event, head deflections, impact forces, and accelerations were estimated. Two-dimensional multibody modeling was used to simulate the fall events. Authors found that head-first falls onto a rigid surface (e.g., concrete) from 1 m or less were unlikely to cause skull fractures, whereas similar falls from 6 m were likely to cause skull fractures. The authors found a positive correlation between head acceleration and increasing head injury. When comparing head-first falls onto different surfaces, simulations showed that peak head accelerations associated with impacts onto soil and sand were 15%–50% of those values obtained during impacts onto rigid (concrete) surfaces. This early study demonstrated the capabilities of computer modeling to provide a better understanding of factors that can influence head injury in falls. A limitation of this study is the lack of a rigorous validation process.

Bertocci et al. (45) attempted to demonstrate the usefulness of computer simulation techniques in the investigation of pediatric stair fall events. Stair falls are a common falsely reported scenario in child abuse. The aim of this study was to investigate the influence that stair characteristics have on biomechanical measures associated with lower extremity injury risk. In this study, a computer simulation model of a 3-year-old child falling down stairs was developed using rigid-body software. The authors found that the number and slope of steps, as well as stair surface friction and elasticity, affected lower extremity biomechanical measures, and thus injury risk. The authors indicate that, while absolute values of the outcome measures should not be relied on in an unvalidated model such as this, relationships between fall environment factors and biomechanical measures can be studied through computer simulation.

Prange (46) utilized finite element modeling to predict axonal head injury in a 1-month-old infant exposed to minor falls and abusive events, including shaking. The model focused specifically on axonal injury risk and did not assess subdural hemorrhaging and skull fracture injury risk. Simulated 1.5-m falls from a horizontal posture (leading with head) onto a 10-cm-thick mattress were found to generate stresses and strains below axonal injury thresholds. Shaking scenarios and moderate inflicted head impacts onto the foam mattress generated higher brain stresses and strains than investigated falls. Severe inflicted head impacts were found to generate the largest strains and stresses and were indicative of extensive axonal injury. This is one of the only modeling studies investigating infant axonal head injury.

Wolfson et al. (47) used multibody computer modeling to investigate shaking in a 12-month-old child. In this study, torso accelerations taken from shaking experiments with a customized doll were used as inputs to a multibody model that consisted of a 12-month-old CRABI torso, arms, neck, and head. The authors investigated the effect of neck stiffness on head angular velocity and acceleration. The model was also used to evaluate the effect of the chin impacting the chest and the occiput impacting the posterior torso during shaking. Modeling outcomes indicated that impact of the head with the torso was necessary to generate conditions exceeding current injury thresholds for concussion. However, this model was also not validated and results must be interpreted with caution.

Because bed falls are so commonly used as false histories in child abuse, Bialczak et al. (48) developed and validated a multibody model of a 12-month-old child falling from a bed. (See **Figure 2**) In this study, the child was represented as a multibody model of the 12-month-old CRABI test dummy. The child was positioned in a side-lying posture and a force was delivered to the posterior torso to initiate the fall from the 66-cm-high surface onto the impact surface. The model was validated to predict linear head and torso acceleration using experimental results from 10 bed fall trials, along with a rigorous comparison of model and experimental findings using various statistical tests. The study did not discuss injury risk outcome in bed falls but did provide an indication of the possibilities that modeling offers in the study of such a fall scenario. Additionally, it is perhaps the only published validated computer model focused on the investigation of short-fall scenarios in children.

IARV: injury assessment reference value

SPECIAL TOPICS

Challenges in Developing Injury Criteria for Children

When judging consistency of an injury and the stated cause in the young child or infant, a major hurdle that remains is the lack of data regarding appropriate injury thresholds. The concept of injury criteria has been used in the automotive safety area for years and has been incorporated into many governmental regulations (e.g., federal motor vehicle safety standards) that mandate occupant crash protection through improved motor vehicle design. In the automotive safety field, injury protection values have been established for ATDs or human surrogates that allow for correlation of their mechanical response to injury risk in humans. Injury assessment reference values (IARVs), or injury criteria, were originally proposed for use with a midsized adult male ATD (49). Adaptations of these adult reference values to child ATDs also have been recommended (21, 22, 50, 51). Injury protection values established for use with instrumented ATDs can provide insight to the level of injury risk associated with a certain exposure or event based on measurable parameters, such as acceleration, force, displacement, etc. These reference values establish limits beyond which injury is unlikely (52). However, the ability of IARVs to accurately predict injury in humans may be limited by ATD biofidelity.

Injury criteria have typically been derived based on a combination of experiments using human volunteers, cadaver testing, animal testing, computer simulation, and accident reconstruction (53) that characterize the relationship between injury outcome and measurable parameters. Unfortunately, these methods are indirect and each has limitations in terms of ability to accurately predict injury risk. Experiments relying on cadaveric testing, often considered the gold standard, are commonly based on a small sample size representing a limited human population subset, and typically introduce limitations regarding tissue integrity, cardiovascular and pulmonary pressurization, and the absence of active muscle response (53).

Animal surrogate studies have also been conducted in an effort to establish human injury thresholds, but have been met with ethical and humane objections. Animal injury models are often limited in their ability to be translated to humans owing to their anatomical and physiological differences as compared with humans. Studies using immature animals have been conducted in an effort to estimate pediatric injury thresholds, thereby attempting to account for age-dependent tissue properties (54). A discussion of appropriate animal models regarding traumatic brain injury is reviewed by Duhaime (55). Neonate and infant piglets have been used in the study of head injury and long-bone fracture in an effort to understand pediatric injury mechanisms and thresholds (55–62).

Studies to establish injury thresholds rarely include pediatric cadaveric specimens or tissues owing to ethical concerns, requiring that injury thresholds for children and infants largely be

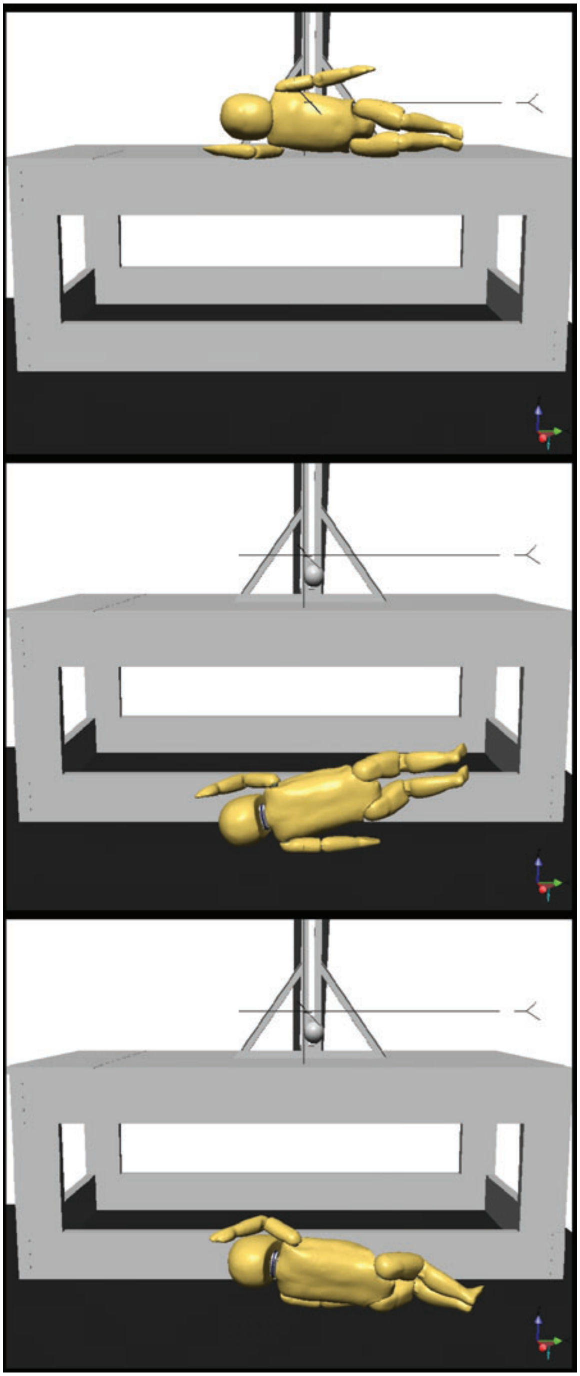

Figure 2

Computer simulation model sequence of child anthropomorphic test device falling from structure representing a bed or sofa.

derived based on adult injury criteria. In doing so, geometric, inertial, and material property scaling is applied to adult injury thresholds. These techniques assume that pediatric tissue properties and geometric/inertial properties are related to those of adults by established mathematical relationships, or dimensional analysis. However, many anatomical and physiological differences exist between children and adults, and consequently, pediatric injury criteria may be misrepresented when scaling has been used and underlying assumptions are not met. For example, an infant skull substantially differs in structure from an adult skull, consisting of bone segments joined together by sutures, along with openings within the skull (fontanelles). The infant skull structure has been shown to be much more flexible than an adult skull (63), suggesting a differing biomechanical response to impact and likely leading to differing injury mechanisms. Clearly, adult-based scaled head injury criteria, which rely on the assumption of a rigid skull, may not be capable of accurately predicting head injury risk in an infant (21). An additional challenge in developing pediatric injury thresholds is accounting for and characterizing the developmental and growth process. For example, an infant skull structure changes relatively rapidly across a short duration. Structural changes, including closing fontanelles, as well as continual bone development translate into significant differences when comparing skull properties, even across infants and children (64–66).

The ability to predict pediatric injury outcome associated with exposure to a specific event rests, in part, on the availability of reliable injury thresholds. Biomechanical studies described previously in this review that have relied on pediatric injury criteria to predict injury occurrence or risk must therefore be interpreted with caution. A thorough discussion on developing and existing injury criteria for infants and children is beyond the scope of this review, and therefore references provided within this section are far from inclusive. However, it is hoped that this brief overview highlights some of the challenges faced by those conducting this highly important research of attempting to advance the knowledge of pediatric injury thresholds.

Current Limitations in Biomechanical Research and Key Clinical Issues to Be Addressed

Determining if an injury is the result of abusive or accidental trauma depends on many factors. Conclusions of whether or not it is possible for an injury to result from a specific mechanism cannot be based solely on biomechanical analysis, modeling, or experimental testing and the derived models for injury threshold. Critical limitations of current state-of-the-art biomechanics-based research for predicting injury in children include human surrogate biofidelity as well as a lack of knowledge regarding pediatric tissue properties and associated biomechanical response. Other key clinical issues that current injury predictive models are unable to account for include the following:

1. The affect of muscle tone on the likelihood of injury: How does decreased tone in the young infant, or absence of tone in the unconscious child or infant, affect susceptibility to different types of injury? Model accuracy will be improved as models are able to address the clinical parameters of muscle tone.
2. The affect of cyclic trauma on likelihood of injury: How does rapid, cyclic trauma over a short period of time (seconds) affect energy propagation to different tissues of the body, and does this cyclic trauma alter the injury threshold of those tissues in a predicable manner? Biomechanical models intended to study trauma in cases of child abuse must address the clinical nature of the problem of a child's or infant's exposure to cyclic trauma that would occur during shaking.
3. The affect of repetitive trauma on the likelihood of injury: How do multiple exposures to traumatic forces over long periods of time (hours, days, or weeks, for example) affect tissue

response to trauma and the likelihood of injury? Specifically, how is the injury threshold affected by preexposure to trauma, and how does the time interval between exposures affect the likelihood of injury? To advance child abuse diagnostic capabilities, a predictive injury model is needed that addresses recurrence of exposure to traumatic forces, as many child abuse victims suffer multiple and recurrent traumatic events.

Current biomechanical-based injury predictive models are limited in their ability to determine how repetitive trauma influences injury thresholds. In cases of abusive trauma, caregivers often report multiple episodes of inflicting trauma over a period of weeks or months, not just a one-time event. In support of the repetitive trauma history is the common finding of both old and new subdural brain hemorrhages, and/or old and new fractures on autopsies of infants or children who have died from abusive trauma. How repetitive trauma affects injury thresholds is critical to understanding what occurred to cause these injuries. Such biomechanics-based knowledge will have important medical as well as legal implications. Future research investigating injury in potential child abuse victims must be able to analyze the effects of repetitive trauma as well. Future research using finite element modeling may allow an accounting for these additional factors associated with injury mechanism and injury thresholds. Tools available for biomechanics research may allow a critical gain in the understanding of human child and infant injury thresholds and how repetitive trauma plays a role in injury causation. This knowledge is not attainable through conventional methods such as clinical research.

Another challenge regarding biomechanical investigation and modeling of abusive and accidental trauma involves muscle tone and its influence on injury outcome, especially with regard to head and neck injuries in children. Infants have relatively poor muscle tone and do not yet have many of the protective reflexes (e.g., outstretched arm in response to a fall). Additionally, caregivers who have stated they shook their baby often report the infant goes limp during the shaking. From a biomechanics point of view, increased neck muscle tone provides greater resistance to inertial loading compared with a low muscle tone or limp state (52). Because muscle tone affects biomechanical response (52), its affect on injury risk and outcome is also an area where computer modeling research is needed, especially in regard to infant shaking. Future predictive injury models will need to account for muscle tone and its influence on injury outcome.

Another limitation of biomechanical-based predictive injury models is the inability to account for patient-specific properties. A lack of knowledge of how different disease states, such as osteoporosis in the premature infant, influence injury thresholds makes patient-specific assessments more difficult. Future injury assessment tools must be able to take into account patient-specific data to improve accuracy and objectivity. Current technologies already exist that allow much better assessments of microstructures that influence bone strength and likelihood of failure. Additional advancement of these techniques will allow their application for clinical assessments in young children and infants.

Controversial Topics

Currently, two of the most controversial topics in child abuse assessment are the attribution of mechanisms associated with abusive head trauma and whether shaking alone can result in life-threatening or fatal injuries or if impact is required as well. In the early 1970s, Caffey (8) proposed that shaking of infants resulted in subdural hematomas and later coined the term whiplash shaken infant syndrome. Injuries were attributed to violent shaking of the infant out of anger. Controversy remains over the mechanistic cause of subdural and retinal hemorrhages in infants. Many accounts of shaking alone have been provided by persons convicted of child abuse; many others confess to both shaking and striking or throwing the baby. Often times, such a confession will be retracted and replaced with a history of a seemingly minor fall. Social and legal arenas are where these questions most often arise; answers to these questions must come, in part, from scientists dedicated to understanding injury in children. Rigorous biomechanics research investigating the mechanisms leading to these brain and eye injuries in infants is an important element in addressing this controversy. It is premature, however, for conclusions to be drawn from current head injury models (HIMs) (i.e. head injury criteria) owing to pivotal limitations. A review of head injury criteria and their limitations is provided by Cory et al. (67). This review describes the application of head injury criteria to the research of childhood head injuries and examines several prediction models developed over the past three decades. Biomechanical predictive head injury model limitations are also well described by Jones et al. (36). Experimental limitations include that "no quantitative head injury tolerance data exists specifically for children," and that "criteria used for children are therefore estimates obtained through several different techniques." Jones et al. also point out limitations regarding animal models and extrapolation of data to humans, that ATDs respond differently from human tissue in terms of dynamic response, and that mechanical properties of cadaveric tissues may differ from those of the living (36). Furthermore, current head injury criteria do not account for exposure to repetitive inertial loading and motion, such as that in shaking.

HIM: head injury model

As technologies and science improve, more confidence can be placed in experimental and computational results. Trends and parametric comparisons can provide information regarding potential injury outcomes, but until more appropriate injury thresholds, more biofidelic human surrogates, and more accurate computer models are developed, conclusions regarding whether or not shaking alone can cause the injuries associated with abusive head trauma is premature. Multiple factors are required for a predictive injury model to be valid clinically, and results must always parallel real-world observations.

Adults who do harm to infants and young children are usually not forthright about injury causation. The child's survival, or justice for the child if killed, depends on sound objective assessment based in the best scientific evidence possible. It is also imperative that innocent people not be accused of wrongful doing; it is critical that premature conclusions not be made based on predictive injury models that require further improvements with biofidelity or computation model validation. Medical, social, and legal decisions must pull together all resources available to make the best decisions possible. Current biomechanical HIMs are sometimes used to exonerate caregivers accused of abusing a child. Such weight should not be placed on injury predictive models with limitations discussed herein.

Conclusions of experimental results and degree of certainty regarding injury prediction in children must be reflective of the limitations of the model. These limitations are critical to acknowledge, especially when making forensic-based decisions regarding injury causation and plausibility.

CONCLUSIONS

Consequences of inaccurate injury plausibility assessments are unacceptable. The abused child is left behind in a dangerous and potentially fatal environment when the diagnosis of abuse is missed or the significance of the injury causation is underestimated. The case of an innocent family investigated for abusing their child can be just as damaging. Cases where the conclusion is one of guilt can result in the temporary or permanent loss of custody of their child or children; and in some cases, wrongful incarceration occurs. Even in cases where the conclusion is one of innocence, damage to the family unit can still occur.

Continuing to improve the scientific understanding of the type and severity of exposure required to cause specific injuries in children may improve medical decision-making, the effectiveness of social interventions, and the accuracy legal proceedings. Only with a collaborative effort from the fields of medicine and bioengineering will the state of the art of injury science in children be advanced to allow more accurate assessments, which in turn will result in better outcomes for maltreated children as well as innocent families.

The greatest promise to gaining insight into injury risk associated with real-world events is through the use of a multipronged medical and biomechanical approach that draws on the use of human surrogates, computer modeling, case-based biomechanical investigation, and cadaveric or animal tissue models. Technological advances leading to more accurate injury prediction models and devices capable of obtaining patient-specific data for case assessments will have a significant impact on the accuracy of differentiating abusive from accidental injuries in young children in the near future.

SUMMARY POINTS

1. Child abuse is the leading cause of trauma-related death in children under 4 years of age—many of these children present for medical care with earlier warning signs of maltreatment where the diagnosis of abuse was missed or the significance of the injury was not recognized.
2. Certain injuries, including subdural hematomas, retinal hemorrhaging, and the classic metaphyseal lesion, are relatively common in cases of child abuse and controversial as to their mechanistic cause and therefore require further biomechanical and clinical analysis.
3. Characterization of events by their biomechanical measures and corresponding injuries can potentially be useful in determining the compatibility between a stated cause and associated injuries.
4. Biomechanics research utilizing case-based biomechanical investigations, anthropomorphic test dummies as human surrogates, computer modeling, and animal models have helped to provide a better understanding of injury in children.
5. Computer modeling can be useful in exploring how changes in a specific variable (e.g., fall height, impact surface) can affect injury risk, reducing the need to conduct possibly more costly physical experiments and providing answers to questions that might otherwise be unattainable.
6. Critical limitations of current state-of-the-art biomechanics-based research for predicting injury in children include lack of biofidelity in human surrogates and a lack of knowledge regarding injury thresholds for different stages of development, as well as child-specific injury thresholds.
7. Conclusions of experimental and computer modeling results and degree of certainty regarding injury prediction in children must not extend beyond the scope and limitations of each individual study.
8. Biomechanics research can play an important role in increasing our knowledge and understanding of injury mechanisms in children. Sound and robust biomechanics research can inform us in the future regarding likelihood of injury; likewise, real-world clinical experience must inform biomechanics research.

9. A better understanding of injuries in infants and children could potentially allow a better understanding of what safe guards are required to prevent such injuries and may allow a more focused and tailored effort for the interventions that is required to stop the abuse; a more accurate and informed understanding of injuries in children may also help decrease the likelihood of innocent families undergoing an investigation for child abuse

FUTURE DIRECTIONS

1. Improvement of child surrogate biofidelity for use in experiments assessing injury risk associated with falls and other events is needed.
2. Improvement is also needed in the understanding of pediatric injury mechanisms, particularly as they relate to controversial topics such as exposure to shaking.
3. Accurate pediatric injury thresholds must be developed to attain an improved understanding of injury mechanisms with enhanced predictions of injury occurrence.
4. Multidisciplinary collaborative approaches should be provided to train both engineers and clinicians who will be better equipped to integrate knowledge across both disciplines needed in the determination of pediatric injury etiology.
5. Research that combines real-world clinical experience with bioengineering research methodologies may help improve safety and outcomes for both children and their families.

DISCLOSURE STATEMENT

The authors are not aware of any biases that might be perceived as affecting the objectivity of this review.

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