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Applications of Biomechanics Aiding in the Diagnosis of Child Abuse

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Injury biomechanics is the field of study focusing on the biomechanical behavior of the human body under injury-producing conditions. One of the unique challenges faced by pediatric emergency medicine clinicians is distinguishing between inflicted and noninflicted injuries in children. Biomechanics is one tool that can aid in determining the compatibility between a child's injury and the reported mechanism of injury. An overview and examples of various biomechanical approaches used to distinguish between inflicted and noninflicted injuries in children are described.
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Injury biomechanics is the field of study focusing on the biomechanical behavior of the human body under injury-producing conditions at both the macroscopic and microscopic levels. It is a multidisciplinary field bringing together engineering and medicine. Injury of the human body occurs by deformation of anatomic structures beyond their failure limits, resulting in damage of tissue or alterations in normal function. Injury biomechanics uses the principles of engineering mechanics to study the behavior of biologic tissue exposed to injurious conditions. Injury biomechanics research relies upon analytical, experimental, and numerical simulation techniques to answer questions such as how an injury has occurred (injury mechanism), how tissue responds to specific injurious conditions, and what levels of exposure to force, acceleration, and so on are injurious to the body (injury tolerance).

One of the unique challenges faced by pediatric emergency medicine clinicians is distinguishing between inflicted and noninflicted injuries in children. Biomechanics is a tool that can aid in determining the compatibility between a child's injury and the reported mechanism of injury. Most of the current biomechanical research working toward distinguishing inflicted versus noninflicted injuries in children can be classified into 4 primary categories: (1) case-based investigation or assessment, (2) test dummy or human surrogate experiments, (3) computer modeling or simulation, and (4) animal injury models (Figure 1). A brief description of these categories of biomechanical research, as well as examples of studies using these various biomechanical approaches in the area of pediatric injury and child abuse, is provided below.

Case-Based Investigations or Assessments

A better understanding of injuries that can result from a specific event can be achieved through detailed investigations and dynamic reconstructions of how noninflicted injuries occur. Knowing the types of injuries that can result from a specific event type (eg, stair fall, bed fall) and understanding the dynamics of the event that led to a child's injuries can be important to those attempting to determine whether a stated cause and resulting injuries are compatible. For example, it would be useful for clinicians to know the possible types of injury that could be expected from a stair fall. Furthermore, an understanding of the dynamics of a fall event and associated

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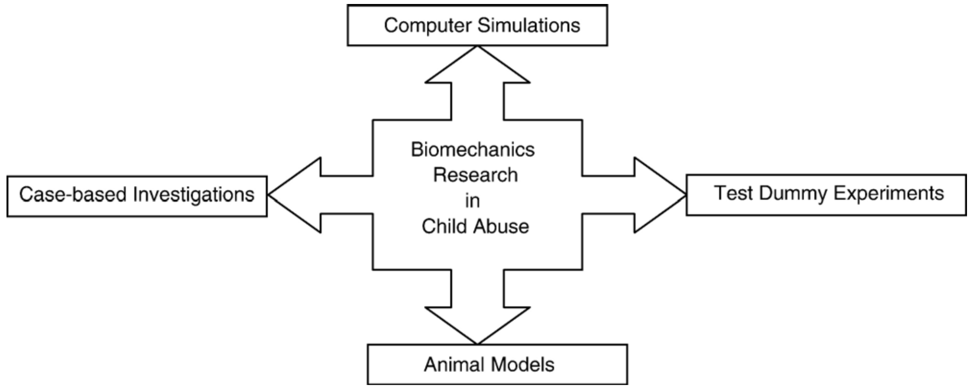

Figure 1 Classifications of biomechanics research contributing to the field of child abuse detection.

body contact points could aid in determining whether a child's injuries could have been produced from the history provided by the child's caregiver.

Characteristics of a fall such as the initial position, fall height, impact surface, and landing position are also important in understanding resulting injuries because these factors have been shown to be related to injury risk [1-5]. Furthermore, calculated biodynamic outcome measures of a fall, such as the child's energy, impact velocity, and momentum, can also provide insight into an event's relative injury-producing potential. These measures can be useful when attempting to make overall comparisons of fall events.

Examples of Studies Using Case-Based Investigations or Assessment

A 1977 study conducted by Snyder et al [6] investigated impact tolerances of the head and lower extremities in free-fall events occurring in children, female adults, and the elderly. This study used a combination of techniques and investigative strategies to create a database, analyze injury patterns, and define an association between biomechanical measures and injury severity. These researchers relied upon scene investigations, medical record assessment, theoretical biodynamic calculations, experimental free falls using anthropometric test devices (ATDs, commonly referred to as "test dummies"), and 2-dimensional computer simulation models to predict key biomechanical impact measures that have previously been correlated with injury risk. It was found that for given fall conditions, children were generally injured less severely than adults exposed to the same conditions. Whole-body energy, impact velocity, and momentum were calculated for each fall case. Correlations between injury severity level and whole-body biomechanical measures were observed only for headfirst type falls. For children 18 months and younger, a fall distance of 4 to 10 ft was determined to be the threshold for skull fracture. Headfirst falls from greater than 10 ft onto a rigid surface were predicted to result in skull fracture or concussion, and at least an Abbreviated Injury Scale (AIS) severity 2 score of AIS-2 (moderate) injuries for adults and children.

Pierce et al [7] used case-based assessment to gain a better understanding of femur fractures resulting from stair falls and to develop an injury plausibility model. Twenty-nine children and infants, 2 to 36 months old, who presented to the emergency department with a femur fracture from a reported stair fall, underwent a detailed history assessment, physical examination, and fracture characterization. Injury scene investigations and a biomechanical assessment of the event were conducted. A number of key factors, including the biomechanical compatibility of the injuries and event, were used in the injury model to distinguish between plausible and non-plausible scenarios. This study demonstrated the important role that biomechanical compatibility assessment plays when developing a predictive model. The study also determined key biomechanical measures such as energy, momentum, and impact velocity associated with each stair fall case. Among those cases determined plausible, momentum was found to be 10 times higher in transverse fractures as compared with buckle or spiral fractures. This type of biomechanical characterization can aid in the understanding of the conditions necessary to produce specific types of injuries.

Test Dummy or Human Surrogate Experiments

ATDs are human surrogates that have been used for many years in automotive crash studies to represent motor vehicle occupants. ATDs are a mechanical analogue of a human and provide opportunities to measure mechanical quantities such forces, strains, and accelerations during exposure to impact, accelerations, or other potentially injurious conditions using onboard instrumentation (eg, accelerometers, force sensors). These measurements can then be compared with established injury thresholds to provide an indication of the level of injury risk to a specific body region. ATDs must be designed to represent the anthropometrics (geometry), mass, and mass distribution of the target human; they must be biofidelic (human-like) in their response to impact, acceleration or other injurious conditions of interest; and they must be durable and repeatable in their response to a given exposure. Currently, there are approximately 16 ATDs representing infants and children that are commercially available. This number can be expected to grow in the future as the desire to better understand the biomechanical response of a child to various conditions increases. However, given the paucity of data regarding the biomechanical properties of children, development of biofidelic pediatric ATDs remains a significant challenge.

Although ATDs have been primarily used in the automotive crash safety area, more recently, efforts to investigate noncrash events such as falls (Figure 2) and shaking have relied upon ATDs to gain a better understanding of injury potential and factors that influence injury risk. These studies have laid a foundation toward building a knowledge base of injury risk associated with specific events and a better understanding of the types of injuries that may result from a specific event.

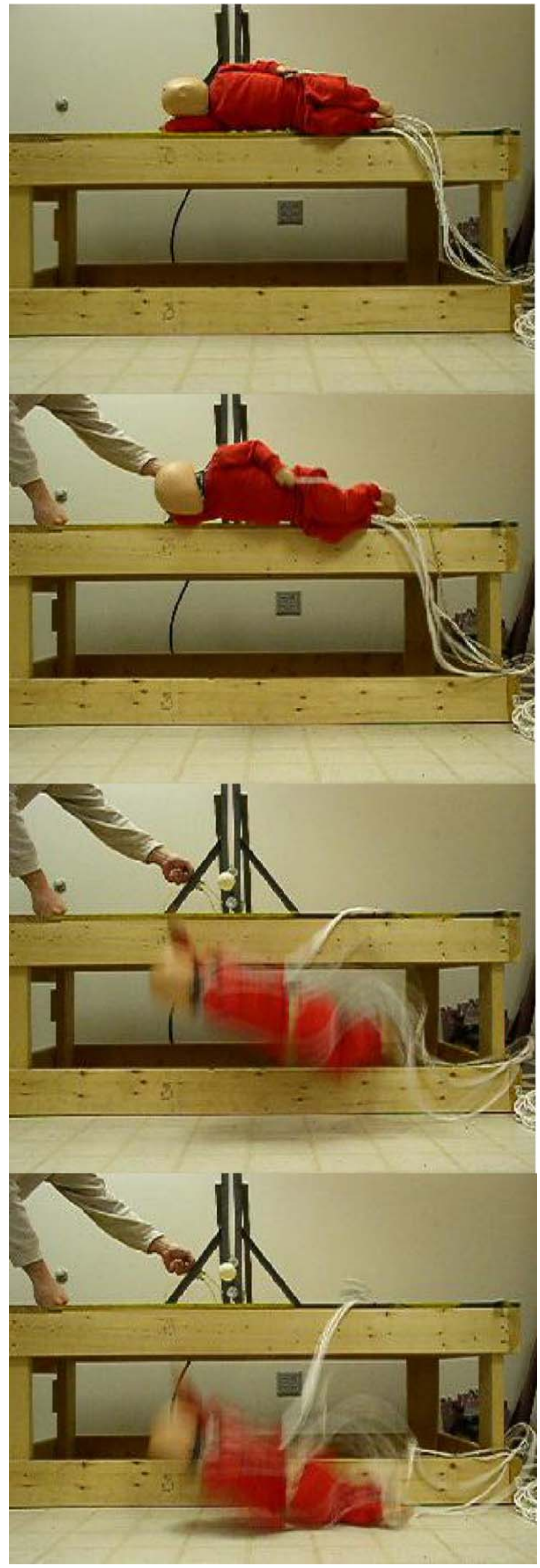

Figure 2 Example of test dummy used in bed fall experiments.

Examples of Studies Using Child Surrogates or Test Dummies

Prange et al [8] used a custom-built anthropomorphic surrogate representing a 1.5-month-old infant to investigate inflicted and noninflicted head injury risk. The surrogate used in this study consisted of a torso, neck, and head, with a single resistance-free hinged joint located at the C5 through C6 level to represent the neck, allowing neck flexion and extension in the sagittal plane. The weight of the surrogate's head and 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 (plastic) for the skull and latex rubber for the scalp. Fall experiments consisted of placing the test dummy in a supine position and dropping it from 1-, 3-, and 5-ft heights with the head in a slightly lower position than the body to assure headfirst impact. The impact surface was varied at each height and included crib mattress foam, carpet padding, and concrete. The effects of vigorous shaking and impacting the surrogate head onto different surfaces were also investigated in this study. The authors sought to describe the rotational response of the head because subdural hemorrhage and diffuse axonal injuries are thought to result from rotational acceleration of the head. The authors concluded that inflicted impacts onto hard surfaces were more likely to lead to inertial head injuries than shaking or headfirst falls from 5 ft.

Bertocci et al [9] assessed head and lower extremity injury risk associated with bed falls onto wood, padded carpet, linoleum, and playground foam impact surfaces using an instrumented Hybrid II 3-year-old ATD. The Hybrid II 3-year-old ATD is commonly used in automotive crash testing and represents the segment mass, mass distribution, and anthropometric measures of a 50th percentile 3-year-old child. In this study, the ATD was instrumented to measure linear head accelerations and femur loading during bed falls. The authors found that impact surface had an effect on outcome measures; however, there was a low risk of contact-type head injury (injuries resulting from the head colliding with a rigid surface, eg, skull fracture) and lower extremity fractures from bed falls onto the evaluated surfaces.

Jenny et al [10] investigated head injury risk in a number of different scenarios using 3 different ATDs. The ATDs used represented a 5.5-lb infant, a 7.7-lb infant, and a 6-month-old (17.2-lb) infant. The 6-month-old Child Restraint Air Bag Interaction (CRABI) ATD (First Technology Safety Systems, Plymouth, MI) 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 (Aprica, Osaka, Japan) 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. In this study, the various ATDs were shaken, thrown, bounced, and dropped in a series of experiments. Experimental results demonstrated that both the mass of the test dummy and characteristics of the test dummy 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 indicating that infants or younger children may be at greater risk for head injury for a given shaking event.

Computer Modeling or Simulation

Computer modeling is widely used to simulate a myriad of physical events and is a useful tool in engineering analysis and design. It 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. Computer modeling can also serve as a valuable tool in the investigation of noncrash events to better understand how injuries may occur, how the human body responds, and which factors may influence injury risk. Computer modeling is particularly useful in exploring how changes in a specific variable (eg, fall height, impact surface) can affect injury risk, reducing the need to conduct more costly physical experiments and providing answers to questions that might otherwise be unattainable. Studies investigating the influence of a single 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- or 3-dimensional systems. Geometric segments representing body segments, often defined as ellipsoids, are connected by joints that control the relative motion between 2 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 represent 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 and/or acceleration. The motion or response of the human body model is governed based upon the laws of physics. If the model is not governed by the laws of physics and is instead prescribed by the modeler, it is then referred to as an animation. 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. Also of key importance to developing reliable models is the need for validation. That is, the model must be shown to correlate well with a physical experiment before being used to predict outcomes of a similar event.

Modeling can be done using manual calculations, self-developed computer programs, or commercial computer software programs. Given the computational intensity necessary to develop 3-dimensional 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 requires a substantial amount of time. Examples of simulation software include MADYMO (TNO Automotive, Delft, the Netherlands), Dynaman (Gesac, Boonsboro, Md), and Visual Nastran 4D (MSC Software, Santa Anna, Calif). 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. Some software programs such as MADYMO and Visual Nastran 4D also offer the capability of finite element analysis where a single body segment can be treated as a series of small elements allowing for a more detailed analysis, but requiring significant increases in computational time.

Falls are often falsely reported in child abuse; therefore, it is important to understand the type of injuries and the factors that can influence injury risk associated with falls. Computer modeling can provide great insight into this clinical dilemma.

Examples of Studies Using Computer Modeling or Simulation

Mohan et al [11] conducted an early study to examine the details of headfirst falls in children 10 years and younger, and to estimate head impact tolerances (head accelerations and forces associated with impact from a fall that would be injurious). Thirty cases involved children 10 years and younger; 6 cases were chosen for in-depth analysis and evaluation using computer simulation. Witnesses were contacted and interviewed, and hospital records were obtained. Fall site investigations were conducted to capture fall characteristics. Head deflections, impact forces, and accelerations were estimated. MVMA 2-dimensional crash victim simulator was used to simulate each fall events. The models consisted of a 10-segment body that included flexibility of the cervical, thoracic, and lumbar spine regions. Anthropomorphic data, body segment mass, and mass distribution used in the models were derived from the literature based upon the fall victim's height, weight, and age. The authors found that headfirst falls onto a rigid surface (eg, concrete) from 39 in (1 m) or less were unlikely to cause skull fractures, whereas similar falls from 19.6 ft (6 m) were likely to cause skull fractures. The authors also found a positive correlation between head acceleration and increased head injury. When comparing headfirst falls onto different surfaces, simulations showed that peak head accelerations associated with impacts onto soil and sand were 15% to 50% of those values obtained during impacts onto rigid (concrete) surfaces. This study demonstrated the capabilities of computer simulation in promoting a better understanding of factors that can influence head injury in falls.

Bertocci et al [12] demonstrated the usefulness of computer simulation techniques in the investigation of pediatric stair fall events. Because stair falls are a common falsely reported scenario in child abuse, the aim of this study was to investigate the influence of stair characteristics on biomechanical outcomes. A computer simulation model of a 3-year old falling down stairs was developed using Working Model 3D (MSC Software, Santa Ana, CA) to investigate the influence that stair characteristics have on biomechanical measures associated with lower extremity injury risk. 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 influenced injury risk. The authors indicated that although absolute values of the outcome measures should not be relied upon in an unvalidated model such as this, relationships between fall characteristics and biomechanical measures can be studied through computer simulation.

Animal Injury Models

Researchers have also looked to animal models to gain a further understanding of injury mechanisms and injury thresholds because this knowledge might otherwise not be obtainable using human subjects. Although insight may be gained from these injury models, it is often at the cost of pain, suffering, and death of the animals used in the experiments. Therefore, animal models should be used as a last option after other alternative investigative methods have been exhausted. The utmost of care must be given to the design of animal model research to assure that outcomes will be translatable to the target human population and that findings will be of value. The assumption made in developing animal models is that the response to specific stimuli obtained in a laboratory animal or animal specimen will also be observable in humans outside of the laboratory. However, there is often uncertainty as to how well the animal or animal specimen represents the specific body region of interest in terms of structure and function, and whether the animal's biologic response parallels that of a human. Functional similarity (outcome) between the animal and human does not necessarily imply causal similarity (the mechanism to obtain the outcome) [13]. A high level of confidence regarding functional and causal similarity should be assured before embarking on animal studies and the development of animal models.

Animal injury biomechanical models have been used in a variety of ways in support of child abuse diagnosis, primarily with the intent to better understand response to injurious or noninjurious conditions, injury causation, and injury thresholds. For example, animal injury models have been used to gain an understanding of the effects of acceleration-deceleration and shaking on the brain, as well as to develop a predictive long bone fracture model. Although cadaveric response data have formed the basis of many adult injury thresholds, similar pediatric data have been lacking, and animal models have been relied on to fill a portion of the void.

Examples of Studies Developing Animal Injury Models

A pivotal early study by Marguilies and Thibault [14] developed an animal injury model to determine the threshold for diffuse axonal brain injury (DAI). This study explored the effects of inertial loading (noncontact) on the brain. At the time of this study, previous studies had focused primarily on the development of head injury thresholds associated with impact. In this study, the authors used a combination of approaches, including primate studies, physical experiments, and simulation models to develop tolerance criteria for DAI. In the animal model portion of the study, baboon heads were exposed to rotational acceleration without impact.

Diffuse axonal brain injury was found to occur most often in those baboons exposed to lateral rotations of the head. The derived tolerance criteria were found to be dependent upon rotational acceleration, rotational velocity, and brain mass. Using physical model experiments and analytical models, the authors extended the applicability of their animal studies and also described the relationship among rotational acceleration, rotational velocity, and the onset of diffuse axonal injury in humans, including infants. This tolerance criterion has been used extensively to evaluate whether specific events, particularly as it relates to shaking, could lead to DAI.

Because fractures are a common presentation in child abuse, Pierce et al [15] aimed to develop an infant femur fracture model that accounts for variation in bone mineralization. This study subjected infant porcine femurs to bending and torsional (twisting) loads to the point of fracture to determine bone strength. Bone geometry and DEXA measures (bone mineral density and bone mineral content) were assessed before mechanical testing. The authors found that bending conditions consistently produced transverse fractures within a given range of loads, and that a combination of geometric bone parameters and DEXA measures predicted bone bending strength. Torsional loading failed to produce consistent fracture morphology, likely because of test setup constraints. This study demonstrated that radiographic bone measures, obtained clinically, show promise in the development of a predictive immature femur fracture model. Such a model takes an initial step toward determining a specific child's femur resistance to fracture and in gaining an understanding of the conditions that a child may have been exposed to leading to their femur fracture.

Summary

Injury biomechanics presents an opportunity for engineers and clinicians to collaborate in addressing important clinical problems associated with the diagnosis of child abuse. Clinician-engineer teams have emerged around the country, bringing their expertise to bear on challenges in child abuse diagnosis. Creative educational and training programs bringing these professions together around the issues of child abuse are needed to make advances in the field. The biomechanical approaches described herein provide an overview of the approaches used in biomechanical research focused on child abuse and pediatric injury. Research Studies cited in this article should provide readers with an understanding of the potential contributions that injury biomechanics can provide in determining the compatibility between a child's injury and stated mechanism.

References

1. Macarthur C, Hu X, Wesson DE, et al. Risk factors for severe injuries associated with falls from playground equipment. Accid Anal Prev 2000;32:377-82.
2. Chalmers DJ, Marshall SW, Langley JD, et al. Height and surfacing as risk factors for injury in falls from playground equipment: a case-control study. Inj Prev 1996;2:98-104.
3. Mott A, Rolfe K, James R, et al. Safety of surfaces and equipment for children in playgrounds. Lancet 1997;349:1874-6.
4. Robinovitch SN, Chiu J. Surface stiffness affects impact force during a fall on the outstretched hand. J Orthop Res 1998;16:309-13.
5. Warner KG, Demling RH. The pathophysiology of free-fall injury. Ann Emerg Med 1986;15:1088-93.
6. Snyder RG, Foust DR, Bowman BM. UM-HSRI-77-8: study of impact tolerance through free-fall investigations. Highway Safety Research Institute, The University of Michigan, 1997.
7. Pierce MC, Bertocci G, Janosky J, et al. Femur fractures resulting from stair falls among children: an injury plausibility model. Pediatrics 2005;115:1712-22.
8. Prange MT, Coats B, Duhaime AC, et al. Anthropomorphic simulations of falls, shakes and inflicted impacts on infants. J Neurosurg 2003;99:143-50.
9. Bertocci GE, Pierce MC, Deemer E, et al. Using test dummy experiments to investigate pediatric injury risk in simulated short-distance falls. Arch Pediatr Adoles Med 2003;157:480-6.
10. Jenny C, Fukuda T, Rangarajan N, et al. Use of anatomic testing devices in modeling abusive and accidental head injuries [Abstract # 2913.447]. Pediatric Academic Society Conference Proceedings, San Francisco, CA, May 2006.
11. Mohan D, Bowman BM, Snyder RG, et al. A biomechanical analysis of head impact injuries to children. J Biomech Eng 1979;101: 250-60.
12. Bertocci GE, Pierce MC, Deemer E, et al. Computer simulation of stair falls to investigate scenarios in child abuse. Arch Pediatr Adolesc Med 2001;155:1008-14.
13. LaFollette H, Shanks N. Two models of models in biomedical research. Philos Q 1995;45:141-60.
14. Marguilies SS, Thibault L. A proposed tolerance criterion for diffuse axonal injury in man. J Biomech 1992;25:917-23.
15. Pierce MC, Valdevit A, Anderson L, et al. Biomechanical evaluation of dual-energy x-ray absorptiometry for predicting fracture loads of an infant femur for injury investigation: an in vitro porcine model. J Orthop Trauma 2000;14:571-6.