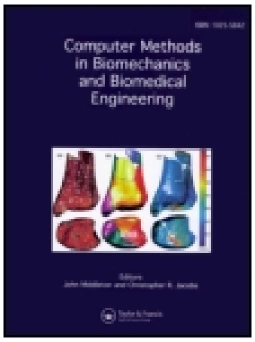

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Paediatric bed fall computer simulation model development and validation

Angela K. Thompson[a1] and Gina E. Bertocci[a,b,c]*

[a]*Mechanical Engineering, University of Louisville, Louisville, KY, USA;* [b]*Bioengineering, University of Louisville, Louisville, KY, USA;* [c]*Pediatrics, University of Louisville, Louisville, KY, USA*

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Falls from beds and other household furniture are common scenarios stated to conceal child abuse. Knowledge of the biomechanics associated with short-distance falls may aid clinicians in distinguishing between abusive and accidental injuries. Computer simulation is a useful tool to investigate injury-producing events and to study the effect of altering event parameters on injury risk. In this study, a paediatric bed fall computer simulation model was developed and validated. The simulation was created using Mathematical Dynamic Modeling® software with a child restraint air bag interaction (CRABI) 12-month-old anthropomorphic test device (ATD) representing the fall victim. The model was validated using data from physical fall experiments of the same scenario with an instrumented CRABI ATD. Validation was conducted using both observational and statistical comparisons. Future parametric sensitivity studies using this model will lead to an improved understanding of relationships between child (fall victim) parameters, fall environment parameters and injury potential.

Keywords: paediatric falls; computer simulation; model validation; MADYMO®

1. Introduction

Falls from beds and other household furniture are common scenarios stated to conceal child abuse (Duhaime et al. 1992; Leventhal et al. 1993; Strait et al. 1995; Shaw et al. 1997; Scherl et al. 2000). A better understanding of the true injury risk associated with these falls is needed to aid clinicians in distinguishing between abusive and accidental injuries. Fall environment factors, such as fall height and impact surface, as well as child factors, such as body mass index, have been shown in previous studies to be related to injury risk in short falls (Bertocci et al. 2003; Prange et al. 2003; Bertocci et al. 2004; Coats and Margulies 2008; Thompson et al. 2009; Ibrahim and Margulies 2010; Thompson et al. 2011). However, many of these studies have been limited by the biofidelity of anthropomorphic surrogates used to represent the fall victim (Bertocci et al. 2003; Prange et al. 2003; Bertocci et al. 2004; Coats and Margulies 2008; Thompson et al. 2009; Ibrahim and Margulies 2010). Moreover, little information is available regarding the injury tolerance and biomechanical response of children. Therefore, most paediatric surrogates are based on scaled adult cadaver or primate data and may not accurately represent a human child.

Computer simulation is a useful tool that can be used to investigate injury-producing events, and to study the effect of changing event parameters on injury risk. Computer simulation has been widely used by the automotive industry to study motor vehicle crash events, and has also been used in a few studies to investigate falls (O'Riordain et al. 2003; Doorly and Gilchrist 2006; Schulz et al. 2008; Doorly and Gilchrist 2009; Forero Rueda and Gilchrist 2009; Adamec et al. 2010). The development of a paediatric bed fall computer model can lead to a deeper understanding of relationships between biomechanical factors, fall environment parameters, child parameters and potential for injury. Additionally, a computer model can extend beyond surrogate experiments by allowing the user to vary surrogate properties. The purpose of this study was to develop a validated 3D computer model simulating an anthropomorphic test device (ATD) representing a 12-month-old child falling from a horizontal surface such as a bed. In a previous study (Thompson et al. 2011), rolling off of a bed or other horizontal surface was found to be the most common short-distance fall scenario in infants and toddlers. Therefore, in this study, a computer simulation model was developed to recreate the 'rolling off the bed' scenario. This model will later be used to investigate the effect of changing fall environment and ATD (fall victim) parameters on biomechanical measures and potential for injury.

2. Methods

A computer simulation model of a paediatric bed fall was developed using MAthematical DYnamic MOdeling® version 7.0 (MADYMO®; TNO Automotive Safety Solutions, Delft, the Netherlands). MADYMO® is a rigid body dynamics software. One advantage of MADYMO® is that it contains a built-in database of models representing the ATDs. In this study, the child restraint air bag interaction (CRABI) 12-month-old ATD represented the

*Corresponding author. Email: g.bertocci@louisville.edu

fall victim. This ATD represents a 50th percentile 12-month-old child in terms of overall height (74 cm) and mass (10 kg), as well as geometric and inertial properties of individual body segments. The model was validated using results from physical bed fall experiments with an instrumented CRABI 12-month-old ATD. Once validated, the predictive capability of the model was assessed by changing the impact surface type and comparing the outcome measures with the experimental results.

2.1 ATD fall experiments

Bed fall experiments were performed using the CRABI ATD (First Technology Safety Systems, Plymouth, MI). The ATD was placed in a side-lying position on a horizontal surface representing a bed (Figure 1). The bed was 61 cm (24 in.) above the ground. Before each fall, ATD joint angles were adjusted using a goniometer to ensure repeated positioning for all testing. Joints were calibrated to manufacturer specifications whereby the joint was tightened until the friction was just sufficient to support the weight of the limb. A pneumatic actuator was mounted to the horizontal surface representing the bed and used to push the ATD off the edge of the bed (Figure 1). Nine falls were conducted onto two different impact surfaces (playground foam and linoleum) for a total of 18 falls. The playground foam surface consisted of rubber tiles 61 × 61 cm, 5.1 cm thick. The linoleum surface was self-adhesive vinyl flooring 0.1 cm thick. The linoleum was adhered to a wood sub-floor (1.5 cm thick plywood), while the playground foam was placed over concrete.

The ATD was instrumented with nine accelerometers (Endevco, San Juan Capistrano, CA, Model 7264-2000) in triaxial arrangements at the centre of mass of the head, overall ATD centre of mass located at the midline within the torso and the pelvis. Two angular rate sensors (ATA Sensors, Albuquerque, NM, Model ARS-06) were also positioned in the head to measure head angular velocity in the anterior–posterior (AP) and medial–lateral (ML) directions. Additionally, a six-axis load cell (First Technology Safety Systems, Plymouth, MI, Model IF-954) was located at the superior aspect of the neck (approximately the C1 vertebrae location). Accelerometer and load cell data were sampled at 10,000 Hz and filtered according to the SAE J211 standards (Instrumentation for Impact Test Part 1 – Electronic Instrumentation 2003). Accelerations, angular velocities and neck forces were filtered at cut-off frequencies of 1000 Hz. Neck moments were filtered at cut-off frequencies of 600 Hz.

Each fall experiment was videotaped and captured using a 3D digital motion capture system (Motion Analysis Co., Santa Rosa, CA) to record fall dynamics. This system uses five infrared cameras at a 100 Hz frame rate. Forty-eight reflective markers (4–5 per body segment) were placed on the ATD, and one marker was placed on the actuator to determine actuator kinematics.

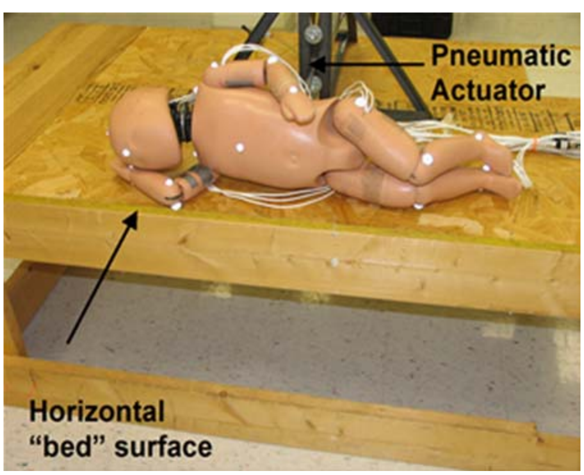

Figure 1. CRABI ATD in side-lying initial position for bed fall experiments. The pneumatic actuator (used to deliver a force to the posterior torso of the ATD to push it from the surface) is shown behind the ATD.

2.2 Model development

2.2.1 Fall environment

The fall environment used in the ATD experiments was recreated in the computer simulation model using rigid body planes and ellipsoids to represent the bed surface and impact surface. Appropriate geometry and surface properties were specified in the model. Initially, the model was created using the properties of playground foam as the impact surface. A rigid ellipsoid was created to represent the actuator. The velocity and acceleration of the actuator were specified to match those measured in the experiments (determined from digital motion capture data).

2.2.2 ATD properties

The 12-month-old CRABI ATD ellipsoid model from the MADYMO® database was imported into the model and positioned on the bed surface as in the experiments. The CRABI model consists of 32 bodies and was created with geometric and inertial properties to match the physical ATD. The CRABI model, developed by TNO-MADYMO®, was created by scaling down the Hybrid III 50th percentile adult ATD model. Anthropometric measurements on the physical ATD were also included in the model development by TNO-MADYMO®. The Hybrid III adult ATD model within the MADYMO® database was previously validated through both component tests and full-body sled impact tests (MADYMO Model Manual, December 2008; TNO Automotive Safety Solutions, Delft, The Netherlands). However, no specific validation was performed by TNO-MADYMO® for the CRABI model after scaling. Due to the lack of validation of the CRABI model and the poor performance of the ATD model (in comparing model outcome measures with results from ATD fall experiments) without any modifications, head and neck properties were measured through component testing of the physical ATD to improve the CRABI model. Additionally, segment masses in the original CRABI model differed from those of the physical ATD and were updated accordingly. Head contact properties used in our model were determined using an experimental head drop test as a part of our study. In this test, the instrumented head of the ATD was dropped from a height of 61 cm (same fall height used in experiments with the full ATD) onto a concrete surface. The head was positioned so that the impact orientation was similar to that found in the ATD fall experiments and the model (impacting on the left parietal aspect of the head). Three trials were conducted. A computer model of the head drop test was created using MADYMO®, and head stiffness properties were adjusted until the resultant head acceleration from the head drop model matched those in the experiments. The resulting load–deformation curve for the head (Figure 2) was then imported into our bed fall model.

Neck stiffness was determined using static testing whereby the neck was adjusted to a known angle and the bending moment was recorded using a load cell positioned at the superior aspect of the neck. The base of the neck was fixed and rotation angles were recorded using a goniometer (positioned at the centre of the superior aspect of the neck). Stiffness was determined for flexion, extension, lateral bending and torsion (Figure 3). The MADYMO® CRABI ATD model includes two spherical joints (three rotational degrees of freedom) at the superior and inferior aspects of the neck. Due to the head-first nature of the fall, an additional translation joint was added to the neck in our computer model to allow for neck compression.

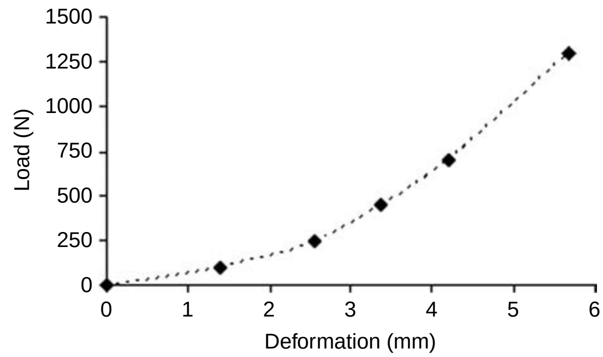

Figure 2. Load–deformation characteristic for CRABI head used in our computer model based upon head drop experiments.

2.2.3 Impact surface properties

In order to determine contact properties between the evaluated impact surfaces and the ATD, additional head drop experiments were performed. Since head contact properties were determined, impact surface properties could be deduced from head–impact surface interactions. Three head drop tests were performed (using the same conditions described in Section 2.2.2) onto each of the impact surfaces (playground foam and linoleum). The stiffness and damping properties of the impact surface in the model were then adjusted until the resulting head acceleration time histories matched those from the physical head drop experiments. The resulting surface stiffness values were 206 N/mm for playground foam and 867 N/mm for linoleum. A constant damping coefficient was insufficient to describe the interaction between the

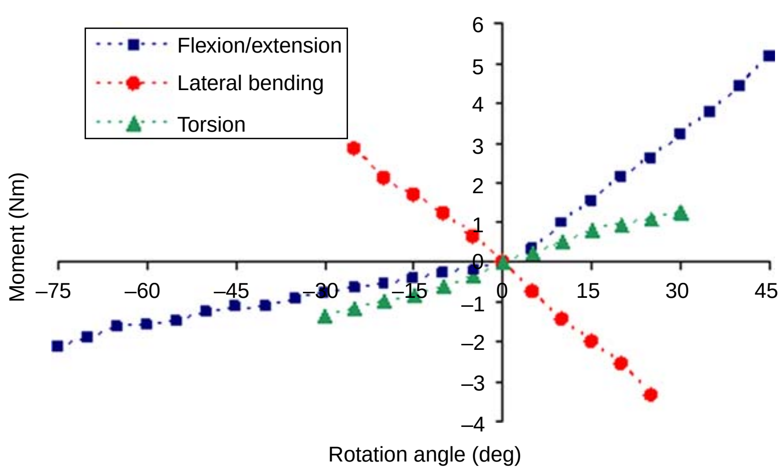

Figure 3. Moment vs. rotational displacement characteristics for CRABI neck used in our model based upon experimental evaluation. Note that flexion characteristics are represented by positive moments/displacements and extension characteristics as negative moments/displacements.

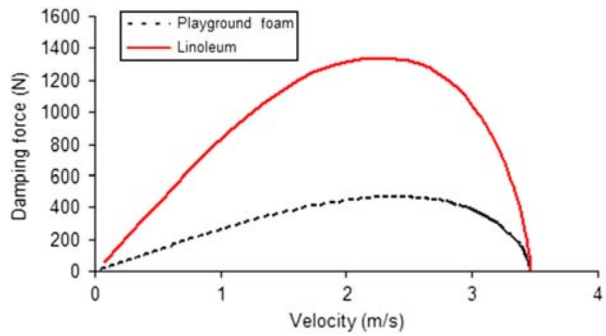

Figure 4. Damping force vs. velocity for head impact onto playground foam and linoleum surfaces.

head and impact surface. Therefore, damping was specified as a nonlinear function of both the velocity and penetration (deformation of the surface upon contact). The resulting damping force was calculated using

$$F_{\mathrm{d}} = c \cdot k \cdot x \cdot v,$$

where c is the damping coefficient (0.15 for playground foam and 0.30 for linoleum), k is the combined contact stiffness for the head and impact surface, x is the penetration and v is the velocity. The resulting damping characteristics for the two impact surfaces are shown in Figure 4. Note that damping properties were determined for the ATD head–impact surface interaction and do not necessarily represent the properties of the surfaces alone. Stiffness and damping properties resulting from the head drop tests were imported into the bed fall model.

2.3 *Model validation*

The first step in the validation process was a visual comparison of the fall dynamics. Both video and digital motion tracking data were used for visual comparisons between the experimental fall dynamics and those seen in the model. The initial position of the ATD was adjusted until the ATD dynamics in the model matched those seen in the experiments. Next, outcome measures from the model were compared to those from the experiments. The measures selected for comparison were the head, torso and pelvis resultant linear accelerations, head angular velocity in the AP and ML directions and upper neck resultant force and resultant moment. Only the primary impact event was investigated. For each outcome measure, the time–history curves from the nine experiments were used to create a min–max corridor. The model time–history curve was then overlaid onto this corridor to compare general curve profiles. The model was tuned until the curve profiles and peaks were similar. Parameters that were tuned include ATD position and orientation, stiffness properties for body segments (other than the head) and joints, including neck stiffness and damping properties. Although neck bending stiffnesses were measured for the physical ATD, these were measured under static (rather than dynamic) loading conditions, and were therefore used only as a starting point in the model.

The model outcome measures were statistically compared to the mean of the nine experimental trials using the playground foam surface. Four statistical tests were chosen to evaluate different aspects of the time–history comparison:

(1) Mean value comparison: The mean value of the model over the time window of the primary impact was compared to that of the mean of the experimental trials. The per cent difference between the two mean values was determined.
(2) Peak value comparison: The peak value and time occurrence of the peak value (in relation to the start of the primary impact) were compared between the model and experimental mean. The per cent difference in magnitude and the time difference between the two peak values were determined.
(3) Relative error: The mean relative error, the standard deviation of the relative error and the maximum relative error were computed to assess the error magnitude between the model and experimental mean over the time window of the primary impact.
(4) Correlation coefficient: The extent of a linear relationship between the model and experimental time–history curves was determined over the time window of the primary impact.

For each statistical test, criteria for validation were determined based on the range of variation measured in the bed fall experiments. Each of the nine experimental trials was compared to the mean of the nine trials using the four tests described above. The maximum per cent difference in mean value, the maximum per cent difference in peak value, the maximum relative error and the minimum correlation coefficient for the nine trials were used as acceptance criteria for model validation. This was repeated for each of the seven outcome measures. Then the model was compared to the experimental mean using the same four statistical tests. If the results of the statistical tests between the model and the experimental mean were as good or better than the acceptance criteria, the model was considered valid. Statistical comparison was made for the time window of the primary impact only. This began at the moment of impact and ended when the signal levelled off near zero (change in signal magnitude beyond this end point was less than 1% of the peak value).

2.4 *Assessment of model predictive capability*

Once the model was validated using playground foam impact surface properties, the surface contact properties were altered to represent the linoleum surface. Without making any additional changes to the model, the model outcomes were statistically compared to the mean of the experimental bed fall trials conducted onto linoleum using the four statistical tests described in Section 2.3. As with the validation tests performed for falls onto playground foam, the acceptance criteria for linoleum falls were determined by comparing each experimental trial to the mean of the experimental trials. If the results of the statistical tests between the model and the experimental mean were as good or better than the results of the statistical comparisons between experimental trials and the experimental mean, the model was considered valid.

3. Results

The first step in model validation was to visually compare fall dynamics between the model and ATD experiments. Figure 5 shows a time sequence of one of the experimental falls onto the playground foam surface along with the corresponding sequence generated from the computer model. Fall dynamics was found to be comparable between the computer model and experiments. In both the model and experiments, the ATD was initially in a side-lying position with the right upper extremity flexed at the elbow with the hand placed beneath the head. The ATD rolled off the horizontal 'bed' surface and impacted the floor surface on the lateral aspect of the head and the shoulder.

After visual comparison of the fall dynamics, outcome measures were compared both qualitatively and quantitatively between the simulation and experimental mean. Simulation model output, experimental mean and experimental min–max corridor time histories of the seven outcome measures for falls onto the playground foam surface were compared (Figures 6–8).

Table 1 shows the results of the validation statistical tests comparing the model and experimental means along with the acceptance criteria for falls onto playground foam. The model outcomes passed the acceptance criteria for each of the statistical tests.

Simulation model output, experimental mean and experimental min–max corridor time histories for each outcome measure were compared for falls onto the linoleum surface (Figures 9–11). Table 2 shows the results of the validation statistical tests between the model and experimental means along with the acceptance criteria. The comparison of the model outcomes with the experimental means passed all statistical tests except one (the torso acceleration mean value test).

4. Discussion

In this study, a computer simulation of a paediatric bed fall was developed and validated using experiments with a paediatric ATD. To the authors' knowledge, this is the first

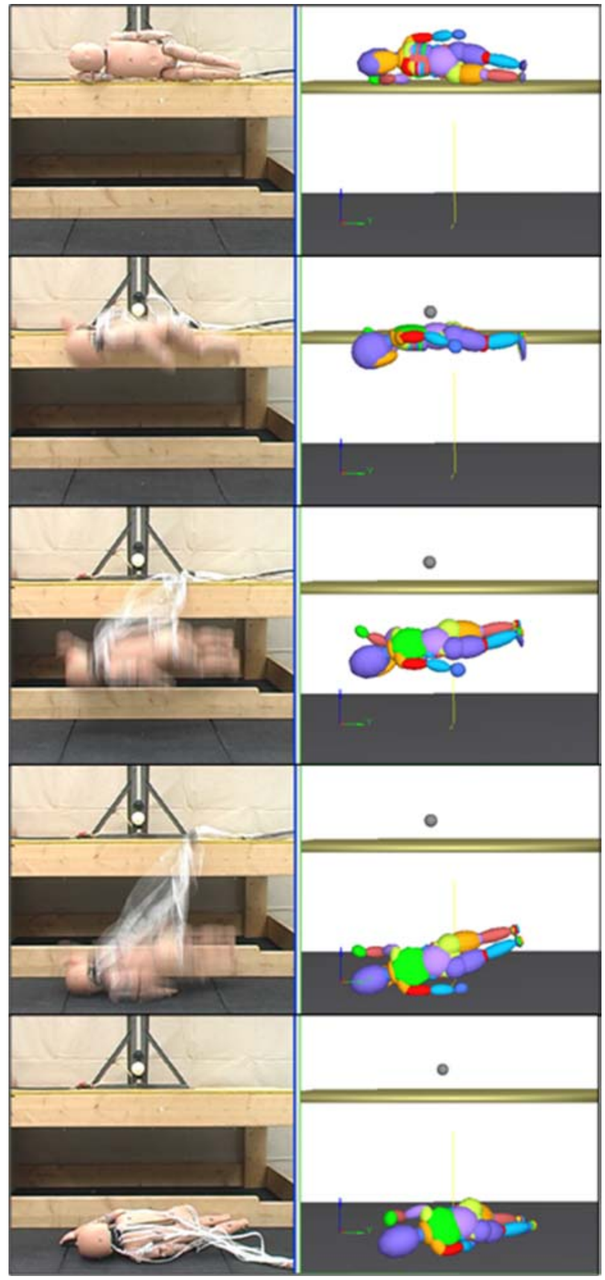

Figure 5. Time sequence comparison of ATD bed fall experiment and computer simulation model fall dynamics.

study that developed a computer simulation model of a short-distance fall using a 12-month-old ATD to represent the fall victim. The model was validated using both qualitative and quantitative methods, and the predictive capability of the model was assessed by altering surface properties and verifying model outcome measures. A validated computer model of paediatric falls will be useful for future investigation of the influence of model parameters on injury outcome measures. Findings from such a study can provide an improved understanding of the relationships between fall parameters (including both child

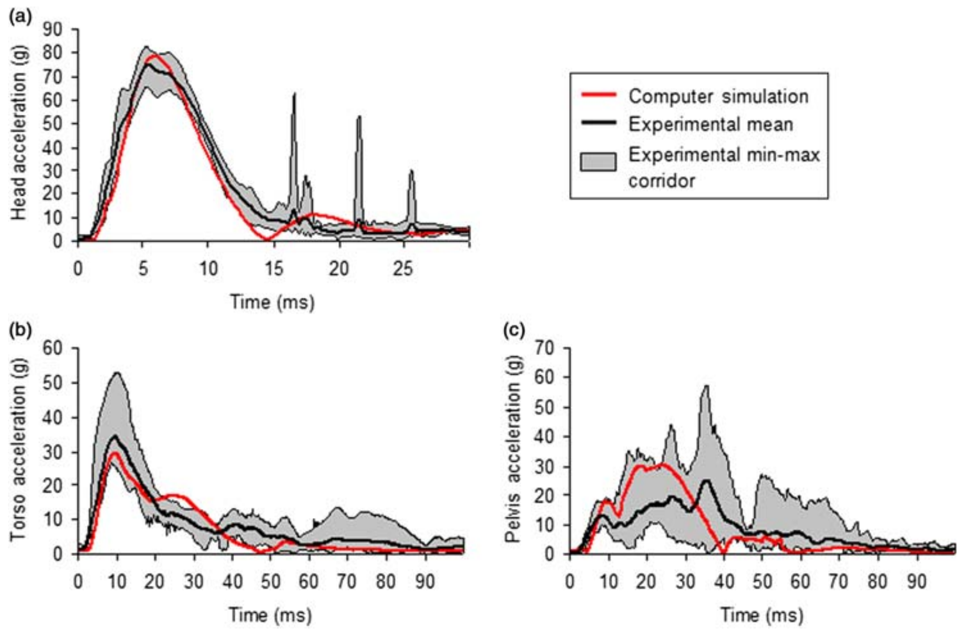

Figure 6. Computer simulation model and experimental time–history comparisons for falls onto playground foam: (a) resultant linear head acceleration, (b) resultant linear torso acceleration and (c) resultant linear pelvis acceleration.

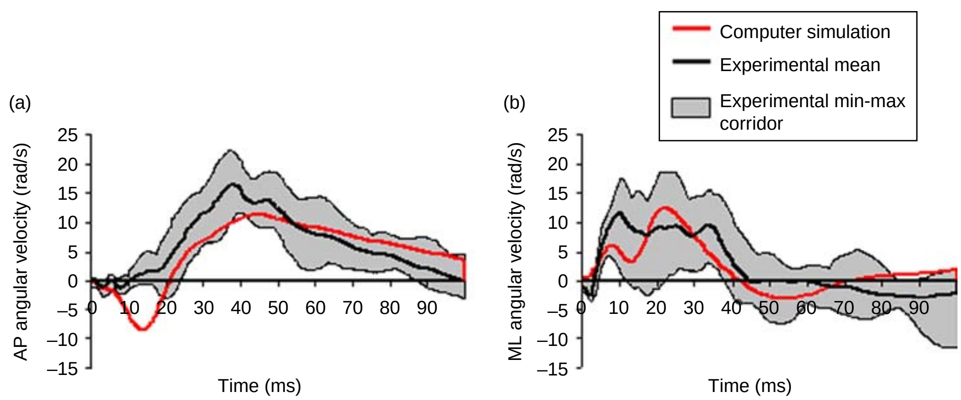

Figure 7. Computer simulation model and experimental time–history comparisons for falls onto playground foam: (a) AP angular head velocity and (b) ML angular head velocity.

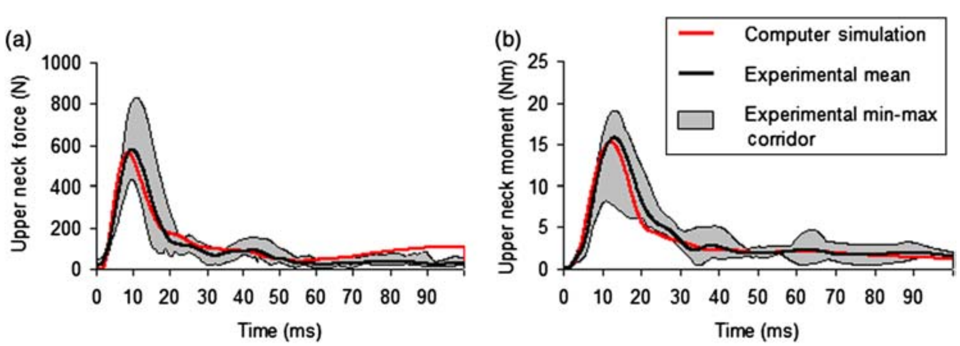

Figure 8. Computer simulation model and experimental time–history comparisons for falls onto playground foam: (a) resultant upper neck force and (b) resultant upper neck moment.

Table 1. Results of statistical tests to evaluate model validation; computer model vs. experimental mean for fall onto playground foam surface.

	Statistical test and acceptance criteria[a]						
	Mean value	Peak value		Relative error			
Outcome measure	Difference (%)	Difference (%)	Time difference (ms)	Mean (%)	Standard deviation (%)	Maximum (%)	Correlation coefficient
Head acceleration	8.8 (12.2)	4.9 (12.7)	0.6 (1.5)	35.0 (35.3)	34.0 (58.8)	149.2 (464.6)	0.98 (0.97)
Torso acceleration	15.5 (15.8)	14.3 (54.3)	0.0 (4.9)	42.2 (76.0)	22.0 (76.0)	86.8 (235.4)	0.92 (0.87)
Pelvis acceleration	1.3 (9.5)	20.7 (129.1)	11.2 (31.2)	54.4 (80.6)	26.6 (74.6)	131.4 (366.8)	0.71 (−0.27)
Head AP angular velocity	19.7 (39.3)	32.1 (34.9)	6.9 (8.7)	289.5 (304.0)	1283.4 (2220.4)	22,958.4 (55,285.3)	0.76 (0.70)
Head ML angular velocity	2.6 (88.4)	8.5 (63.4)	12.3 (25.6)	722.6 (1637.1)	4020.2 (9675.0)	58,897.65 (138,761.9)	0.77 (0.41)
Upper neck force	2.5 (36.8)	2.8 (43.6)	1.2 (1.2)	21.0 (50.2)	18.5 (31.4)	89.6 (115.4)	0.98 (0.93)
Upper neck moment	5.6 (30.4)	3.2 (48.6)	0.9 (2.0)	12.0 (34.5)	11.5 (28.1)	56.8 (110.6)	0.97 (0.91)

[a] Acceptance criteria shown in parentheses.

and environment characteristics) and injury potential in these falls.

During the model validation process, it was necessary to make several modifications to the 12-month-old CRABI model available within the MADYMO® database for use in our simulation model. In our simulated falls, the ATD rolled laterally off the 'bed' surface and landed head first with the lateral aspect of its head impacting the floor. Because of the head-first impact, a compression joint was added to the neck. Additionally, since the CRABI model was developed for use in high-energy motor vehicle crashes, head and neck properties were adjusted to more accurately represent the properties of the CRABI in short-distance falls (a relatively low-energy event). Component tests of the head and neck were conducted to determine more accurate mechanical properties for fall simulations.

Our paediatric bed fall model was validated following a rigorous procedure, and was based on those originally described by DSouza and Bertocci (2010) and Salipur and Bertocci (2010). This validation procedure first qualitatively compared the event dynamics, followed by statistical methods to compare outcome measures between the simulation and physical experiments. Four statistical tests were used to compare different aspects of the simulation and experimental time–history curves. Validation criteria for each statistical test were based on the experimental range. This study used unique criteria for each test and each outcome measure based on experimental variation in the fall scenario being modelled. Although the model passed each of the statistical validation tests, it was still necessary to assess the predictive capability of the model. This was done by altering the impact surface properties, running the fall simulation and repeating the validation statistical tests. The results of this predictive assessment showed that the model was valid for all outcome measures except one (torso acceleration). The difference in the mean value of the torso acceleration did not meet the acceptance criteria for the model simulating a fall onto linoleum. However, the difference between the model result and criteria was fairly small (2.1%). For the purposes of this study, the peak value, relative error and correlation tests represent more important aspects of comparison than the mean value test. The peak value is an important factor in assessing injury potential, and the relative error and correlation tests compare the outcome measure time histories over the entire impact duration. Since the torso acceleration (in the linoleum fall) passes the peak value, relative error and correlation tests and the time–history profiles are in reasonable agreement (Figure 9), we consider this outcome measure valid along with the others that were assessed. In terms of the outcome measures of the seven models evaluated (head linear acceleration, torso linear acceleration, pelvis linear acceleration, head AP angular velocity, head ML angular velocity, upper neck force and upper neck moment), our model provided a

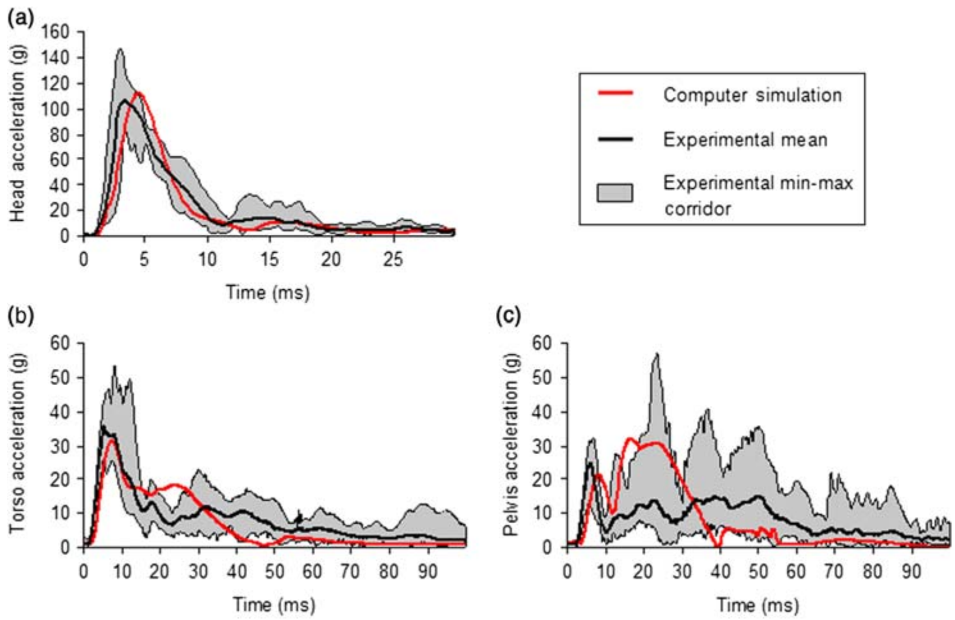

Figure 9. Computer simulation model and experimental time–history comparisons for falls onto linoleum: (a) resultant linear head acceleration, (b) resultant linear torso acceleration and (c) resultant linear pelvis acceleration.

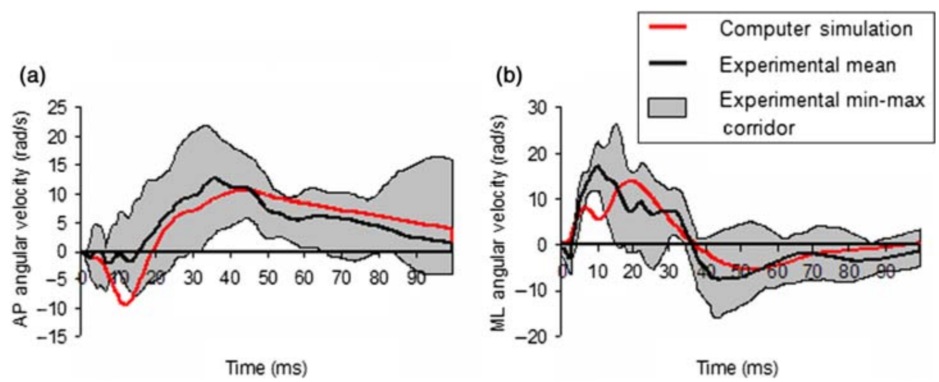

Figure 10. Computer simulation model and experimental time–history comparisons for falls onto linoleum: (a) AP angular head velocity and (b) ML angular head velocity.

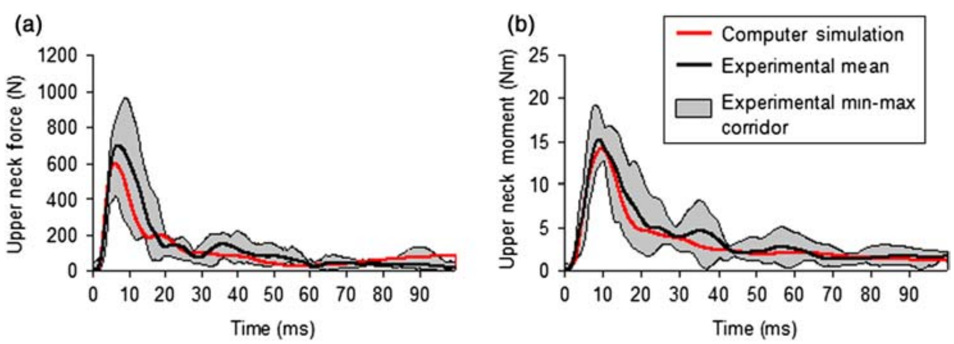

Figure 11. Computer simulation model and experimental time–history comparisons for falls onto linoleum: (a) resultant upper neck force and (b) resultant upper neck moment.

Table 2. Results of statistical tests to evaluate model predictive capability; computer model vs. experimental mean for fall onto linoleum surface.

	Statistical test and acceptance criteria[a]						
	Mean value	Peak value		Relative error			
Outcome measure	Difference (%)	Difference (%)	Time difference (ms)	Mean (%)	Standard deviation (%)	Maximum (%)	Correlation coefficient
Head acceleration	7.3 (11.4)	5.2 (38.0)	1.1 (1.8)	26.2 (55.7)	16.9 (40.1)	82.3 (144.9)	0.94 (0.82)
Torso acceleration	16.8 (14.7)	11.7 (50.0)	2.1 (6.7)	54.0 (73.3)	29.1 (83.3)	168.6 (327.8)	0.83 (0.83)
Pelvis acceleration	0.9 (8.5)	28.2 (129.1)	10.5 (44.7)	84.0 (88.5)	51.4 (80.0)	273.6 (319.4)	0.42 (0.16)
Head AP angular velocity	2.8 (91.4)	17.3 (73.1)	7.9 (9.2)	186.5 (281.2)	1603.1 (2558.1)	49,693.0 (79,399.8)	0.82 (0.57)
Head ML angular velocity	103.8 (252.6)	18.3 (54.8)	9.1 (13.0)	64.4 (161.8)	210.1 (1597.3)	5910.0 (50,354.5)	0.87 (0.43)
Upper neck force	20.5 (31.8)	14.2 (40.5)	1.0 (2.2)	30.2 (45.4)	16.1 (39.5)	78.0 (270.7)	0.95 (0.87)
Upper neck moment	13.0 (30.9)	6.4 (27.1)	0.8 (4.4)	17.5 (43.6)	12.3 (28.7)	55.8 (122.4)	0.98 (0.85)

Note: Shaded cell indicates validation criteria not met.
[a]Acceptance criteria shown in parentheses.

reasonable prediction of a 12-month-old CRABI fall onto a linoleum surface.

Although several studies have evaluated falls using computer simulation, most have focused on reconstructions of real-world fall events. Forero Rueda and Gilchrist (2009), O'Riordain et al. (2003), Doorly and Gilchrist (2006) and Adamec et al. (2010) reconstructed falls in MADYMO® based on eyewitness accounts and information collected from the scene of the fall. The subjects in these studies ranged in age from 6 to 76 years. These studies use human body (non-ATD) models within MADYMO® to represent the subjects. Within MADYMO®, these human body models have been validated. However, no additional validation was performed by the authors of those studies for the fall scenario being modelled. After initial reconstruction of the fall event, the sensitivity of the model to initial conditions was investigated. These studies provide useful information about fall dynamics and model sensitivity to input parameters. However, the results are limited because no validation was performed of the specific scenario being modelled.

In a study by Schulz, a bed fall model of a Hybrid III adult ATD was created using LifeMOD software (LifeModeler, Inc.; San Clemente, CA), and the results were compared to a physical bed fall experiment with the ATD. The ATD was initially lying supine on a bed, and was rolled from the bed surface so that it impacted the floor head first. Although the outcomes of the computer model were compared to the experimental outcomes, no validation process was conducted. Rather several simulations were performed to determine the effect of 2D vs. 3D modelling techniques as well as simulations beginning just before impact vs. simulations of the entire fall. It was found that 3D simulations of the entire fall event provided head acceleration results most similar to those measured in the physical experiments.

Our computer simulation model has several limitations. Most importantly, the model was based on ATD experiments and thus retains any biofidelity limitations of the ATD in terms of representing a human child. This model is not intended to provide absolute predictions of injury in paediatric falls. Rather the model was developed to study relationships between fall environment and ATD parameters and measures related to injury potential. Although the predictive capability of our model was assessed by altering a single parameter (impact surface), the model's predictive capability may be diminished with simultaneous changes in multiple input parameters. Additionally, our model's predictive capabilities are specific to the investigated scenario and are not generalizable to all types of paediatric falls or to children of varying ages experiencing a bed fall. In this study, seven outcome measures (head acceleration, torso acceleration, pelvis acceleration, head AP angular velocity, head ML angular velocity, neck force and neck moment) were used to validate the model. These outcome measures were selected because fall dynamics and head and neck injury measures will be investigated in future parametric sensitivity studies. In order to study other outcome measures (e.g. extremity loading), those measures must also be included in the validation process. Four statistical tests were chosen for validation that assessed different aspects of model outcome measures. Limitations in using the relative error test became evident when evaluating the angular velocity data. Where the velocity data neared zero, the relative error values were extremely high. Other tests could provide improved assessment of comparison for outcome measures with values near zero. Lastly, it should be noted that computer simulations are simplified and discretised representations of real-world events, and therefore may lack accuracy in predicting these events.

5. Conclusion

A computer simulation model of a 12-month-old child surrogate falling from a horizontal surface representing a bed has been developed. The model was validated using data from physical fall experiments conducted using a 12-month-old CRABI ATD to represent the fall victim. General comparison of fall dynamics, statistical comparison of key outcome measures and assessment of the model predictive capabilities were included in the validation process. This model will serve as a useful tool for studying relationships between fall parameters and injury potential. In future sensitivity analyses, fall environment and ATD parameters will be varied to investigate their effect on injury outcome measures. In particular, altering ATD properties within the model may lead to an improved understanding of child (fall victim) characteristics as they relate to injury risk in short-distance falls.

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Note

1. Email: angela.thompson@louisville.edu

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