Accident Analysis and Prevention 50 (2013) 16–24

Contents lists available at SciVerse ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Assessment of injury potential in pediatric bed fall experiments using an anthropomorphic test device

Angela Thompson[a], Gina Bertocci[a,b,c,*], Mary C. Pierce[d]

[a] Mechanical Engineering, University of Louisville, Louisville, KY, USA
[b] Pediatrics, University of Louisville, Louisville, KY, USA
[c] Bioengineering, University of Louisville, Louisville, KY, USA
[d] Children's Memorial Hospital, Northwestern University's Feinberg School of Medicine, Chicago, IL, USA

ARTICLE INFO

Article history:
Received 9 February 2012
Received in revised form 23 July 2012
Accepted 6 September 2012

Keywords:
Accidental falls
Biomechanics
Child abuse
Injury assessment

ABSTRACT

Falls from beds and other furniture are common scenarios provided to conceal child abuse but are also common occurrences in young children. A better understanding of injury potential in short-distance falls could aid clinicians in distinguishing abusive from accidental injuries. Therefore, this study investigated biomechanical outcomes related to injury potential in falls from beds and other horizontal surfaces using an anthropomorphic test device representing a 12-month-old child. The potential for head, neck, and extremity injuries and differences due to varying impact surfaces were examined. Linoleum over concrete was associated with the greatest potential for head and neck injury compared to other evaluated surfaces (linoleum over wood, carpet, wood, playground foam). The potential for severe head and extremity injuries was low for most evaluated surfaces. However, results suggest that concussion and humerus fracture may be possible in these falls. More serious head injuries may be possible particularly for falls onto linoleum over concrete. Neck injury potential in pediatric falls should be studied further as limitations in ATD biofidelity and neck injury thresholds based solely on sagittal plane motion reduce accuracy in pediatric neck injury assessment. In future studies, limitations in ATD biofidelity and pediatric injury thresholds should be addressed to improve accuracy in injury potential assessments for pediatric short-distance falls. Additionally, varying initial conditions or pre-fall positioning should be examined for their influence on injury potential.

1. Introduction

Falls from beds and other furniture are common scenarios provided to conceal child abuse (Duhaime et al., 1992; Leventhal et al., 1993; Strait et al., 1995; Shaw et al., 1997; Scherl et al., 2000). However, short-distance household falls are common occurrences in young children and sometimes result in injury. Because of this, clinicians may have difficulty distinguishing between accidental and inflicted injuries, particularly when the stated scenario is a household fall. Objective assessments of injury potential in these falls may aid clinicians in distinguishing between abusive and accidental injuries. The biomechanics associated with short-distance falls (typically defined as falls from heights less than 4 ft) has been investigated in previous studies, but primarily focused on head injury outcomes (Bertocci et al., 2003, 2004; Prange et al., 2003; Coats and Margulies, 2008; Thompson et al., 2009; Ibrahim and Margulies, 2010). In this study, biomechanical measures relating to head, neck, and extremity injury were examined.

To investigate outcomes relating to injury potential in short-distance household falls, simulations of falls from a horizontal surface (representing a bed or other elevated furniture surface) using a 12-month-old anthropomorphic test device (ATD) were performed. In a clinical study of pediatric falls, rolling off of a bed or other horizontal surface was found to be the most common short-distance fall scenario in infants and toddlers (Thompson et al., 2011). Therefore, in this study, the ATD was positioned to recreate this "rolling off the bed" scenario. The effect of different impact surfaces on injury potential was also examined.

2. Methods

2.1. Test setup

A child restraint air bag interaction (CRABI) 12-month-old ATD (First Technology Safety Systems, Plymouth, MI) was placed on the edge of a 24 in. (61 cm) high horizontal surface representing a bed,

* Corresponding author at: 500 S. Preston St., University of Louisville, Health Science Research Tower, Rm 204, Louisville, KY 40202, USA. Tel.: +1 502 852 0296.
E-mail addresses: angela.thompson@louisville.edu (A. Thompson), g.bertocci@louisville.edu (G. Bertocci), mpierce@luriechildrens.org (M.C. Pierce).

0001-4575/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.aap.2012.09.011

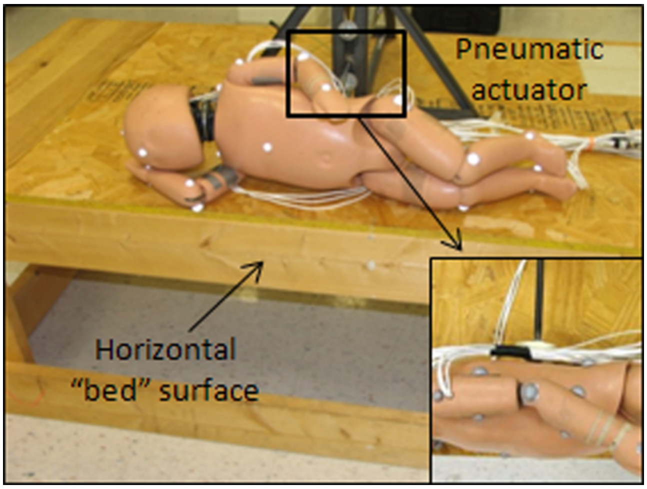

Fig. 1. CRABI anthropomorphic test device (ATD) in side-lying initial position for bed fall experiments. The pneumatic actuator (used to deliver a force to the posterior torso of the ATD to push it from the surface) is shown behind the ATD.

couch, or other similar furniture (Fig. 1). The ATD was positioned on the bed in an initial side-lying position and pushed from the surface onto the floor using a pneumatic actuator. The actuator was positioned at the ATD posterior mid-torso (approximately the center of mass location). The actuator provided a consistent initial force just sufficient to push the ATD from the bed surface. Actuator velocity was measured using a motion capture system; peak velocity was 0.95 m/s. Five different impact surfaces were evaluated during the fall experiments. Nine fall trials were performed for each fall scenario based upon a power analysis of prior experiments (Thompson et al., 2009).

2.1.1. ATD instrumentation

The CRABI ATD represents a 50th percentile 12-month-old child in terms of overall height (29.7 in./0.75 m) and mass (21.8 lb/9.9 kg), as well as geometric and inertial properties of individual body segments. The ATD was instrumented with triaxial linear accelerometers (Endevco, Model 7264-2000) located at the center of mass of the head, the overall body center of mass in the torso, and the pelvis. Additionally, two angular rate sensors (ATA Sensors, Model ARS-06) were placed at the center of mass of the head to measure angular velocities in the anterior–posterior (AP) and medial–lateral (ML) directions. Two six-axis load cells (First Technology Safety Systems, Model IF-954) were located at the superior and inferior aspects of the neck (approximately the C1 and C7 vertebrae locations) to measure neck loads. Three uniaxial strain gages and one shear strain gage (Vishay Micro-Measurements, Models CEA-13-125UN-350 and CEA-13-062UV-350) were adhered to each extremity at the longitudinal center of a metal rod representing the humerus or femur. The strains from the three uniaxial gages (120 degrees apart around the rod circumference) were used to determine humerus and femur axial loads and moments, and the strain measured by the shear strain gage was used to determine torsional loads.

Prior to each fall, ATD joint angles were adjusted using a goniometer to ensure repeated positioning for all trials (Table 1). Joints were calibrated to manufacturer specifications: tighten until the friction is just sufficient to support the weight of the limb.

2.1.2. Impact surfaces

Five different impact surfaces were evaluated during fall experiments: playground foam, padded carpet, wood, and two types of linoleum flooring (Linoleum A and Linoleum B). These surfaces were selected to simulate some common household surfaces, and also to provide surfaces with a range of stiffnesses. Linoleum A was no-wax self-adhesive vinyl flooring adhered to a wooden platform (1 mm or 0.04 in. thick). The platform (which served as the wood surface) was 183 cm × 183 cm (6 ft × 6 ft) and consisted of 1.9 cm (3/4 in.) plywood covering 5.1 cm × 10.2 cm (2 in. × 4 in.) joists spaced 40.6 cm (16 in.) from the center of one joist to the center of the next. Linoleum B was linoleum tile, 0.32 cm (1/8 in.) thick placed over a concrete floor. The playground foam surface consisted of 61 cm × 61 cm (2 ft × 2 ft) tiles, 5.1 cm (2 in.) thick, and was placed over a concrete subfloor. The carpet was open loop and was 1.3 cm (1/2 in.) thick with 1.0 cm (3/8 in.) thick foam padding and was tacked to the wooden platform.

Table 1
Initial ATD joint angles.

Initial joint angle positions (degrees)	
Right shoulder angle	140°
Right elbow angle	100°
Left shoulder angle	0°
Left elbow angle	150°
Hip angle (both)	150°
Knee angle (both)	150°

2.2. Data acquisition and analysis

A LabView program was developed for data acquisition. Accelerometer, rate sensor, load cell, and strain data were sampled at 10,000 Hz and filtered according to SAE J211 standards. The filter was a 4th order low-pass Butterworth filter. Head acceleration, angular velocity, and neck force data were filtered with a 1000 Hz cut off frequency. Neck moments and femur and humerus strains were filtered with a 600 Hz cutoff. All falls were videotaped (30 Hz) to capture overall fall dynamics.

2.2.1. Head injury outcomes

Peak resultant linear head accelerations were determined. Additionally, angular head accelerations were determined by differentiating the measured angular head velocities from the angular rate sensors. Peak angular accelerations, peak change in angular velocities, and impact durations were determined for each fall trial for comparison with published head injury thresholds.

2.2.2. Neck injury outcomes

Peak neck loads at the occipital condyles were determined for comparison with proposed injury criteria. Neck loads were transformed from the upper neck load cell to the occipital condyle location in accordance with the procedure described by Eppinger et al. (1999). Also, neck forces and moments were used to calculate neck injury criteria, or N_{ij} values, for combined axial loading and moments as established by the National Highway Traffic Safety Administration (NHTSA) (Eppinger et al., 1999). N_{ij} were calculated as

$$N_{ij} = \frac{F_z}{F_{int}} + \frac{M_y}{M_{int}} \quad (1)$$

where the subscripts ij represent the four combined loading mechanisms in the sagittal plane: tension–extension (TE), tension–flexion (TF), compression–extension (CE), and compression–flexion (CF). F_z and M_y are the tension/compression force and flexion/extension moment, respectively, measured at the occipital condyles and F_{int} and M_{int} are the critical load values (Table 2).

2.2.3. Upper and lower extremity injury outcomes

The measured strains were used to determine bilateral axial compression, bending moment, and torsional arm and leg loads