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The effect of hardhats on head and neck response to vertical impacts from large construction objects

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ABSTRACT

We evaluated the effectiveness of hardhats in attenuating head acceleration and neck force in vertical impacts from large construction objects. Two weight-matched objects (lead shot bag and concrete block) weighing 9.1 kg were dropped from three heights (0.91 m, 1.83 m and 2.74 m) onto the head of a 50th percentile male Hybrid III anthropomorphic test device (ATD). Two headgear conditions were tested: no head protection and an ANSI Type-I, Class-E hardhat. A third headgear condition (snow sport helmet) was tested at 1.83 m for comparison with the hardhat. Hardhats significantly reduced the resultant linear acceleration for the concrete block impacts by 70–95% when compared to the unprotected head condition. Upper neck compression was also significantly reduced by 26–60% with the use of a hardhat when compared to the unprotected head condition for the 0.91 and 1.83 m drop heights for both lead shot and concrete block drop objects. In this study we found that hardhats can be effective in reducing both head accelerations and compressive neck forces for large construction objects in vertical impacts.

1. Introduction

According to the Workplace Injury Database compiled by the US Bureau of Labor Statistics, there were on average 100 fatal and 7300 non-fatal head injuries per year sustained from falling objects on the job in the US between 2003 and 2012 (BLS, 2013). The US Department of Labor's Occupational Safety and Health Administration (OSHA) requires employees to wear head protection if: objects might fall from above and strike them on the head; they might bump their heads against fixed objects; or, there is a possibility of accidental head contact with electrical hazards. To this end, hardhats are chosen typically for head protection at construction sites, manufacturing facilities, and industrial locations.

OSHA requires that protective headgear meet the American National Standards Institute (ANSI) Standard Z89.1 – Protective Headgear for Industrial Workers. ANSI Z89.1-2009 states that its purpose is to establish minimum performance requirements for protective helmets that reduce the forces of impact and penetration (ANSI, 2009). This standard also states that protective helmets provide limited protection and are effective against small tools, small pieces of wood, bolts, nuts, rivets, sparks and similar hazards. Construction materials and industrial equipment, however, can be more massive than the small objects described in the ANSI Z89.1-2009. A query of the National Electronic Injury Surveillance System (NEISS) database from the US Consumer Product Safety Commission (CPSC) resulted in cases with objects such as 2 × 4 s, sheet metal, bricks and metal pipes falling and injuring patients.

Though there have been many studies in which data were collected to examine the injury mitigation capabilities of recreational sports helmets (Funk et al., 2007; Greenwald et al., 2008; Guskiewicz et al., 2007; Mertz et al., 2003; Scher et al., 2006) and motorcycle helmets (Scher et al., 2009), these studies do not translate well to hardhats. Recreational sports and motorcycle helmets have energy attenuating foam (typically expanded polystyrene or expanded polypropylene) that rests between the outer shell and the head. When a large impact force is applied to the helmet, the energy attenuating foam compresses and cracks to dissipate energy. Unlike the recreational sports and motorcycle helmets, hardhats use a suspension system (webbing and/or plastic straps) to hold the hard shell off the head. Deformation of the suspension system components and shell can attenuate energy from an impact. Because the

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Table 1
Table of tests conducted. X's denote the categories in which tests were conducted. Three tests were conducted for each category.

Drop height (m)	Unhelmeted		Hardhat		Snow sport helmet	
	Concrete block	Lead shot	Concrete block	Lead shot	Concrete block	Lead shot
0.91	X	X	X	X		
1.83	X	X	X	X	X	X
2.74	X	X	X	X		

design and materials are different, mitigation data from research on recreational sports and motorcycle helmets would likely not apply well to hardhats.

The purpose of this study was to evaluate the head injury mitigation afforded by a standard (Type-I) hardhat during impacts from larger falling objects, similar to those found at construction sites. We hypothesize that hardhats will reduce significantly head accelerations and neck forces compared to the unprotected condition at all drop heights tested, based on an experimental repeated-measures study design.

2. Materials and methods

Testing was conducted at the Center for Advanced Product Evaluation (CAPE). Construction objects were dropped from specified heights onto the head of a 50th percentile male Hybrid III anthropomorphic test device (ATD). Two weight-matched construction objects of different materials were dropped: (1) a 9.1 kg (20 lb) hollow concrete mason half block, and (2) a 9.1 kg (20 lb) bag of lead shot. Lead shot was chosen to represent construction objects that can conform such as, a bag of concrete mix or a box of nails. Three different drop heights were selected: 0.91 m (3 ft), 1.83 m (6 ft), and 2.74 m (9 ft), measured from the top of the head to the bottom of the dropped object. The ATD was placed in an upright-seated position with back support and both arms supported to prevent lateral motion; see Fig. 1. For each test, the experimenter dropped the construction object, allowing it to fall freely and impact the ATD (with or without head protection) near the vertex of the head.

For each drop height, tests were run with the two headgear conditions: (1) with no head protection and (2) with an ANSI Type-I, Class-E hardhat with a 4-point plastic ratchet suspension that met or exceeded the requirements in ANSI/ISEA Z89.1-2009. All hardhats were manufactured between August 2012 and February 2013 (less than 8 months prior to testing). In addition, for the 1.83 m drop height, a set of tests using each construction object was conducted with recreational snow-sports helmets that met or exceeded the requirements of ASTM Standard F2040 – Standard Specification for Helmets Used for Recreational Snow Sports. Three tests were conducted for each construction object, drop height, and headgear condition combination (Table 1). For all tests that used head protection, a double layer of nylons was applied to the ATD to reduce the friction between the head and the hardhat or helmet. Each piece of head protection was placed on the head and adjusted according to the standard or the manufacturer's instructions. Ratchet straps were adjusted to fit tightly on the ATD head and then rotated back one click.

A linear, triaxial accelerometer (3× Endevco, Model No. 7264B-2000, San Juan Capistrano, California) was mounted at the center-of-mass of the ATD head; the range of each accelerometer was ±1000 Gs (resolution: 0.03 Gs) along each axis. Angular velocity sensors (DTS, Model No. ARS-8K and ARS-1500, Seal Beach, CA) measured the rotation rate of the head; the range was ±26 rad/s (resolution: 0.0008 rad/s) along each axis. A six-axis load cell was mounted at the upper neck (Humanetics, Model No. 1716A, Rochester Hills, Michigan); it had a range of ±8900 N (resolution: 0.22 N) in the fore-aft and lateral directions, ±13,350 N (resolution: 0.40 N) along the vertical axis, and a torque range of ±280 Nm (resolution: 0.004 Nm) about each axis. All ATD transducers conform to SAE J2570. Data were acquired using a Messring NA33 16-bit high-speed data acquisition system (Krailling, Germany) at a sampling frequency of 20 kHz and using a 4 kHz anti-alias filter; the data acquisition conformed to SAE Standard J211-1 – Instrumentation for Impact Test (SAE J211).

2.1. Data processing

All data filtering and processing conformed to SAE J211 and SAE Standard J1727 – Calculation Guidelines for Impact Testing. For each trial, the resultant linear head acceleration was determined. The Head Injury Criterion (HIC) values were calculated for each trial using Eq. (1):

$$\mathrm{HIC} = \left[\frac{1}{t_2 - t_1}\int_{t1}^{t2} a dt\right]^{2.5}(t_2 - t_1) \quad (1)$$

where a is the resultant head acceleration, and t_1 and t_2 were chosen over a 15 ms interval such that the equation was maximized.

For each trial, power spectrum densities were analyzed to determine an appropriate filter frequency for the angular rate data; a 100 Hz low-pass filter was determined to be appropriate and was used to filter the angular rate data. The angular acceleration data were then calculated by differentiating the angular rate data, and the peak resultant angular head accelerations were ascertained for each test trial.

Neck impulse duration for each trial was determined using upper neck compression. A threshold of 500 N was set to determine impulse duration. Durations of force exceeding stepped increments of 50 N from 1100 N to 8000 N were also calculated to determine likelihood of neck injury based on peak force level and force duration.

The likelihoods of skull fracture, severe brain injury, and mild traumatic brain injury (mTBI) were determined using risk curves from peak resultant linear acceleration, HIC and peak resultant angular acceleration provided by data in Funk et al., 2007; Hutchinson et al., 1998; Mertz et al., 2003; Zhang et al., 2004; Rowson and Duma, 2013. Cervical spine injury was deemed likely if the peak compressive force on the upper neck exceeded 4000 N or if the force was greater than 1100 N for pulse durations longer than 30 ms (Mertz et al., 2003; Nightingale et al., 1996a,b, 2002).

Paired t-tests were used to compare resultant linear acceleration, HIC, resultant angular acceleration, compression force in the upper neck, and upper neck compression impulse duration for unprotected and hardhat conditions for each drop object (lead shot and concrete block) at drop heights of 0.91 and 1.74 m. For the 1.83 m drop height, a one-way ANOVA was used because there were three headgear conditions: unprotected, hardhat and helmet. Post hoc analysis was completed using the Bonferroni correction when significance was found in the one-way ANOVA. Results of the t-tests and ANOVAs were used to test the hypothesis with a significance level of 0.05.

3. Results

3.1. Metrics related to head and neck injury

The free fall impact speeds for each drop height were 4.3 m/s, 6.0 m/s and 7.3 m/s for the 0.91 m, 1.83 m and 2.74 m drop heights. The bottom of the lead shot bag impacted near the vertex of the hardhat/ATD and the bottom of the concrete block, or a bottom corner of the concrete block impacted the hardhat/ATD near the vertex for all tests (Fig. 2). Exemplar data of resultant linear acceleration