Materials and Methods

1. Experimental setup

Head impact tests were performed using an instrumented manikin. The test manikin was customerbuilt using the body of an off-the-shelf manikin (50th Percentile Rescue Randy, Model #149-1344, GT Simulators, Davie, FL), a 50th percentile crash test dummy headform (Standard 50th Headform ATD-3215, Eyeglass Headform, Humanetics, Farmington Hills, MI), and a 50th percentile Hybrid III neck (Model #78051-90-H, Humanetics, Farmington Hills, MI) with a reinforced spine. The headform had an aluminum skull. The test manikin was further reinforced with aluminum shoulder elements. The height and body mass of the test manikin with all customized elements was close to a standard 50th percentile male. The manikin was fitted with a fall protection harness to facilitate lifting. The accelerations of the head during impact were measured using a triaxial, piezoelectric accelerometer (Model #66F11, Endevco, Depew, NY). The accelerometer was installed close to the center of gravity of the manikin's head. At the start of the test, the manikin was hoisted to a height of 5 feet (1.5 m) and was kept at a slightly inclined posture. The mobility of the manikin's limbs was significantly truncated, to limit "flailing" and other unpredictable dynamic effects. The hanging manikin was released by an electromagnetic release mechanism, such that the instrumented manikin experienced free fall and impacted a flat surface with the manikin's back of the head being struck first. The impact surface had one of two different covering materials (concrete or plywood-covered). The impact velocity of the manikin's head was approximately 4 m/s immediately before the contact.

2. Test procedure

The accelerations in three directions ($a_x(t)$, $a_y(t)$, and $a_z(t)$) of the manikin's head were collected at a sampling rate of 1000 Hz. High speed videos (1000 Hz) were synchronized with the acceleration data to capture the manikin's drop and impact events. Two impact surface conditions were considered: a plywood (thickness 1/2-inch or 12.5 mm)-covered concrete block or a solid concrete block. Four representative helmet models were selected in the study; two of them were basic helmet models and two of them were advanced helmet models. All four helmet models were categorized as Type I helmets according to ANSI Z89.1 standard. All four helmet models had a belt-type suspension. Compared to the basic models, the advanced models had an additional foam layer between the belt-type suspension and the shell. All four selected helmet models were equipped with a suspension tightening ratchet and were provided with a removable chin strap attachment. Two independent factors regarding proper helmet wearing were considered: (1) chin strap usage (with or without), and (2) tightness of the suspension system (tight, comfortable, and loose). Under each of the test conditions, impact tests were replicated four times. In addition, we performed impact tests without a helmet under all other applicable test conditions. This group of tests (without helmets) was considered as a control or reference group. There was a total of 192 trials for the impact tests with helmets [4 (helmet models) x 2 (chin strap used or not used) x 3 (suspension tightness levels) x 2 (impact surface conditions) x 4 (repetitions)] and 8 trials for the control group [2 (impact surface conditions) x 4 (repetitions)].

3. Head Injury Criterion (HIC) calculations

Head Injury Criterion (HIC) values were calculated using the head accelerations collected in the experiments. HIC is a parameter associated with the severity of brain injury during an impact. HIC has been applied in the automobile industry to evaluate the chance of survival during a vehicle impact test. If the time-history of the head acceleration ($a(t)$) is determined from impact tests, then HIC value can be determined by:

$$\text{HIC} = {}^{T_o \le t_1 < t_2 \le T_e}\left[\left(\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right)^{2.5}(t_2 - t_1)\right]_{\max} \quad (1)$$

where T_o and T_e is the start and end of the test time, respectively; and t_1 and t_2, respectively, is the initial and final instant of a time interval, during which the HIC is calculated. The time interval (t_2-t_1) for HIC_{15} is 15 ms. The integration in Eq. (1) was numerically calculated using the trapezoidal rule.

The resultant of the acceleration magnitude, $a(t)$, is calculated from the triaxial acceleration data by:

$$a(t) = \sqrt{a_x(t)^2 + a_y(t)^2 + a_z(t)^2}. \quad (2)$$

where $a_x(t)$, $a_y(t)$, and $a_z(t)$ are the components of the acceleration in three directions and in G.