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Concussions

Evaluation of the Fall Protection of Type I Industrial Helmets

JOHN Z. WU, CHRISTOPHER S. PAN, CLAYTON COBB,
ANDREW MOOREHEAD, TSUI-YING KAU, and BRYAN M. WIMER

National Institute for Occupational Safety and Health, Morgantown, WV, USA

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Abstract—The performance of Type I industrial helmets for fall protection is not required to be tested in standardized tests. The current study analyzed the fall protection performance of Type I industrial helmets and evaluated if the use of a chin strap and the suspension system tightness have any effect on protection performance. Head impact tests were performed using an instrumented manikin. There were 12 combinations of test conditions: with or without chin strap usage, three levels of suspension system tightness, and two impact surfaces. Four representative helmet models (two basic and two advanced models) were selected for the study. Impact tests without a helmet under all other applicable test conditions were used as a control group. There were four replicates for each test condition—a total of 192 impact tests with helmets and eight impact tests for the control group. The peak acceleration and the calculated head impact criteria (HIC) were used to evaluate shock absorption performance of the helmets. The results showed that all four helmet models demonstrated excellent performance for fall protection compared to the barehead control group. The fall protection performance of the advanced helmet models was substantially better than the basic helmet models. However, the effects of the use of chin straps and suspension system tightness on the helmets' fall protection performance were statistically not significant.

Keywords—Industrial helmet, Manikin, Fall impact, Head impact criteria (HIC), Abbreviated injury scale (AIS).

INTRODUCTION

Many epidemiological studies indicate that work-related traumatic brain injury (WrTBI) is one of the most serious occupational injuries among construction workers, resulting in extensive medical care, multiple days away from work, permanent disability, and sometimes death.[15,19,21,22,32,33] Approximately 15.6% of the WrTBIs were the results of being struck on the head by objects.[5,17,21] In the United States, over 30% of crane accidents were due to being struck by loads or objects.[36] The risk of head injuries in struck-by incidents could potentially be reduced when wearing protective helmets. Wearing an industrial helmet is recognized as one of the important prevention strategies in construction sites to reduce WrTBIs.[18,33] Occupational Safety and Health Administration (OSHA) regulations require workers to wear a helmet to reduce the risk of head injury from falling objects.[27]

Industrial helmets are categorized as Type I or Type II according to ANSI Z89.1 standard.[3] These two helmet types have different purposes: Type I helmets are designed for top impact to protect against falling objects, whereas Type II helmets are designed for both lateral and top impacts. Type I helmets are the most popularly used in construction sites and by manufacturers as "general purpose" helmets for workers' safety protection. Besides the hazard of being struck by falling objects, slips, and trips, falls are another major hazards that are associated with high rates of accidents in typical construction sites.[20] A surveillance study of Nigerian construction workers showed that the hazards of falling from low heights (such as falling from a ladder, slips, trips, and other low falls) are ranked second out of 11 types of identified hazards.[6] The performance of Type I industrial helmets for fall protection has not been tested, since Type I helmets are not required to be tested for lateral impacts in standardized tests.[3,4]

The retention system is an important component to keep a helmet on the wearer's head. The retention system of a construction helmet typically consists of a

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Address correspondence to Christopher S. Pan, National Institute for Occupational Safety and Health, Morgantown, WV, USA. Electronic mail: cpan@cdc.gov

removable chin strap and a suspension system. The suspension system consists of a head cradle, which is attached to the helmet shell *via* typically four to six anchors, and a suspension tightness mechanism commonly known as "ratchet" in the U.S. The strength of the chin strap and buckle for industrial helmets are required to be tested in international standards[3,4]; however, it is not required in any standards to test the suspension tightening adjustment mechanism. For bicycle or motorcycle helmets, there are extensive studies on testing methods for the retention system.[12] The strength of the chin strap for motorcycle and bicycle helmets is designed to compromise the conditions of the strap mechanism failure and neck injury. During an impact, the chin strap should be strong enough to keep the helmet on the rider's head and, at the same time, not apply too much force on the rider's neck to cause fracture or breakage. A previous study showed that the incorrect use of helmets' retention systems caused an increase in severe TBIs in many fatal motorcycle accidents.[9] In many cases of motorcycle fatal accidents, the chin straps of the victims' helmets were found to be loose or open. However, for widely used industrial helmets, the effects of retention systems on their protection performance have not been evaluated.

The chin strap and the suspension tightness adjustment ratchet are two important components in a typical Type I industrial helmet. Different from a motorcycle or bicycle helmet, the use of the chin strap is optional for a Type I industrial helmet. There are no helmet test standards for industrial helmets that focus on the evaluation of the protective performance of a helmet with proper use of the chin strap and suspension tightness ratchet. The current study aimed: (1) to analyze the impact absorption performance of Type I industrial helmets during fall impacts; (2) to evaluate if the use of the chin strap and suspension tightness had effects on the protection performance of Type I industrial helmets.

METHOD

Experimental Setup

Head impact tests were performed using an instrumented manikin. The test manikin was custom-built 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, as shown in Fig. 1. The height and body mass of the test manikin with all customized elements was close to an average (or 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, as illustrated in Fig. 2. 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 (solid concrete or plywood-covered concrete). The impact velocity of the manikin's head was approximately 4 m/s immediately before the contact.

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.[3] The Type I helmet is designed to protect against top impacts from a falling object. 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

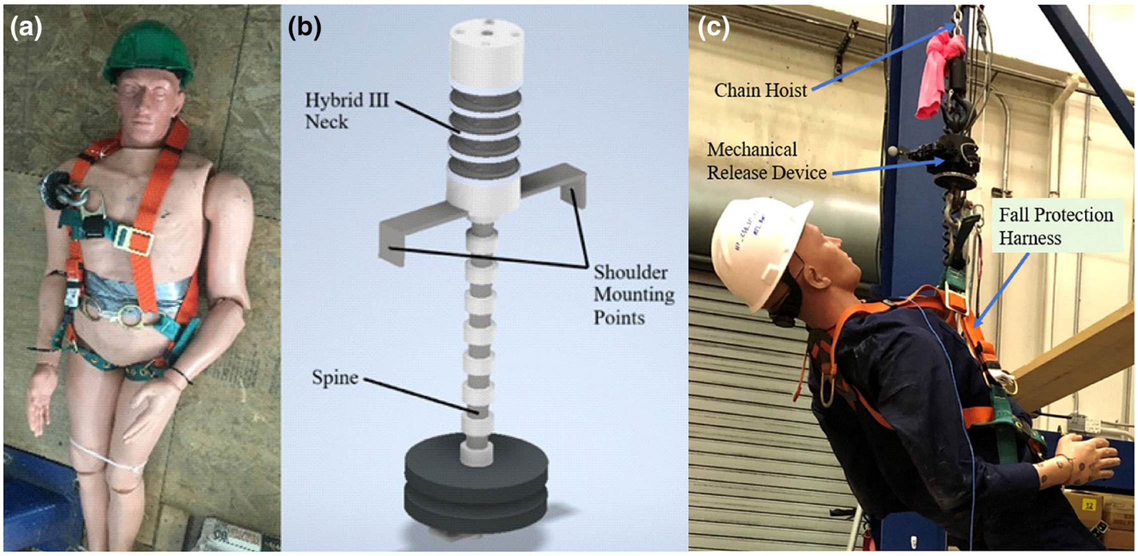


FIGURE 1. Experimental set-up. (a) The instrumented test manikin with a fall protection harness and an industrial helmet. (b) The 50th percentile Hybrid III neck with a reinforced spine and aluminum shoulder elements. (c) The test manikin was hoisted before a drop impact.

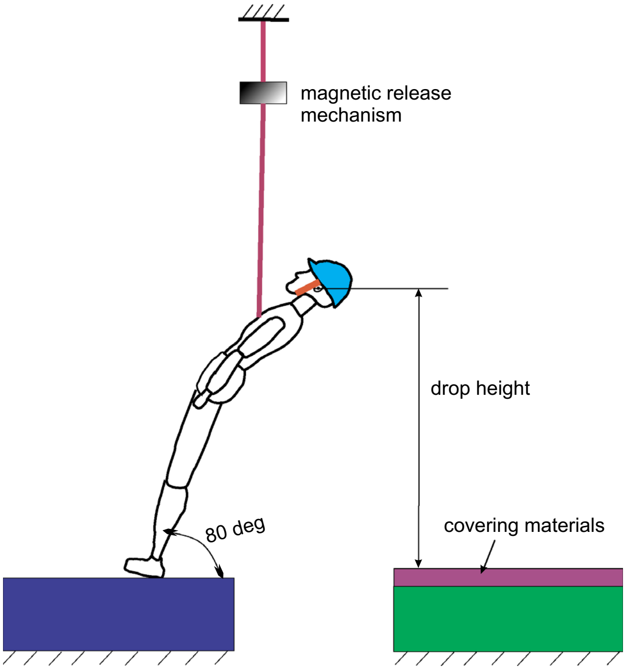


FIGURE 2. Schematic of test procedure. The test manikin was dropped freely from the same posture and height (5 feet) to an impact surface of two different conditions (solid concrete or plywood-covered concrete).

of tests (without helmets) was considered as a control or reference group. There were a total of 192 trials for the impact tests with helmets [4 (helmet models) × 2 (chin strap used or not used) × 3 (suspension tightness levels) × 2 (impact surface conditions) × 4 (repetitions)] and 8 trials for the control group [2 (impact surface conditions) × 4 (repetitions)]. A new helmet was used for each of the impact tests.

HIC and Injury Probability Evaluations

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.[25] If the time-history of the head acceleration ($a(t)$) is determined from impact tests, then HIC value can be determined by[25,28,29]:

$$\mathrm{HIC} = \max_{T_o \le t_1 < t_2 \le T_e} \left[\left(\frac{1}{t_2 - t_1} \cdot \int_{t_1}^{t_2} a(t)dt \right)^{2.5} (t_2 - t_1) \right], \tag{1}$$

where T_o and T_e are the start and end of the test time, respectively; and t_1 and t_2, respectively, are 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:

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

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

The abbreviated injury scale (AIS) system was developed in the mid-1960s to describe the severity of injuries throughout the body. The most updated version is AIS-2005,[11] which is currently adopted by the automobile industry (Euro NCAP and NHTSA).[25,26] The injury is scaled in six levels based on AIS-2005, ranging from AIS1 (minor) to AIS6 (maximal) (Table 1). In vehicle impact tests,[14] analysis is based on injury probability for AIS4 and less. In the current analysis, we consider only the probabilities for the serious and severe injuries, i.e., *p*(AIS3) and *p*(AIS4). In Fig. 3, *p*(AIS3) and *p*(AIS4) are plotted as a function of HIC_{15}, according to Ref. 29. An HIC_{15} value of 700 represents a 50% probability having a serious injury [*p*(AIS3)] or a 15% probability having a severe injury [*p*(AIS4)], which is the maximal acceptable impact level in a vehicle crash test.[25,29]

TABLE 1. Abbreviated Injury Scale (AIS-2005).

AIS code	Injury severity	Fatality (%)
1	Minor	0.0
2	Moderate	0.1-0.4
3	Serious	0.8-2.1
4	Severe	7.9-10.6
5	Critical	53.1-58.4
6	Maximal	(Untreatable)

Statistical Analysis

The average values for each of the parameters were calculated by the arithmetic mean of four repetitions for each of the test conditions. In the analysis, the helmet use/type, the chin strap use, the suspension tightness, and the impact surface condition were considered as independent variables, whereas the peak acceleration (Acc) and HIC were considered as dependent variables.

For each of the dependent variables, peak Acc and HIC, analyses of variance (ANOVAs) were performed separately to evaluate the effects of different combinations of the experimental conditions. Four different ANOVA models were applied in the analysis. The first two models were used to analyze the impact tests of the manikin wearing four different helmet types, where the independent variables were: (a) helmet type, (b) chin strap use, (c) tightness of the suspension system, (d) impact surface conditions, and their associated interactions. In the latter two models, the independent variables have been sorted into two groups: (I) helmet use/type [i.e., no helmet (bare head), and four different helmet types], (II) impact surface conditions (concrete

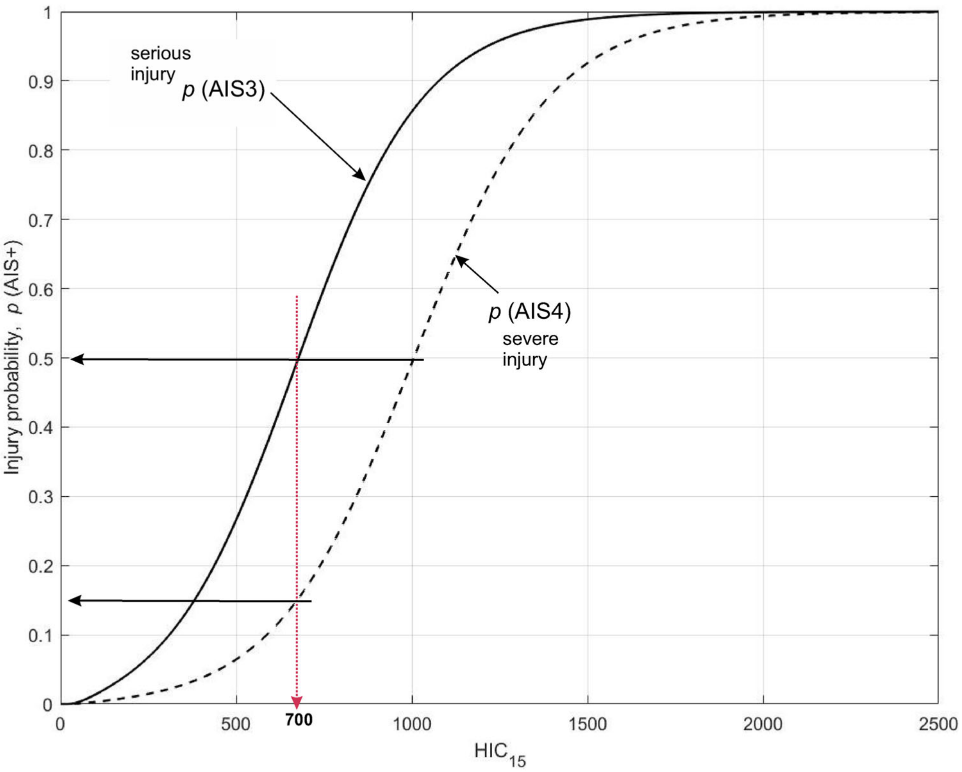


FIGURE 3. The probabilities of serious (AIS3) and severe (AIS4) injuries as a function of HIC_{15}.

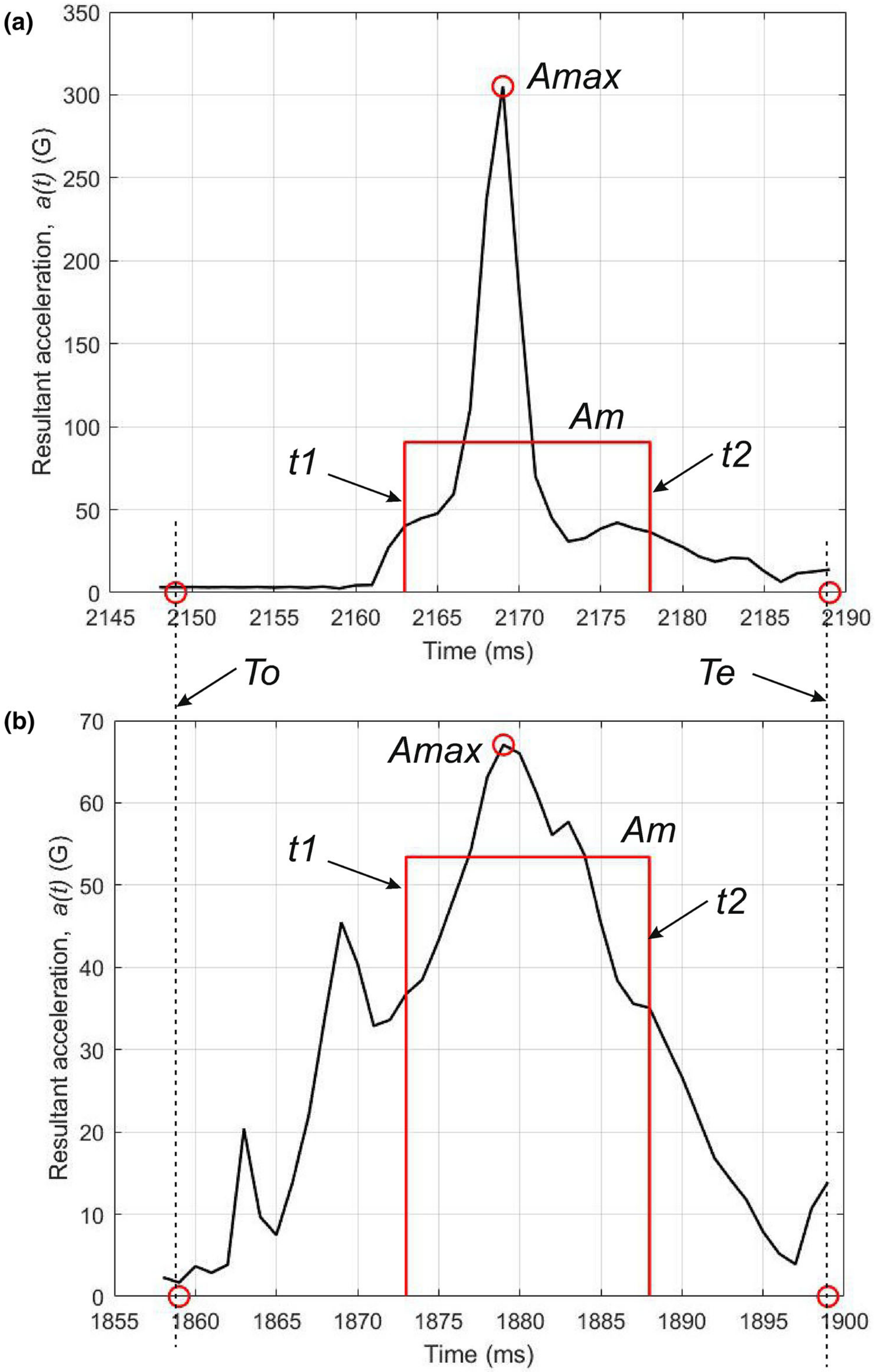


FIGURE 4. Two representative scenarios of the time-histories of the head accelerations during the impacts. The peak acceleration ($A_{\max}$) can differ substantially from the mean acceleration (A_m).

TABLE 2. Summary of ANOVA results.

		Peak acceleration (Acc)		HIC	
Effect of experimental conditions	DF	*F* value	Pr > *F*	*F* value	Pr > *F*
(A)					
(a) Helmet type	3	132.62	<**0.0001**	63.89	< **0.0001**
(b) Chin strap use	1	0.01	0.9267	2.67	0.1044
(c) Suspension tightness	2	9.72	**0.0001**	2.02	0.1360
(d) Impact surface	1	90.52	<**0.0001**	147.21	< **0.0001**
(a) × (b)	3	3.44	**0.0187**	3.13	**0.0276**
(a) × (c)	6	1.50	0.1810	0.38	0.8906
(a) × (d)	3	21.51	<**0.0001**	2.72	**0.0468**
(b) × (c)	2	0.24	0.7871	0.42	0.6604
(b) × (d)	1	2.54	0.1134	0.26	0.6086
(c) × (d)	2	1.79	0.1708	0.79	0.4544
(a) × (b) × (c)	6	4.68	**0.0002**	2.95	**0.0097**
(a) × (b) × (d)	3	9.40	<**0.0001**	4.94	**0.0027**
(b) × (c) × (d)	2	0.60	0.5492	1.06	0.3498
(a) × (c) × (d)	6	4.85	**0.0002**	2.29	**0.0386**
(a) × (b) × (c) × (d)	6	4.35	**0.0014**	0.63	0.7094
(B)					
(I) Helmet Use / Type	4	139.52	<**0.0001**	71.98	< **0.0001**
(II) Impact Surface	1	88.09	<**0.0001**	176.63	< **0.0001**
(I) × (II)	4	14.82	<**0.0001**	14.40	< **0.0001**

The bolded values indicate the calculated statistical parameters with a significance level less than 0.05.

and plywood-covered), and their interaction (I × II). For multiple comparisons, the Bonferroni-adjustment was used to determine significant differences among the experimental conditions. All significance level (α) used for this study was set at 0.05. Statistical Analysis System (SAS) software (SAS version 9.4, SAS Institute Inc., Cary, NC, USA) was used to perform all statistical analyses. Prior to any statistical testing, the normality assumption was examined using a probability plot.

RESULTS

From the time histories of the head acceleration measurements, the maximal peaks during the impacts were first found and a time period (T_e and T_o) for the HIC calculation was then determined. In the current study, $T_e - T_o = 60$ ms was used to calculate HIC$_{15}$. Two representative scenarios in the analysis are illustrated in Figs. 4a and 4b. The mean acceleration magnitude (A_m) during the interval ($t_2 - t_1$) is defined as:

$$A_m = \frac{1}{t_2 - t_1} \cdot \int_{t_1}^{t_2} a(t)dt. \qquad (3)$$

In the data processing, the maximal value of A_m within the time period from T_o to T_e was found and HIC was then calculated: $HIC = (t_2 - t_1)\max(A_m^{2.5})$. In our analysis, A_{max} was found to vary greatly even for the same test conditions, whereas A_m and HIC data were more consistent and less noisy. As illustrated in Fig. 4, the peak acceleration (A_{max}) can differ substantially from A_m, thereby also differing from the value of HIC. In these two representative samples (Figs. 4a and 4b), the ratio of A_{max}/A_m varies from 3.0 (for sample A) to 1.2 (for sample B). This is because the HIC depends not only on the magnitude of the acceleration pulse, but also on the width of the acceleration pulse. In all following results, the values of HIC were calculated using $t_2 - t_1 = 15$ ms, i.e., HIC$_{15}$.

The ANOVA results for manikin impact tests with four different helmet models are shown in Table 2A. Since the higher-order interactions were significant, the results for each of the helmet models by experimental conditions are presented, as in Figs. 5, and 6. For HIC, the four-way interaction was not significant, and all results are summarized in Fig. 7. For peak Acc, the four-way interaction was significant, therefore, the results are presented separately for each of the helmet types in various combinations of experimental conditions.

The effects of the chin strap use, suspension tightness, and impact surface material on the peak Acc and HIC are shown in Figs. 5 and 6, respectively. In these figures (Figs. 5 and 6), the results for the basic models A and B, the advanced models A and B are shown in plots A, B, C, and D, respectively. The effects of the chin strap use and the suspension tightness on HIC

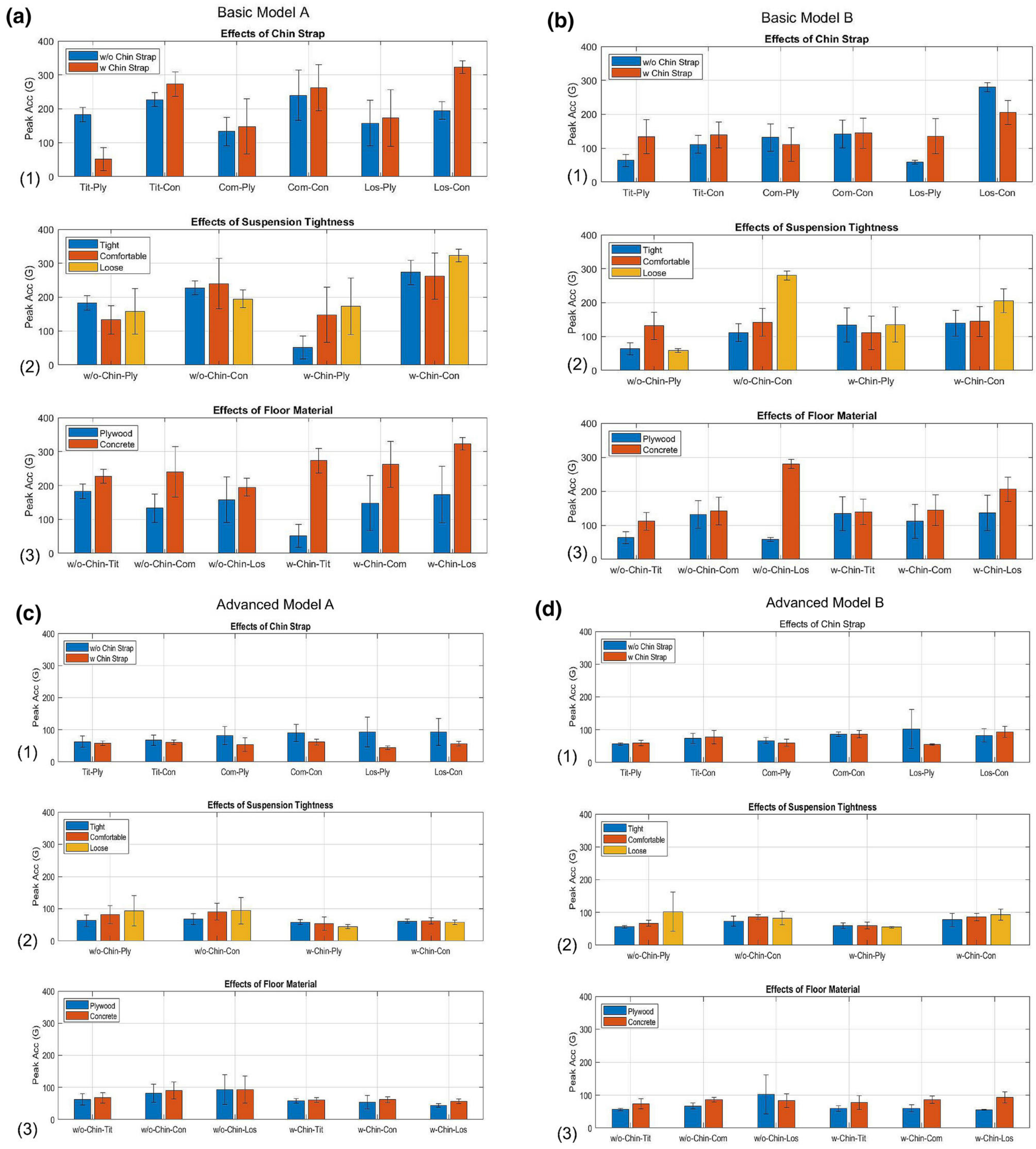
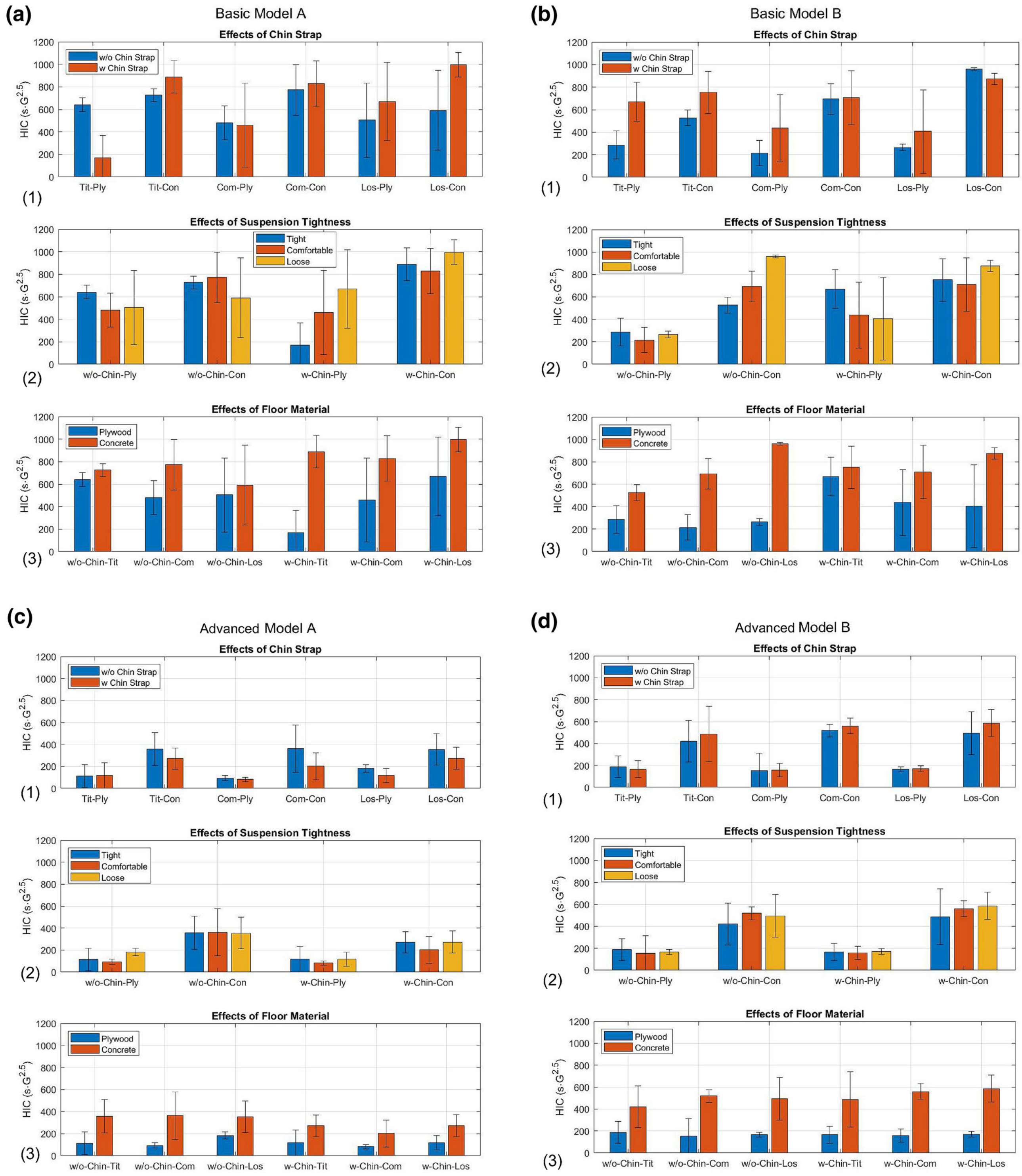


FIGURE 5. The effects of different test conditions on peak acceleration for four different helmet models. (a) Basic helmet A. (b) Basic helmet B. (c) Advanced helmet A. (d) Advanced helmet B. Test combinations in plots (1): ''Tit-Ply''—tight suspension and plywood-covered surface, ''Tit-Con''—tight suspension and concrete surface, ''Com-Ply''—comfortable suspension and plywood-covered surface, ''Com-Con''—comfortable suspension and concrete surface, ''Los-Ply''—loose suspension and plywood-covered surface, and ''Los-Con''—loose suspension and concrete surface. Test combinations in plots (2): w/o-Chin-Ply—without chin strap and plywood-covered surface, w/o-Chin-Con—without chin strap and concrete surface, w-Chin-Ply—with chin strap and plywood-covered surface, and w-Chin-Con—with chin strap and concrete surface. Test combinations in plots (3): w/o-Chin-Tit—without chin strap and tight suspension, w/o-Chin-Com—without chin strap and comfortable suspension, w/o-Chin-Los—without chin strap and loose suspension, w-Chin-Tit—with chin strap and tight suspension, w-Chin-Com—with chin strap and comfortable suspension, and w-Chin-Los—with chin strap and loose suspension.


(a)
Basic Model A
Effects of Chin Strap
w/o Chin Strap
w Chin Strap
HIC ($s \cdot G^{2.5}$)
0
200
400
600
800
1000
1200
Tit-Ply
Tit-Con
Com-Ply
Com-Con
Los-Ply
Los-Con
(1)
Effects of Suspension Tightness
Tight
Comfortable
Loose
w/o-Chin-Ply
w/o-Chin-Con
w-Chin-Ply
w-Chin-Con
(2)
Effects of Floor Material
Plywood
Concrete
w/o-Chin-Tit
w/o-Chin-Com
w/o-Chin-Los
w-Chin-Tit
w-Chin-Com
w-Chin-Los
(3)
(b)
Basic Model B
Effects of Chin Strap
Effects of Suspension Tightness
Effects of Floor Material
(c)
Advanced Model A
Effects of Chin Strap
Effects of Suspension Tightness
Effects of Floor Material
(d)
Advanced Model B
Effects of Chin Strap
Effects of Suspension Tightness
Effects of Floor Material

◀FIGURE 6. The effects of different test conditions on HIC for four different helmet models. (a) Basic helmet A. (b) Basic helmet B. (c) Advanced helmet A. (d) Advanced helmet B. Test combinations in plots (1): "Tit-Ply"—tight suspension and plywood-covered surface, "Tit-Con"—tight suspension and concrete surface, "Com-Ply"—comfortable suspension and plywood-covered surface, "Com-Con"—comfortable suspension and concrete surface, "Los-Ply"—loose suspension and plywood-covered surface, and "Los-Con"—loose suspension and concrete surface. Test combinations in plots (2): w/o-Chin-Ply—without chin strap and plywood-covered surface, w/o-Chin-Con—without chin strap and concrete surface, w-Chin-Ply—with chin strap and plywood-covered surface, and w-Chin-Con—with chin strap and concrete surface. Test combinations in plots (3): w/o-Chin-Tit—without chin strap and tight suspension, w/o-Chin-Com—without chin strap and comfortable suspension, w/o-Chin-Los—without chin strap and loose suspension, w-Chin-Tit—with chin strap and tight suspension, w-Chin-Com—with chin strap and comfortable suspension, and w-Chin-Los—with chin strap and loose suspension.

follow the same significant patterns as those on the peak accelerations. The effects of the chin strap use on the peak Acc and HIC vary for different helmet models and test conditions. For example, the chin strap use had significant effects on the peak acceleration and HIC for the basic helmet A when tested under conditions of "Tit-Ply" and "Los-Con" [$p < 0.05$, Fig. 5a(1) and 6a(1)], but it did not have significant effects on the peak head acceleration and HIC under all other test conditions; for the basic helmet B, the chin strap use had significant effects on the peak head acceleration and HIC when tested under conditions of "Tit-Ply", "Los-Ply", and "Los-Con" [$p < 0.05$, Figs. 5b(1) and 6b(1)], but it had no significant effect under all other test conditions. In some scenarios, e.g., for the test conditions of "Tit-Ply" and "Los-Con", the effects of the chin strap use on peak accelerations and HIC for these two helmet models (basic models A and B) are opposite. For the same test condition, the chin strap use increased the peak acceleration and HIC in one helmet model, however, it decreased the peak acceleration and HIC in another helmet model. For example, the peak acceleration was lowered with chin strap use in advanced model A (Fig. 7c); however, this pattern was not observed in advanced model B (Fig. 7d). Similar pattern was also observed for the effects of suspension tightness.

In the analysis, we were mainly concerned about HIC, as the HIC score is relevant to the head injury severity.[29] The effects of the suspension tightness and chin strap use on HIC varied among different helmet models [Figs. 7a(1-2), 7b(1-2), 7c(1-2), and 7d(1-2)], whereas the effect of the impact surface was consistent for all four helmet models, and was statistically significant [Figs. 7a(2-3), 7b(2-3), 7c(2-3), and 7d(2-3)]. The HIC values from the concrete surface were significantly higher than those on the plywood-covered surface and the mean value differences were 314, 373, 344, 186 ($s \cdot G^{2.5}$) for basic model A and B [Figs. 7a(2-3) and 7b(2-3)], and advanced model B and A [Figs. 7d(2-3) and 7c(2-3)], respectively. For the effect of chin strap use on HIC, we observed a consistent lower value of HIC in chin strap use [177 ($s \cdot G^{2.5}$)] as compare to without chin strap [244 ($s \cdot G^{2.5}$)] among different suspensions in advanced model A only [Fig. 7c(1-2)]; however, the patterns were reversed in the other three helmet models [Figs. 7a(1-2), 7b(1-2), and 7d(1-2)].

The analyses of the effects of helmet use/type and impact surface condition on peak Acc and HIC are shown Fig. 8; and the corresponding ANOVA results are presented in Table 2B. For all helmet models and under all test conditions, the effects of the impact surface covering showed significant effects on the peak Acc and HIC. Wearing each of the four different helmet models significantly ($p < 0.0001$) reduced both peak Acc and HIC, when compared to the control group (without helmet) (Figs. 8a and 8b). The mean value of peak Acc and HIC were highest in the control group, followed by basic model A, basic model B, advanced model B, and the lowest in advanced model A, in an order of 411, 197, 138, 75, and 69 (G) for peak Acc, and 1473, 644, 566, 339, 211 ($s \cdot G^{2.5}$) for HIC. The impact surface condition also showed significant effects ($p < 0.05$) on both peak Acc and HIC (Figs. 8c and 8d), with significantly higher value of peak Acc and HIC when impacted on a concrete surface when compared to a plywood-covered surface. The mean value for impacts on the concrete and plywood-covered surface are 159 and 104 (G), respectively, for peak Acc; and 657 and 306 ($s \cdot G^{2.5}$), respectively, for HIC. The effects of the impact surface on peak Acc and HIC when wearing different helmet models, as well as without helmet (control group) were compared, as in Figs. 8e and 8f. The effect of impact surface appeared to be more substantial for the basic helmet models than for the advanced helmet models. The impact surface had the maximal effects for control group (without helmet), where the average peak Acc increased from 314 to 507 (G), an increase of 60%, and the average HIC increased from 745 to 2201($s \cdot G^{2.5}$), an increase of 195%, for the impact on the plywood-covered surface when compared to the concrete surface.

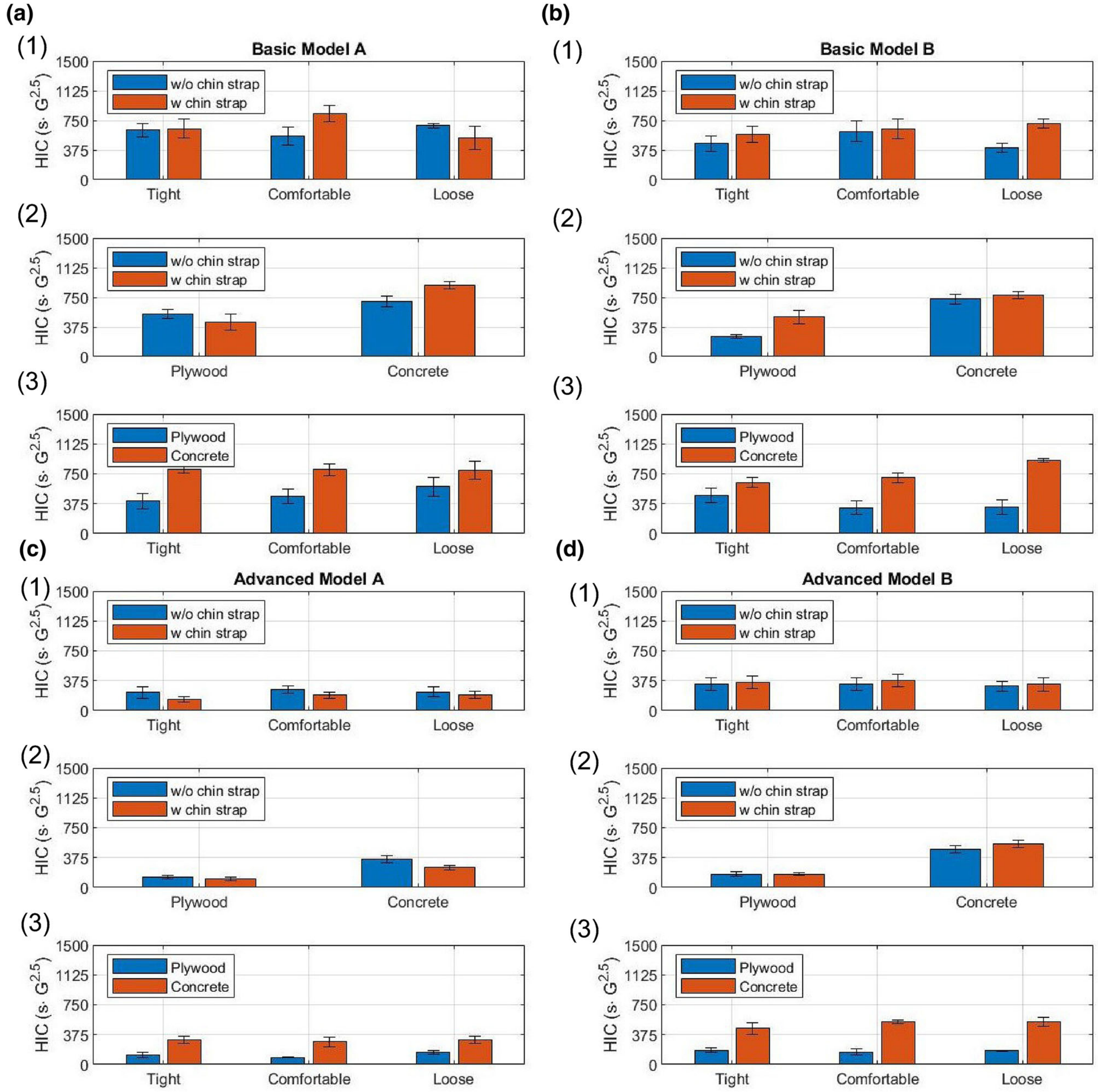


FIGURE 7. Effects of different test conditions on HIC by four different helmet models. (a) Basic helmet A. (b) Basic helmet B. (c) Advanced helmet A. (d) Advanced helmet B.

DISCUSSION AND CONCLUSIONS

Type I industrial helmets are the most widely used helmet models in construction and by manufacturing industries. According to ANSI Z89.1,[3] Type I helmets are designed to protect the wearer from head injury due to top impact resulting from dropping/falling objects. As a result, Type I helmets are not required to be tested for lateral impacts by any international testing standards. However, slips, trips, and falls are major hazards in construction and manufacturing industries associated with high rates of incidents. The ability of Type I industrial helmets to provide head protection during falls has not been evaluated. The results of the current study indicate that wearing Type I industrial helmets may generally reduce head injury risks from a fall. Head protection performance was found to be substantially different for different Type I helmet models.

By imposing the mean HIC values of the impacts without helmets and with different helmet models

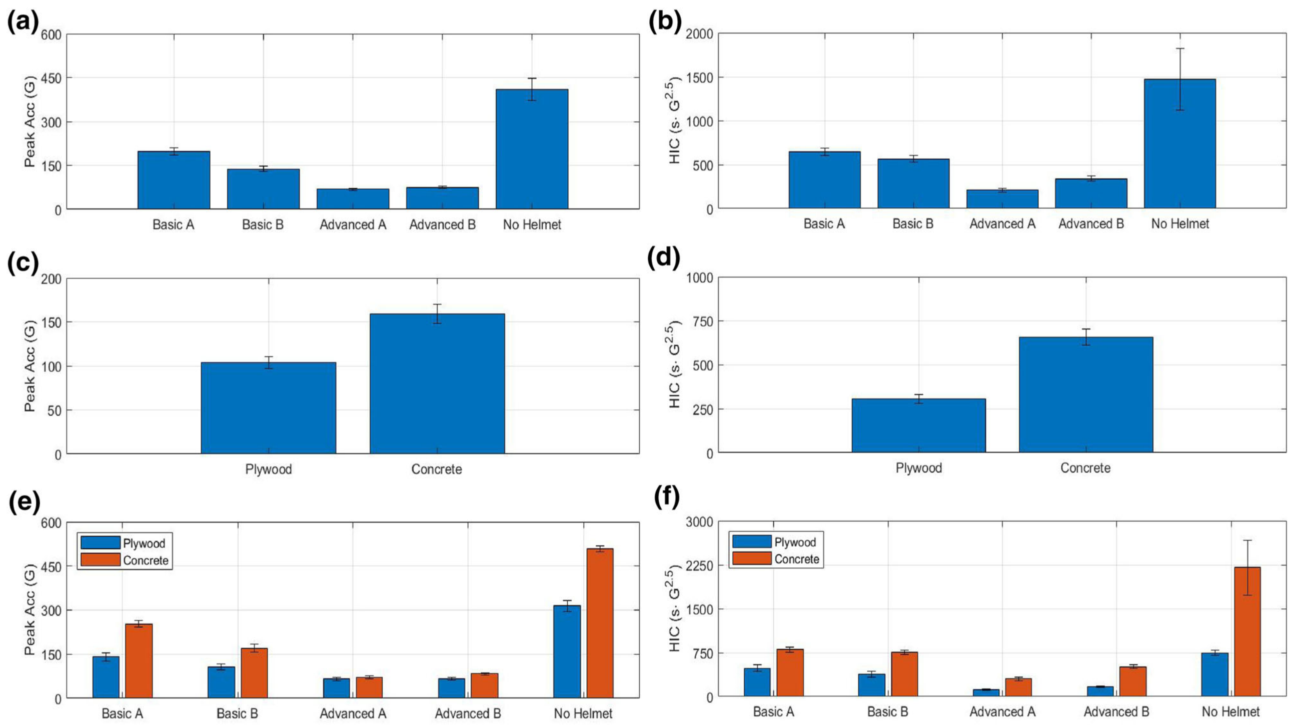


FIGURE 8. Peak accelerations and HIC by helmet use, helmet type, and impact surface condition. Left column (a, c, and e): Peak acceleration. Right column (b, d, f): HIC. A and B: Combined effect of helmet use and helmet type ($p<0.0001$). (c, d) Effect of impact surface condition ($p<0.0001$). (e, f) Effect of surface condition by helmet use and helmet type (significant effects of impact surface for basic model A, B, and control group, $p<0.0001$).

(Fig. 8) on the relationships between injury probability and HIC (Fig. 3), the probabilities for serious [p(AIS3)] and severe [p(AIS4)] injuries in these scenarios can be estimated (Fig. 9).

Impacts of the manikin without wearing a helmet on the plywood-covered concrete surface (Fig. 9A) resulted in serious [p(AIS3)] and severe [p(AIS4)] injury probability of 59% and 20%, respectively. The injury probabilities from the impacts of the manikin wearing different helmet models are found to be: $p(\text{AIS3}) = 27\%$ and $p(\text{AIS4}) = 6\%$ for basic helmet model A, $p(\text{AIS3}) = 16\%$ and $p(\text{AIS4}) = 3\%$ for basic helmet model B, $p(\text{AIS3}) = 3\%$ and $p(\text{AIS4}) = 0.5\%$ for advanced helmet model A, and $p(\text{AIS3}) = 4\%$ and $p(\text{AIS4}) = 0.8\%$ for advanced helmet model B. Our results indicate that head injury risk level from a fall without wearing a helmet was not acceptable ($p(\text{AIS3}) > 50\%$). However, the head injury risk level from a fall could be reduced to an acceptable level [$p(\text{AIS3}) \leq 50\%$] by wearing any of the four tested helmet models.

The performance difference between the basic helmet models and advanced helmet models became more apparent in the test configurations that resulted in more severe impacts. Injury probabilities for head impacts on the concrete surface without wearing a helmet were found to be $p(\text{AIS3}) > 99\%$ and $p(\text{AIS4}) > 99\%$, which were well above acceptable levels. Injury probabilities while wearing a helmet were: $p(\text{AIS3}) = 68\%$ and $p(\text{AIS4}) = 26\%$ for basic helmet model A, $p(\text{AIS3}) = 62\%$ and $p(\text{AIS4}) = 22\%$ for basic helmet model B, $p(\text{AIS3}) = 10\%$ and $p(\text{AIS4}) = 2\%$ for advanced helmet model A, and $p(\text{AIS3}) = 28\%$ and $p(\text{AIS4}) = 6\%$ for advanced helmet model B. Wearing advanced helmets A and B reduced the head injury probabilities to an acceptable level [$p(\text{AIS3}) \leq 50\%$]. Although the head injury risk level has been greatly reduced by wearing basic helmets A and B, to $p(\text{AIS3}) = 68\%$ and $p(\text{AIS3}) = 62\%$, respectively, they were still not acceptable.

Traditionally, the shock absorption performance of industrial helmets has been mostly tested using metal headforms in standardized drop towers.[3,4,13,34] In standardized tests for industrial helmets, the focus has been on the helmets' ability to provide protection against brain injury. Injury risk to the spinal cord resulting from head impact has not been addressed in standardized industrial helmet tests. Dummy crash tests have, for a long time, been used for testing of motorcycle and bicycle helmets[1,2] and football helmets.[10,16] In the crash dummy impact tests, the helmets' ability to provide protection against both spinal cord and brain injuries can be evaluated.[7] Dummy crash tests have seldom been used to evaluate the

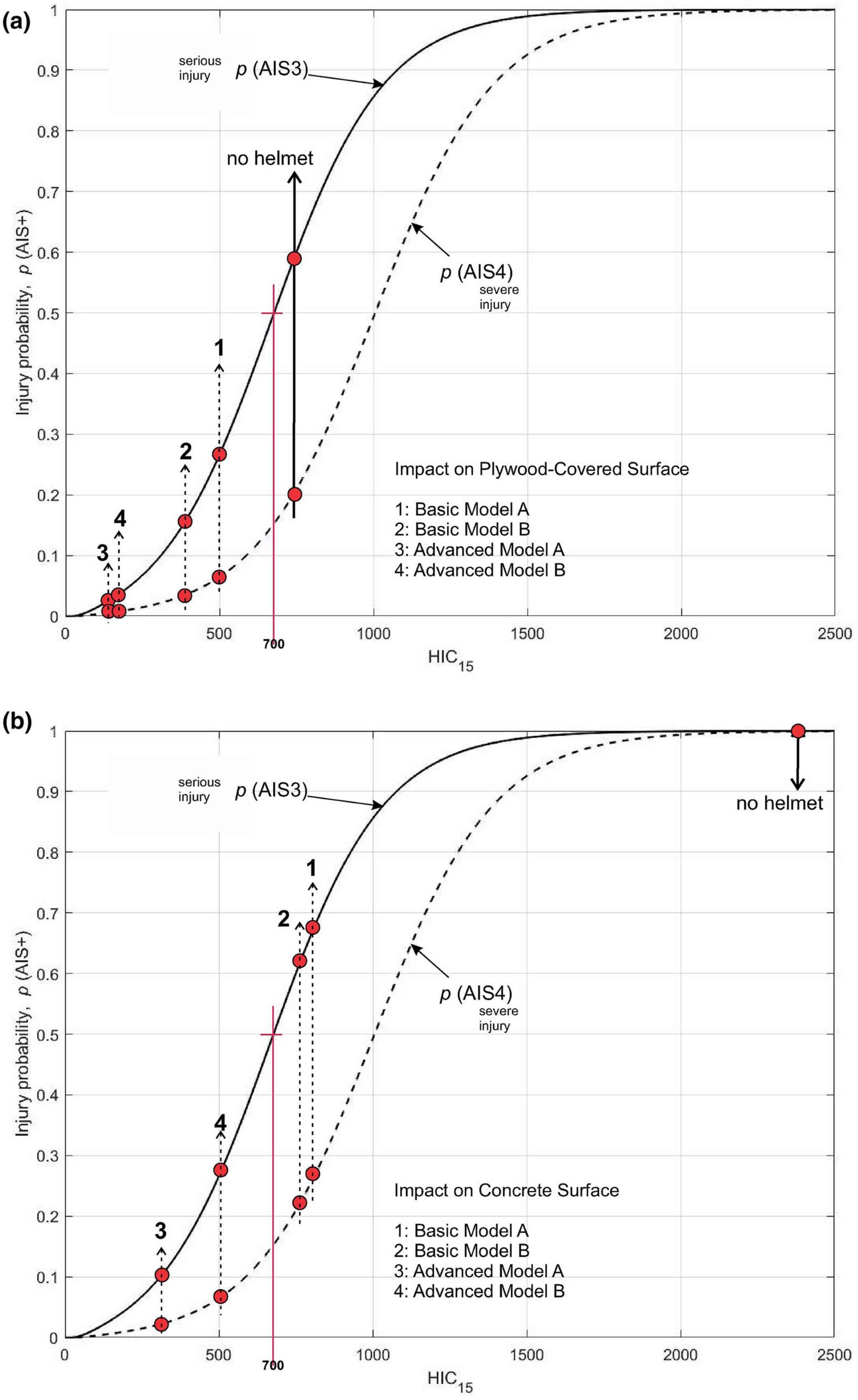


FIGURE 9. Analysis of the fall protection performance of different helmet models when impacting on the surfaces with different covering materials. (a) Impacts on the plywood-covered concrete surface. (b) Impacts on the solid concrete surface.

performance of construction helmets.[31] The magnitude of the impact forces and the interactions between the helmet and human head, which can be measured in customized dummy crash tests, especially when a chin strap is used, are more realistic than what is achieved with standardized tests.

One limitation of the current study is that only one triaxial accelerometer was installed in the manikin's head. Consequently, head rotations and the neck forces during the impact could not be evaluated. Another limitation of the current study is that the acceleration data was collected at 1000 Hz, which is lower than many published studies.[23,24] In automobile collision tests, the minimal sampling rate for the head acceleration measurement is 8000 Hz according to the SAE J211 standard.[30] Based on a previous study,[8] a reduction of the sampling rate from 8000 to 1000 Hz will introduce an error of 2% in the HIC valuation. According to another study, the minimal sampling rate of wearable sensors for evaluation of head kinematics in sports was suggested to be 300 Hz for helmeted conditions and 500 Hz for unhelmeted conditions.[35] Based on this analysis of relevant studies,[8,35] we are confident that the errors caused by the low sampling rate in the current study should be in an acceptable range. The results may be smoother and less noisy, if a higher sampling rate were used, combined with an appropriate digital filter processing.

A commercial metallic headform was used for the impact tests in the current study, which may not be the best choice. The head accelerations, thereby the HIC, measured in our impact tests may be exaggerated, when compared with the realistic scenarios, especially for the impact tests with barehead. The head impact tests using a headform equipped with proper soft rubber covering may create a more realistic test condition.

Our results showed that chin strap use and suspension system tightness would affect the peak acceleration and HIC differently for different impact conditions and for different helmet models. However, if the observed results were averaged over test conditions, these two factors would have no measurable effects on the helmets' protection performance. Head impact on the concrete surface resulted in significantly higher head injury risk (i.e., higher HIC value) than head impact on the plywood-covered surface.

In summary, we have tested, in the current study, the fall protection performance of four representative Type I construction helmets. Type I helmets provided excellent fall protections of the head compared to not wearing a helmet. Fall protection performance of the advanced helmet models were substantially better than those of the basic helmet models.

SUPPLEMENTARY INFORMATION

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CONFLICT OF INTEREST

The helmet samples were donated by helmet manufacturers. No benefits in any other form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript.

DISCLAIMERS

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

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