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An Approach to Characterize the Impact Absorption Performance of Construction Helmets in Top Impact

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Abstract

The helmets used by construction site workers are mainly designed for head protection when objects are dropped from heights. Construction helmets are also casually called “hard hats” in industries. Common construction helmets are mostly categorized as type 1 according to different standards. All type 1 helmets have to pass type 1 standard impact tests, which are top impact tests—the helmet is fixed and is impacted by a free falling impactor on the top crown of the helmet shell. The purpose of this study was to develop an approach that can determine the performance characterization of a helmet. A total of 31 drop impact tests using a representative type 1 helmet model were performed at drop heights from 0.30 to 2.23 m, which were estimated to result in impact speeds from 2.4 to 6.6 m/s. Based on our results, we identified a critical drop height that was used to evaluate the performance of helmets. The peak impact forces and peak accelerations varied nonproportionally with the drop height. When the drop height is less than the critical height, the peak force and peak acceleration increase gradually and slowly with increasing drop height. When the drop height is greater than the critical height, the peak force and peak acceleration increase steeply with even a slight increase in drop height. Based on the critical drop height, we proposed an approach to determine the safety margin of a helmet. The proposed approach would make it possible to determine the performance characteristics of a helmet and to estimate the safety margin afforded by the helmet, if the helmet first passes the existing standardized tests. The proposed test approach would provide supplementary information for consumers to make knowledgeable decisions when selecting construction helmets.

Keywords

construction helmet; experiment; impact test; top strike; safety margin

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Introduction

Work-related traumatic brain injury (WrTBI) is one of the most common occupational injuries among construction workers,[1–5] resulting in extensive medical care and rehabilitation, multiple days away from work, permanent disability, or death. Multiple construction industry trades have been identified as being at the greatest risk for an occupational fatality caused by impact-related head injuries.[6,7] Nonfatal WrTBIs are one of the most serious workplace injuries among emergency department–treated work-related injuries and are much more likely to result in hospitalization compared with other types of injuries.[8] WrTBI has been identified as one of the costliest workplace injuries in the state of Washington.[9] Presently, construction helmets are considered the most common and effective personal protective equipment available to protect against WrTBI in the US construction industry. The Occupational Safety and Health Administration[10] regulation requires that a helmet must be worn when working in areas where there is potential for injury to the head from falling objects.

Industrial or construction helmets are also casually called "hard hats" in industries. Helmets used by construction workers[11,12] are mostly categorized as type 1 according to different standards and are mainly designed for head protection when objects are dropped from heights. All type 1 helmets have to pass type 1 standard impact tests, which are top impact tests and are considered essential tests to evaluate the helmets' shock absorption performance in different industrial standards. There are four international test standards (Table 1). In the US standard ANSI/ISEA Z89.1–2014, *American National Standard for Industrial Head Protection*,[13] an impactor (mass 3.6 kg) drops freely from a height onto the helmet to achieve an impact velocity of 5.5 m/s. The maximal transmitted force shall be smaller than 4.45 kN to pass the test; in addition, the averaged transmitted force cannot exceed 3.78 kN. In an impact test required by European standard BS EN 397:2012+A1:2012, *Industrial Safety Helmets*,[14] an impactor (mass 5.0 kg) drops freely onto the helmet from a height of 1.0 m (theoretical impact velocity 4.43 m/s, Table 1); the acceptable transmitted force shall be less than 5.0 kN. European standard BS EN 14052:2012+A1:2012, *High Performance Industrial Helmets*,[15] has more stringent criteria and is applied to high-performance industrial helmets that yield greater protection. There is another European standard BS EN 12492:2012, *Mountaineering Equipment. Helmets for Mountaineers*. Safety *Requirements and Test Methods*,[16] for mountaineering helmets, which also requires stringent impact tests. For the top impact tests, both BS EN 14052 and BS EN 12492[15,16] standards require an impactor (mass 5.0 kg) be dropped from a height of 2.04 m onto the helmet top. The maximal force transmitted to the helmet shall be less than 5.0 and 10 kN, respectively, for BS EN 14052 and BS EN 12492.[15,16] The top impact tests required by all four major test standards are different in the impact kinetic energy and acceptable transmitted force levels; however, they are identical in test principle—to freely drop an impactor on the helmet top from a certain height and determine the force transmitted to the headform. Although the existing standards have been widely accepted, they are only used for quality control and cannot be applied to evaluate a helmet's shock absorption performance.

There are numerous industrial helmet models on the market. Industrial helmets are typically priced from ten dollars for basic models to hundreds of dollars for advanced designs. All industrial helmets on the market are required to pass existing test standards. However, it is not clear how much of a safety margin a helmet has if it passes the test standard. In other words, the “two-level grading system” of pass/fail as required by the existing helmet test standards is not enough to effectively characterize the shock absorption performance of industrial helmets. The purpose of this study was to develop a helmet-test approach to characterize the shock absorption performance of an industrial helmet. Using the proposed approach, it would be possible for safety engineers to determine the safety margin in helmet selection and for manufacturers to answer consumers’ questions as to the reason why helmets with advanced designs are more expensive. The shock absorption performance of an industrial helmet is its ability to attenuate the impact force transmitted to the head form in the tests. The peak impact forces on the head are considered one of the major factors that cause traumatic brain injuries.[17,18] We hypothesize that the shock absorption performance of an industrial helmet is dependent on the magnitude of the impact force or impact kinetic energy; specifically, the helmets’ shock absorption performance will decrease with increasing magnitude of the impact force or impact kinetic energy.

Method

EXPERIMENTAL SETUP

One representative type 1 helmet model was used in this study. Type 1 is a basic helmet and is used widely in the construction worksites. A type 1 helmet is designed for top impact protection only and is not designed for protection of lateral impacts from the front, side, or rear. In this study, only type 1 impact tests were performed—a free falling impactor is impacted on the top crown of the helmet shell that is fitted on a fixed headform. Impact force transmission tests of the helmets were performed using a commercial drop tower test machine (H.P. White Laboratory, MD, USA), which complies with the ANSI Z89.1 standard[13] (fig. 1). The drop tower consists of a pedestal, a headform, linear bearing rail, drop carriage, drop impactor, and lift mechanism. Upon command, the impactor is released to free fall along the guiding rail and drops onto the crown of the helmet. The forces transmitted to the headform are measured using a force cell (Model 925M113, Kistler, Amherst, NY, USA) with a single axis in the impactor drop direction (vertical), a capacity of 22.2 kN (5 k lbf), and an accuracy of ±2.5% full scale. The force cell was installed between the base of the tower and the headform. The acceleration was measured using a single axis accelerometer (Model 357B03, PCB Electronics, Depew, NY, USA), which was installed at the mass center of the impactor and in the drop direction (vertical) and had a peak range of 19.6 km/s^2 (2,000 g). The impact velocity was measured at approximately 0.5 in (12.5 mm) before the impact via an optical laser velocity gate (type E3X-MDA41, OMRON, Kyoto, Japan); the recording frequency of the gate was 25.6 kHz. The impactor has a mass of 3.6 kg and is semispherical with a radius of 48 mm at the striking face. According to ANSI Z89.1, an ISEA-certified headform (size 7, Cadex) was used. The headform is made of aluminum and has a mass of 3.64 kg. The force and acceleration data were collected at a sampling rate of 25 kHz. The data from the force cell and accelerometer were unfiltered, as we have to pick the peak values. The force cell and accelerometer were both calibrated according to the recommendations found in ANSI Z89.1[13] (Appendix C2 and C3).

TEST PROCEDURE

A total of 31 drop impact trials were performed at 15 different drop heights, as described in Table 2. In order to examine the data variations, we performed benchmark tests with four repeats at each of four different drop heights: 0.30 m (1 ft), 0.91 m (3 ft), 1.52 m (5 ft), and 1.83 m (6 ft). Each drop impact trial was performed using a new helmet sample, which was disposed of following the trial. The control parameter was the drop height; the acceleration of the impactor and reaction force at the base of the headform, which is the force transmitted through the helmet, were measured (fig. 2). The drop heights tested were from 0.30 m (1 ft) to 2.23 m (7.33 ft) (Table 2), which would result in impact velocities approximately from 2.4 to 6.6 m/s in a frictionless condition. The mass of the impactor was fixed at 3.6 kg.

Before the impact tests, we examined the energy loss in the system for the height range from 0.30 m (1 ft) to 2.13 m (7 ft). By dropping the impactor at a height, h, the energy loss, δ, is estimated by

$$\delta = \left| \frac{\frac{1}{2}v^2 - gh}{gh} \right| \times 100\% \qquad (1)$$

where v is the measured velocity just before impact and g is the gravitational acceleration.

TEST DATA PROCESS

The time-histories of force were processed using a custom program developed using MATLAB software to find the maximal peaks (F_{max}), which appeared in the initial impact. The unfiltered raw data were used in the determination of the peak impact forces and accelerations, as requested by ANSI Z89.1 standard.[13] For each of the trials, a sampling period of 50 ms around the maximal peak (25 ms before and after the peak) was then identified. Time-histories of the force and acceleration for each trial were plotted for its sampling period. Finally, the peak force and acceleration of the trials were plotted versus the corresponding drop heights.

In order to evaluate the helmet shock absorption performance, we defined an impact transmission coefficient, η, which is the ratio of peak transmitted force (F_{max}) and the involved impact potential energy (mgh):

$$\eta = \frac{F_{max}}{mgh} \qquad (2)$$

where F_{max} is the peak maximal transmitted force in the impact, h is the drop height, and m is the mass of the impactor. η measures the amount of force yielded by unit potential impact energy—the lower the η value, the better the helmet shock absorption performance.

Results

For the benchmark repeat tests, the average peak impact force at drop height of 0.30 m (1 ft), 0.91 m (3 ft), 1.52 m (5 ft), and 1.83 m (6 ft) was determined at 1.05 (0.04) kN, 1.90 (0.03) kN, 2.50 (0.02) kN, and 2.71 (0.12) kN, respectively, with relative standard deviation of 3.74 %, 0.55 %, 1.16 %, and 4.4 %. The average relative standard deviation of the measurements is 1.9 %.

The energy losses in the drop tower system during the impact tests at five drop heights from 0.30 m (1 ft) to 1.83 m (6 ft) are listed in Table 2. The average energy loss in the system is 6 %, and it tends to decrease with increasing drop height. The measured impact velocity is approximately 3 % smaller than that estimated in a frictionless condition.

Representative raw data for the time-histories of the force and acceleration around the impact are shown in figure 3*A* and 3*B*, respectively. The plots of the force and acceleration show two peaks, corresponding to the initial and secondary impacts between the impactor and the helmet shell. After the initial impact, the impactor bounced back and separated from the helmet shell, resulting in a flat region in the force and acceleration time-histories (fig. 3*A* and 3*B*). For this particular case, the contact duration between the impactor and the helmet shell for the initial impact is approximately 26 ms; the contact duration for the second impact is approximately 20 % longer than that for the initial impact. Meanwhile, the magnitude of the peak force and acceleration decreased by approximately 70 and 50 %, respectively, from the initial impact to the second impact. In this study, we analyzed the peak impact force and acceleration for the first impact.

Representative time-histories of the force for eight different drop heights from 0.30 m (1 ft) to 2.03 m (6.67 ft) are shown in figure 4*A*. It can be seen that the peak force increased gradually from approximately 1.0 to 2.5 kN when the drop height increased from 0.30 to around 1.83 m. When the drop height increased from around 1.83 to 2.03 m, an increase of 0.20 m, the peak force increased steeply from approximately 2.5 to 16 kN (fig. 4*B*). The average duration that the impactor is in contact with the helmet shell is 25 (1.8) ms (i.e., the time that the force is greater than zero), which is nearly independent of the drop height.

Correspondingly, representative time-histories of the acceleration for eight different drop heights, from 0.30 m (1 ft) to 2.03 m (6.67 ft), are shown in figure 5*A*. Consistent with the force changes, the peak acceleration increased gradually from approximately 45 to 80 g when the drop height increased from 0.30 to around 1.83 m. A slight increase of the drop height from around 1.83 to 2.03 m resulted in a steep increase of the acceleration from approximately 80 to 400 g (fig. 5*B*).

For each of the force-time and acceleration-time curves, the peak forces and peak accelerations have been identified. The peak force and peak acceleration, as a function of the drop height, is shown in figure 6*A* and 6*B*, respectively. Both peak force and acceleration values increase gradually with increasing drop height, when the drop height is less than the 1.83-m region. When the drop height is above the 1.83 m region, both peak force and acceleration values increase dramatically. Segmented linear regressions were performed using the data from 0.30 to 1.83 m and from 1.83 to 2.23 m separately (solid lines in figs. 6–

8). The corresponding 95 % confidence intervals were calculated from the linear regressions (dashed lines in figs. 6–8).

We have visually examined each of the helmets, which have have been subjected to the impact tests, trying to identify any structural damage. Even after the most severe impact (i.e., drop height 2.31 m) when the peak force value reached 24 kN, more than four times the values allowed in BS EN 397[14] and ANSI Z89.1,[13] no obvious damage was visually observed on the helmet's shell or in the suspension system.

The impact transmission coefficient (η) as a function of drop height is shown in figure 7. We fitted the data for the drop heights from 0.30 to 1.83 m and from 1.83 to 2.23 m using separate lines (solid lines). We have also calculated the 95 % confidence intervals for the linear regressions (dashed lines). It can be seen that η decreased from 84 to 39 N/J when the drop height increased from 0.30 to 1.83 m. Once the drop height is above 1.83 m, η increased steeply with increasing drop height.

Discussion and Conclusion

There are four major international test standards for construction helmets. The test conditions are expressed in different manners in different standards: ANSI Z89.1[13] specifies the impactor mass and impact speed, whereas European standards BS EN 397,[14] BS EN 14052, and BS EN 12492 specify the impact mass and drop heights. Assuming a frictionless condition for the impactor free fall, the test parameters (i.e., impactor mass, drop height, impact speed, impact kinetic energy, allowable impact force, and impact transmission coefficient) for all four standards are summarized in Table 1. The numbers in bold in the table are theoretically derived. Using the potential impact energy specified in BS EN 397[14] and BS EN 14052/BS EN 12492[15,16] and an impactor mass of 3.6 kg (as in this study and in ANSI Z89.1),[13] the equivalent drop heights for this study were estimated: h_{EN397} = 1.38 m and $h_{EN14052}$ = $h_{EN12492}$ = 2.83 m. The equivalent drop heights of all four test standards are plotted together with our test results, as in figure 8. The tested helmet model easily passes BS EN 397[14] and ANSI Z89.1[13] standards, but it fails to pass BS EN 14052 and BS EN 12492 standards.[15,16] Using the proposed approach, we can roughly compare the four different standards with our test results. Our analysis indicates that for the top impact tests the criterion of ANSI Z89.1[13] is more stringent than BS EN 397[14]; however, both criteria of ANSI Z89.1[13] and BS EN 397[14] are less stringent than BS EN 14052 and BS EN 12492.[15,16]

Our results indicate there exists a critical drop height, h_{cr} = 1.75 m, which is defined at the intersection of the two regression lines (fig. 6). The relationships of force-drop height and acceleration-drop height can be characterized by a flat toe region ($h < h_{cr}$), where the force or acceleration increases slowly with increasing drop height, and a steep linear region ($h > h_{cr}$), where the force or acceleration increases dramatically with even a slight increase in drop height (fig. 6). The scattering of the test data is small when the drop height is below h_{cr}, and the pattern becomes large once the drop height is above h_{cr}, indicating mechanical characteristics became unstable once the drop height exceeds the critical height. Mathematically, the value of h_{cr} can be uniquely determined by the intersection of the two regression lines. The key to precisely determine h_{cr} is to reasonably divide the test data into a "subcritical" and a "postcritical" group. For the helmet model selected in our study, it is straightforward to decide which data should be included into the subcritical group and which data should be included into the postcritical group. The effectiveness of the proposed method has been validated by independent tests using a different type 1 helmet model and by impact tests using a different impactor mass (5.0 kg).[19]

By closely examining the characteristics of the force impulse pattern (fig. 4), we found that when $h < h_{cr}$, the force impulse has a nearly unchanged base width (the impactor remains in contact with the helmet for 25 ms) and a peak that increases slowly and gradually with increasing drop height (fig. 4, drop height 0.30, 0.61, 1.52, and 1.83 m), and when $h > h_{cr}$, an additional sharp peak appears on the base force impulse (fig. 4, drop height 1.88 and 2.03 m). The sharp force peak is very narrow (base width < 1 ms) and has a peak that increases steeply with increasing drop height. The appearance of this sharp force peak may be an indication that the helmet's suspension system loses its ability to absorb or to dissipate the impact energy. It is well-accepted that the TBIs are associated with the peak acceleration and the corresponding duration.[18] The head injury criteria (HIC), which are widely used in automobile industries to evaluate the potential of TBI, are based on the peak acceleration in the brain tissues and its duration.[17,20] The angular accelerations were considered one of the important mechanisms for concussions in sports[21,22] and automobile industries.[23] However, for the top impacts for type 1 helmets, the angular accelerations are negligible.

Although the impact forces and accelerations of the headform were collected in the current study, these data are not suitable for the HIC evaluation because the standardized headform setup, as used in the study, is quite different from the human body in structures and mechanical stiffness. NHTSA[20] proposed to measure the HIC using a customarily constructed SID/H3 dummy, which is essentially a Hybrid III dummy head and neck mounted to a modified SID torso. Technically, it is possible to calculate an HIC value using the acceleration trace at the mass center of the headform; however, the HIC value obtained using the ISEA-certified headform would not be comparable, in scale or magnitude, to those determined using a whole-body dummy (i.e., a SID/H3 dummy as specified in NHTSA[20]). However, the shock absorption performance determined in the helmet impact tests should be implicitly correlated to the HIC—the better the helmet shock absorption, the lower the HIC value.

Impacts beyond the critical drop height cause the mechanical instability of the helmet because the transmitted impact force will increase dramatically with a slight increase in the drop height. Therefore, this height is called the critical drop height, h_{cr}. If a helmet passes a standard test, the safety margin of the helmet for that standard is defined based on the potential impact energy at h_{cr}:

$$\rho_{std} = \left(\frac{J_{cr}}{J_{std}} - 1\right) \times 100\% = \left(\frac{mgh_{cr}}{mgh_{std}} - 1\right) \times 100\% = \left(\frac{h_{cr}}{h_{std}} - 1\right) \times 100\% \quad (3)$$

where ρ_{std} represents the safety margin based on a particular test standard; J_{cr} and J_{std} represent the potential energy at the critical drop height and the potential energy specified in the test standard, respectively, h_{std} is the drop height specified in the standard.

For the helmet model tested in the current project (fig. 8), we obtained h_{cr} = 1.75 m. Because $h_{\text{ANSI-Z89:1}}$ = 1.54 m, the safety margin of the helmet is $\rho_{\text{ANSI-Z89:1}}$ = 13.6%. If the safety margin is estimated based on the European standard BS EN 397,[14] the drop height is estimated based on the prescribed impact potential energy to be h_{EN397} = 1.38 m, and the safety margin of the helmet is estimated at ρ_{EN397} = 26.8%. Using the safety margin, we can demonstrate quantitatively that the helmet may have a greater safety margin using BS EN 397[14] standards than using ANSI Z89.1[13] standard, meaning that ANSI Z89.1[13] may have a more stringent criterion in terms of transmitted impact force. Another way to compare different standards is to assess the impact transmission coefficient, η, at the maximal transmitted impact force (Table 1). A more stringent standard should have a smaller η value if the tested helmet model passes the standards (i.e., ANSI Z89.1 and BS EN 397 for this study).

The critical drop height, h_{cr}, may be comparable to the yield stress for many common engineering materials. For many engineering materials, like most structural steels, once the stress level reaches the yield stress, further increase of the stress will result in excessive plastic deformation and the stiffness of the material will decrease dramatically. In classic mechanics of materials, the allowable stress is usually defined by the yield stress divided by a safety coefficient.[24] In the impact of a helmet, the input variable is the potential or kinetic impact energy. Consequently, it is reasonable to define the safety margin based on the potential energy, which is proportional to the drop height in the tests when the mass of the impactor is fixed.[14]

It is interesting to observe that η slightly decreases, meaning the helmet shock absorption performance or shock attenuation increases, with increasing drop height up to the critical drop height (fig. 7). This trend is opposite to those of force (fig. 6*A*) and acceleration (fig. 6*B*), where the peak force or acceleration increases with increasing drop height. When the drop height exceeds the critical height, h_{cr}, the shock absorption performance declines dramatically, a trend consistent with force and acceleration. This is likely an indication that the helmet's strap suspension system reached its limit.

In the comparison of different test standards (fig. 8), it was assumed that the drop impactor had a fixed mass of 3.6 kg, as in ANZI Z89.1[13] standard. In the study, the drop height was calculated from the prescribed potential impact energy in the standards. However, the European standards BS EN 397, BS EN 14052, and BS EN 12492[14,15,16] prescribe a drop impactor mass of 5.0 kg. The mass of the drop impactor may have an effect on impact force. In other words, if the impact potential energy is the same, dropping impactors of different masses may not necessarily yield the same impact force. Therefore, a rigorous evaluation of the safety margin of the helmet based on the European standards should be based on the impact tests using a drop impactor of 5.0 kg.

The benchmark repeat tests show an average relative standard deviation of the peak force measurements of 1.9 %, suggesting that the tested helmets have a uniform performance. The relative variation of the test data at lower (0.30 m or 1 ft) and higher (1.83 m or 6 ft) drop heights is 3.4 % and 4.4 %, respectively, approximately two times the average value (1.9 %). The large error for the low-drop-height (0.30 m or 1 ft) test is likely caused by the height positioning error in the tests, whereas that for the high-drop-height (1.83 m or 6 ft) test is likely caused by the structural damage in the helmet.

Because this study was conducted to develop a new methodology for helmet testing, it was necessary to perform many replicate tests to support the proposed methodology. One further step toward real application of the proposed method is the development of an optimized test metrics to minimize the number of the helmet samples. Once our testing concept and method are adopted by the helmet industry, engineers would need much fewer helmet samples (likely around 10–12 samples) to determine the helmet performance parameters.

A limitation of this study is that only one representative helmet model was tested. The proposed approach should be applicable for all construction helmets. Different helmet models may exhibit different performance characterization curves if tested using the proposed approach. Helmets made of different materials and with different suspension systems would likely have different shock absorption characteristics. It is not known whether the proposed method can be applied consistently for type 1 and type 2 helmets. For the proposed method to be accepted by industries, further validations need be conducted with more impact tests using different helmet models and helmets by different manufactures.

Another limitation for our study is that only top impacts (i.e., type 1 impacts) were performed. Although lateral impact tests are not required in ANSI Z89.1[13] and BS EN 397[14] standards for type 1 helmets, they are required for type 2 helmets and for high performance industrial helmets (BS EN 14052[15]). It is not known whether the proposed approach may be used for lateral impacts, as helmets may have different performance characterizations in lateral shock absorptions.

In summary, a systematic approach to characterize the shock absorption performance of industrial helmets for top impacts was proposed. The proposed methodology is not meant to replace existing helmet test standards. The proposed approach would make it possible to determine the performance characteristics of a helmet and to estimate the safety margin it would afford if the helmet first passes the existing standardized tests. The proposed test approach would provide supplementary information for consumers to make knowledgeable decisions when selecting construction helmets, thereby improving helmet quality control and workers' safety.

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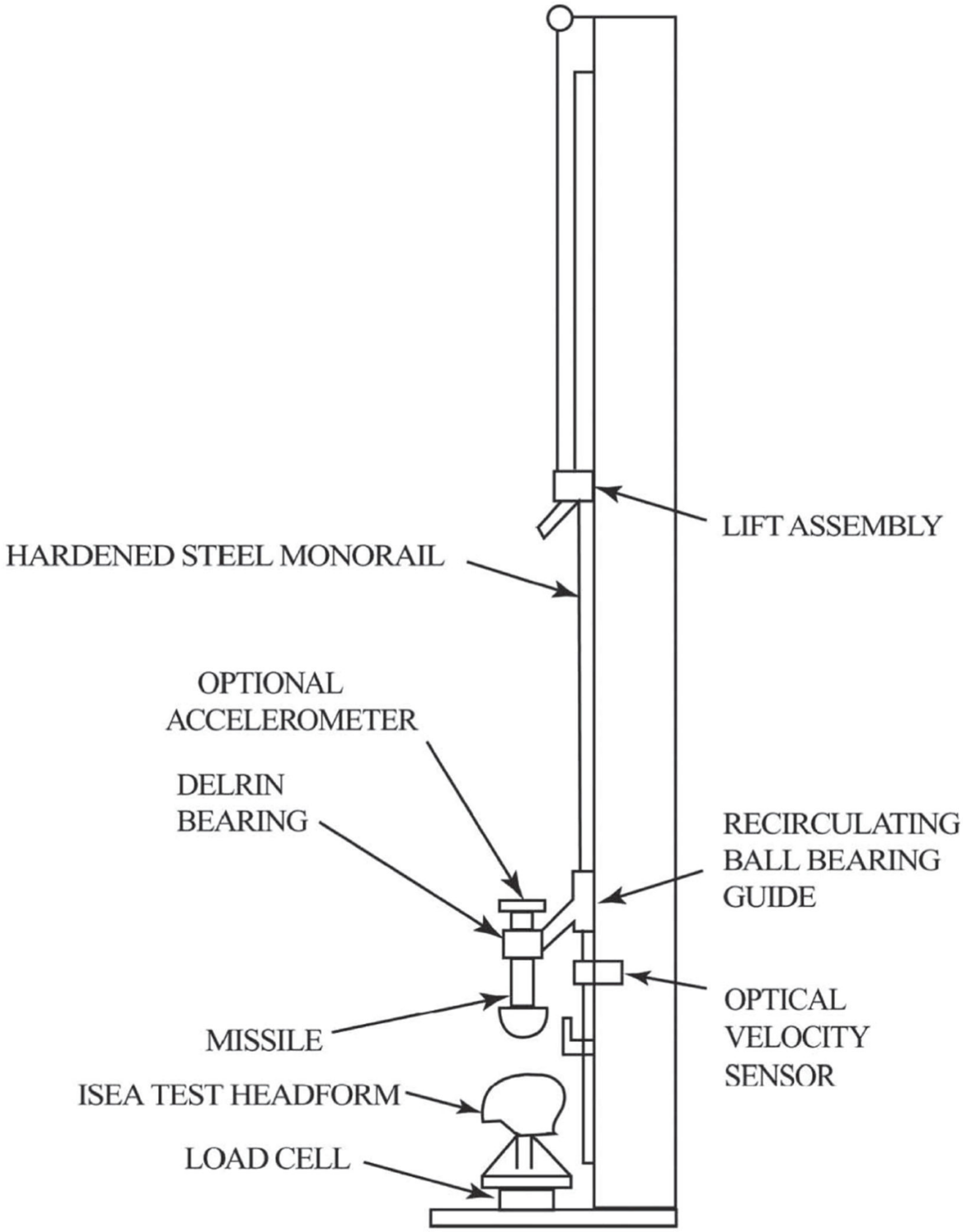

FIG. 1.

Drop tower test machine. The drop tower consists of a pedestal, a headform, linear bearing rail, drop carriage, drop impactor, and lift mechanism. The drawing of the drop tower test machine was adopted from ANSI Z89.1.[13]

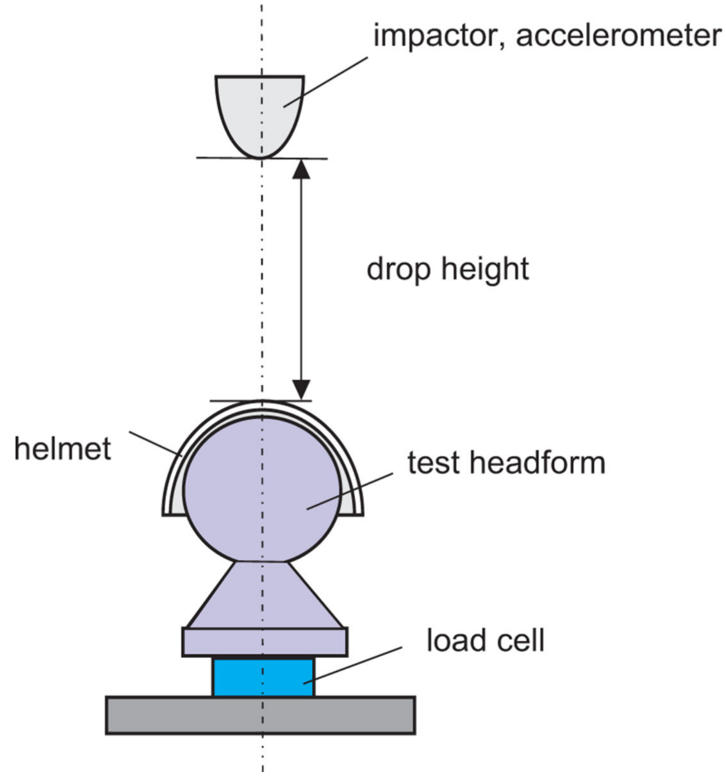

FIG. 2.

Schematics of the test procedure. The control parameter was the drop height; the acceleration of the impactor and reaction force at the base of the headform were measured.

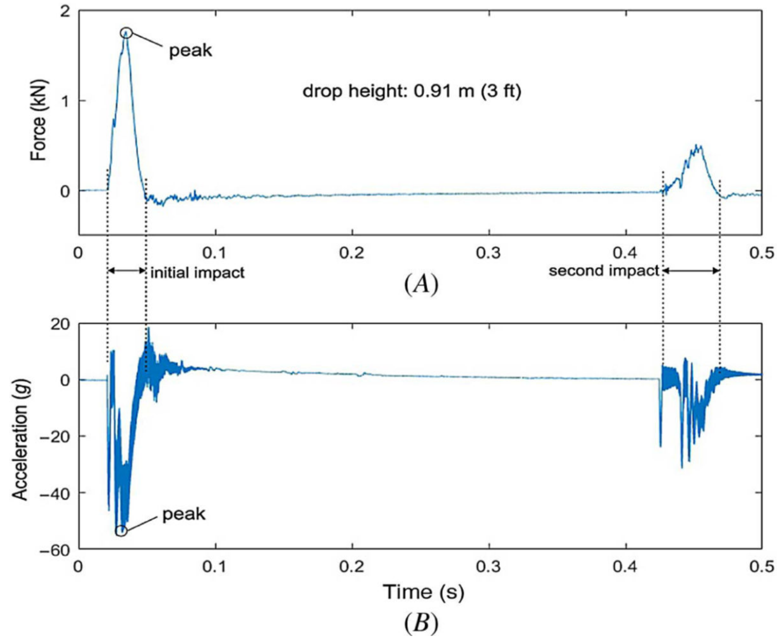

FIG. 3.

The representative raw data for the time-histories of the force (*A*) and acceleration (*g*) (*B*) around the impact. The time-histories of force and acceleration show two peaks, which correspond to the initial and secondary impacts between the impactor and the helmet shell.

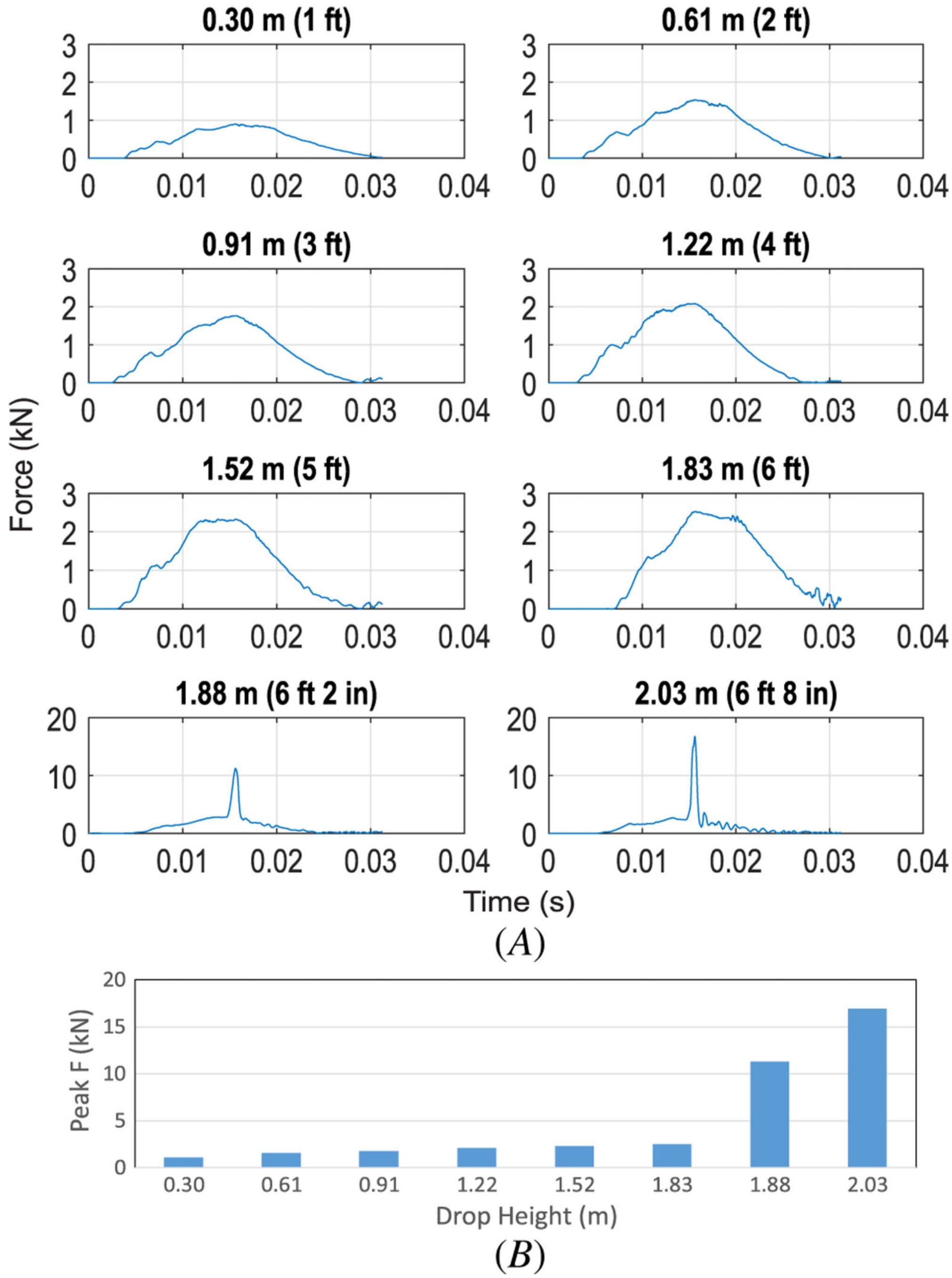

FIG. 4.

Representative impact force measurements. (*A*) The representative time-histories of the force for eight different drop heights from 0.30m(1 ft) to 2.03 m (6.67 ft). (*B*) The peak impact forces.

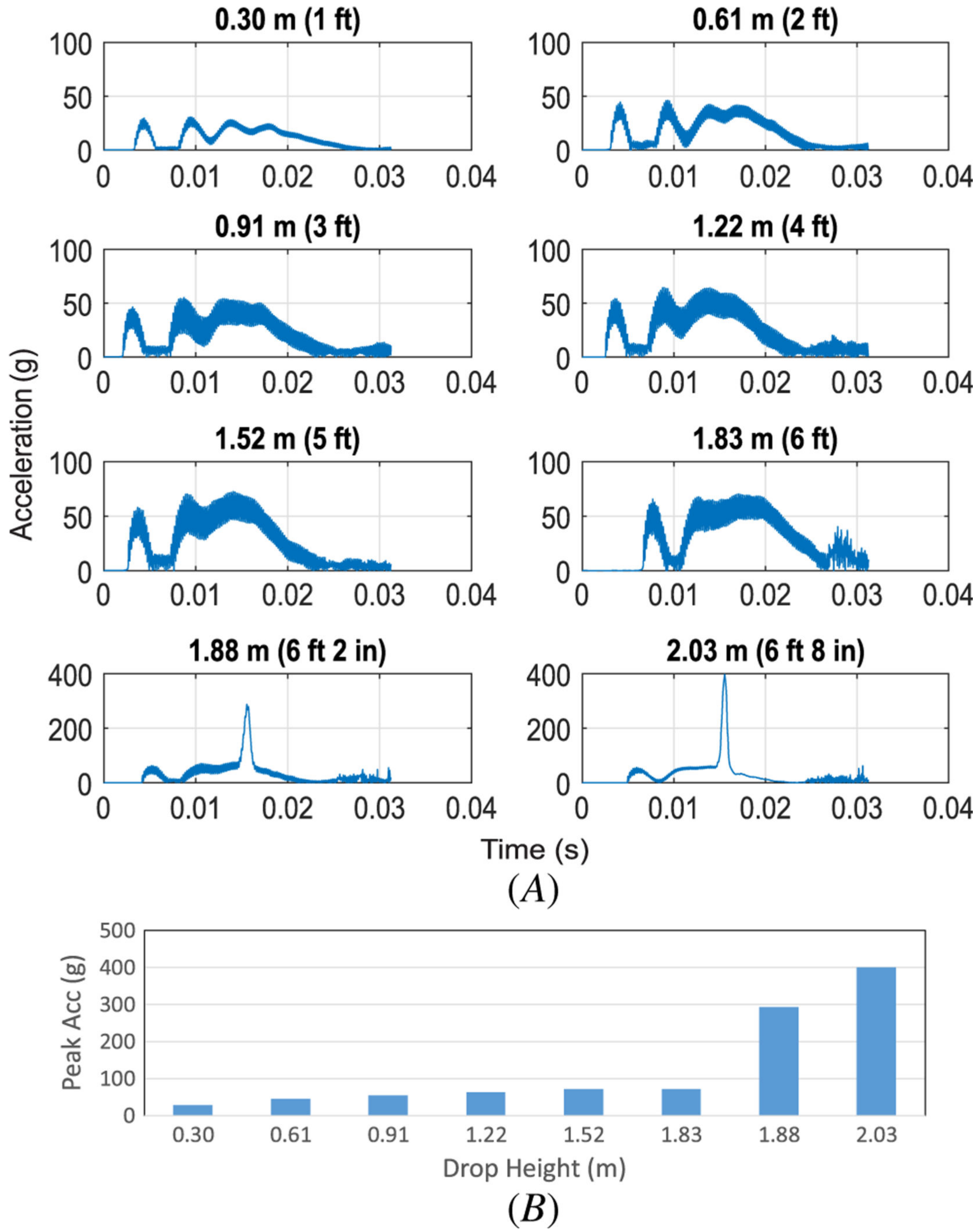

FIG. 5.

Representative impact acceleration measurements. (*A*) The representative time-histories of the acceleration (*g*) for eight different drop heights from 0.30 m (1 ft) to 2.03 m (6.67 ft). (*B*) The peak accelerations (*g*).

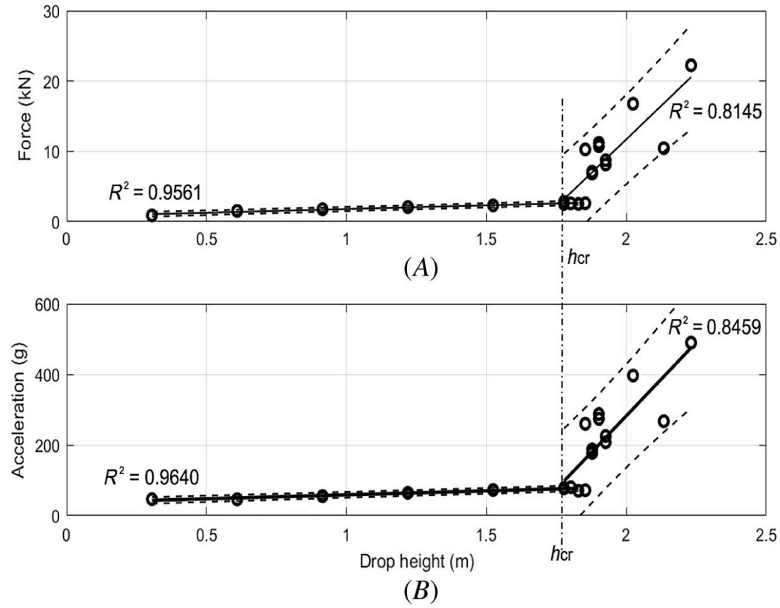

FIG. 6.

Peak force (*A*) and peak acceleration (*g*) (*B*) as a function of the drop height. The data for the drop heights from 0.30 to 1.83mand from 1.83 to 2.23 m were fitted using two separate lines (solid lines). The dashed lines are the 95 % confidence intervals for the linear regressions.

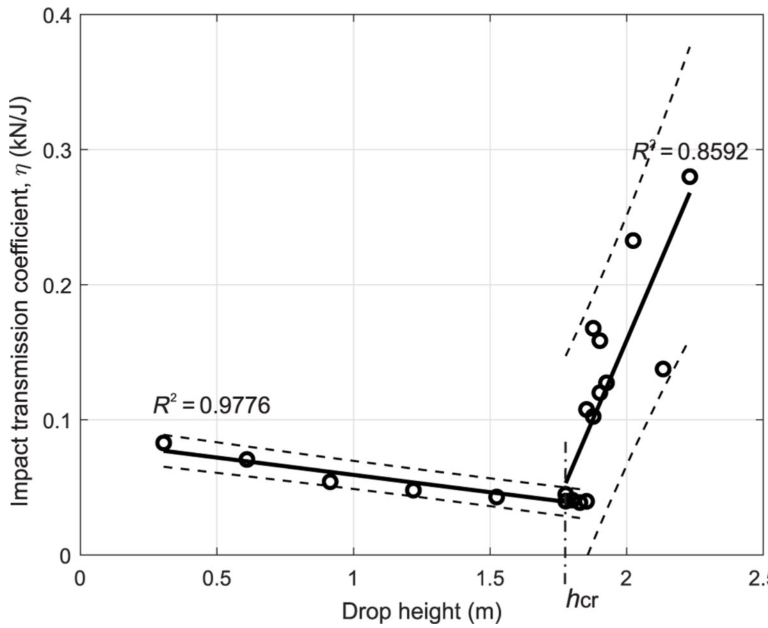

FIG. 7.

Impact transmission coefficient (η) as a function of drop height. The impact transmission coefficient is defined as the force divided by the kinetic impact energy involved in the impact. The data for the drop heights from 0.30 to 1.83 m and from 1.83 to 2.23 m were fitted using two separate lines (solid lines). The dashed lines are the 95 % confidence intervals for the linear regressions.

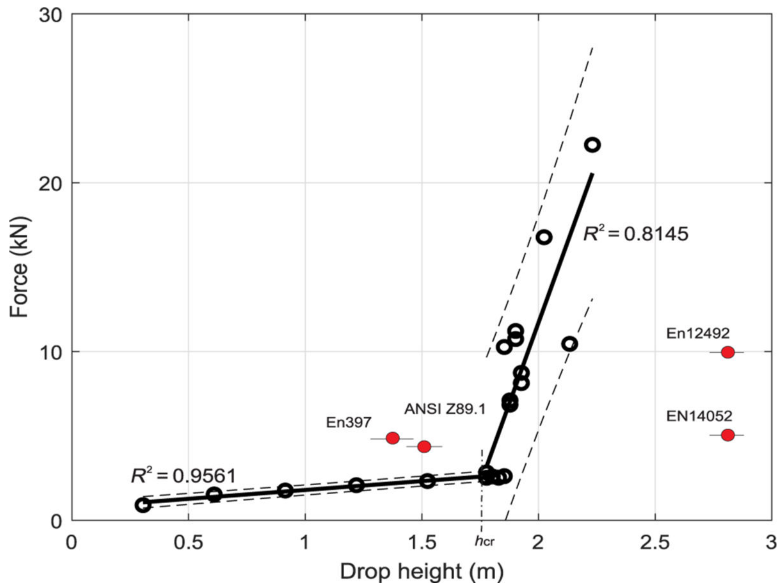

FIG. 8.

Comparison of the current test results with helmet test standards ANSI Z89.1, BS EN 397, BS EN 14052, and BS EN 12492. The red dots represent the test points by different helmet test standards. The equivalent drop heights of the test standards were derived by assuming a frictionless ideal condition for impactor free fall. Using the potential impact energy specified in the standards BS EN 397, BS EN 14052/BS EN 12492 and an impactor mass of 3.6 kg (as in this study and in ANSI Z89.1), the equivalent drop heights were calculated: h_{EN397} = 1.38 m and $h_{EN14052}$ = $h_{EN12492}$ = 2.83 m.

TABLE 1

Parameters for top impact tests specified in different test standards: ANSI Z89.1, BS EN 397, BS EN 14052, and BS EN 12492

Standards	Impactor Mass *m*, kg	Drop Height *h*, m	Impact Speed *v*, m/s	Impact Kin *mgh*, J	Max Trans Force F_{max}, kN	Impact Absorption Coef η, kN/J
ANSI Z89.1	3.60	**1.54**	5.50	**54.45**	4.45	**0.08**
BS EN 397	5.00	1.00	**4.43**	**49.05**	5.00	**0.10**
BS EN 14052	5.00	2.04	**6.63**	**100.06**	5.00	**0.05**
BS EN 12492	5.00	2.04	**6.63**	**100.06**	10.00	**0.10**

Note: In ANSI Z89.1, the impactor mass and impact speed are specified, whereas in BS EN 397, BS EN 14052, and BS EN 12492, the impact mass and drop heights are specified. Other parameters (bold) were derived by assuming a frictionless ideal condition for the impactor free fall.

TABLE 2

Description of top impact tests conducted in the study

Test #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Drop height, h (ft)	1.00	2.00	3.00	4.00	5.00	8.83	5.91	6.00	6.08	6.16	6.24	6.32	6.64	7.00	7.32
Drop height, h (m)	0.30	0.61	0.91	1.22	1.52	1.78	1.80	1.83	1.85	1.88	1.90	1.93	2.02	2.13	2.23
Test repeats	4	1	4	1	4	2	1	4	2	2	2	1	1	1	1
Impact Spd, v (m/s)	2.33		4.11		5.35			5.81							
Est. energy loss, δ (%)	9.2		5.7		4.2			5.8							

Note: A total of 31 drop impact tests using a representative type 1 helmet model were performed at 15 different drop heights. Benchmark tests were conducted with four repeats, and the system energy losses were analyzed at four different drop heights: 0.30 m (1 ft), 0.91 m (3 ft), 1.52 m (5 ft), and 1.83 m (6 ft).