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Application of air-bubble cushioning to improve the shock absorption performance of type I industrial helmets

John Z. Wu[a], Christopher S. Pan[a,*], Mahmood Ronaghi[a], Bryan M. Wimer[a], Uwe Reischl[b]

[a] National Institute for Occupational Safety and Health, Morgantown, WV, USA
[b] Boise State University, Boise, ID, USA

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ABSTRACT

The industrial helmet is the most used and effective personal protective equipment to reduce work-related traumatic brain injuries. The Type I industrial helmet is a basic helmet model that is commonly used in construction sites and manufacturers. The purpose of the current study was to investigate if shock absorption performance of these helmets could be improved by using an air-bubble cushioning liner to augment the helmet's suspension system. Drop impact tests were performed using a commercial drop tower test machine according to the ANSI Z89.1 Type I drop impact protocol. Typical off-the-shelf Type I industrial helmets were utilized in the study. The effects of the air-bubble cushioning on the helmets' shock absorption performance were evaluated by comparing the original off-the-shelf helmet samples to the helmets equipped with an air-bubble cushioning liner. The air-bubble cushioning liner (thickness 5 mm) was placed between the headform and the helmet when being tested. The impactor had a mass of 3.6 kg and was free-dropped from different heights. The maximal peak transmitted forces for each of the tests have been evaluated and compared. Our results show that the shock absorption effectiveness of the air-bubble cushioning is dependent on the magnitude of the impact force. At lower drop heights ($h < 1.63$ m), the air-bubble cushioning liner has little effect on the transmitted impact forces, however, at higher drop heights ($h \geqslant 1.73$ m) the air-bubble cushioning liner effectively reduced the peak transmitted forces. At a drop height of 1.93 m (the highest drop height tested), the air-bubble cushioning liner reduced the peak transmitted force by over 80%. Our results indicate that adding an air-bubble cushioning liner into a basic Type I industrial helmet will substantially increase shock absorption performance for large impact forces.

1. Introduction

Approximately 7.3% of traumatic brain injury (TBI) cases identified by the Ontario Trauma Registry were work-related [1]. A study of an Abu Dhabi (United Arab Emirates) hospital records between 2005 and 2009 indicated that 56 (about 10%) of a total of 581 TBI cases were related to occupational activities [2]. Another study of hospital records in northern Italy from 1996 to 2000 showed that approximately 15% of TBI incidents occurred in work places [3]. A surveyance of the insurance records in Taiwan for 2009 showed that 11% of occupational injuries requiring hospitalization involved TBI [4]. Construction is the leading industry for serious work-related traumatic brain injuries (WrTBI) due to the high incidence of falls and head struck-by incidents [5–7]. Many

* Corresponding author at: NIOSH, 1095 Willowdale Road, Morgantown, WV 26505, USA.
E-mail address: cpan@cdc.gov (C.S. Pan).

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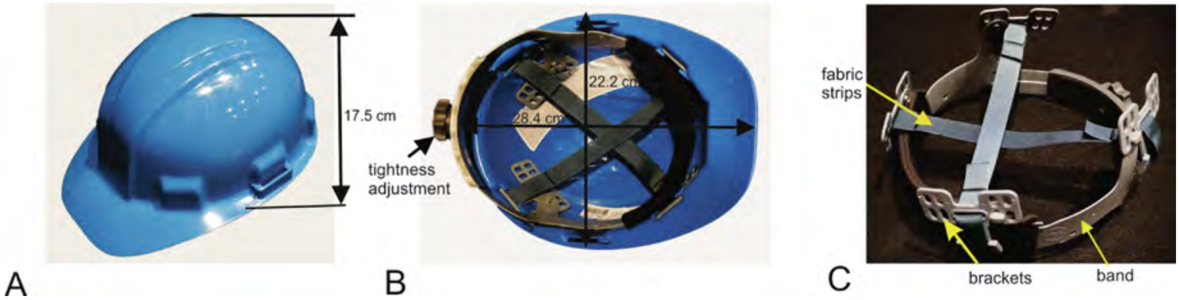

Fig. 1. A representative Type I industrial helmet. (A) Helmet shell. (B) Helmet with suspension. (C) Helmet harness. The helmet shell is typically made of polyethylene or polycarbonate plastics. The suspension system consists of synthetic woven fabric strips and nylon band. The helmet harness is attached to the shell via four brackets. The gap between the top of the suspension strips and the helmet shell is about 3 cm in a natural, unloaded state.

epidemiological studies suggest that WrTBIs are one of the most serious occupational injuries among construction workers, resulting in extensive medical care, multiple days away from work, and permanent disability, or death [5–10]. Approximately 15.6% of WrTBI incidents resulted from struck-by objects on the head [6,11,12]. It is generally accepted that the industrial helmet is the most used and effective personal protective equipment available to reduce WrTBI [1,9]. OSHA (Occupational Safety and Health Administration) regulations require workers to wear a helmet to reduce risk of head injury from falling objects [13].

Industrial helmets (also referred to as construction helmets) are categorized as Type I or Type II according to the ANSI Z89.1 standard [14]. A Type I helmet is designed for top impact protection only, whereas a type II helmet is also designed for protection from lateral impacts [14]. Industrial helmets widely used in construction and manufacturing industries are mostly categorized as Type I. All Type I helmets have to pass the top impact test (i.e., Type I impact test), in which an impactor drops freely from a certain height or at a certain impact velocity onto a fixed helmet; the maximal peak transmitted impact force shall be smaller than a certain limit for the helmet to pass the test. There are three most frequently used international test standards for industrial helmets: ANSI Z89.1 [14], EN397 [15], and EN14052 [16]. The ANSI Z89.1 standard [14] is mainly used in North America, whereas EN397:2012 + A1 [15] and EN14052:2012 + A1 [16] are European standards. In ANSI Z89.1 standard [14], the impactor has a mass of 3.6 kg, freely drops, and impacts the helmet's crown at a velocity of 5.5 m/s. To pass the test, the maximal transmitted force must be less than 4.45 kN. The impact test required by European standard EN397 [15] specifies an impactor (mass 5.0 kg) that freely drops from a height of 1.0 m and impacts onto the helmet; the maximal acceptable peak transmitted force is 5.0 kN. European standard EN14052 [16] is for high-performance industrial helmets. It requires the helmet to be tested not only with top and lateral impacts, but also with off-crown impacts, in which the impactor strikes onto the helmet at angles of 15°, 30°, 45°, and 60°.

A representative Type I helmet mainly consists of a hard shell (Fig. 1A) and a suspension system (Fig. 1B). The helmet shell is typically molded using polyethylene or polycarbonate plastics. According to ANSI Z89.1 [14], the use of chin strap is optional in Type I helmets. The suspension system plays a major role in shock absorption and impact force redistribution. Although the suspension systems of Type I industrial helmets produced by different manufacturers utilized different materials, their structural designs are similar. The suspension system in a typical Type I helmet consists of a synthetic woven fabric strips and bands of molded nylon or vinyl (Fig. 1B-C). The suspension molded bands are attached to the shell via a 4-point or a 6-point ratchet. In addition to s strip-type suspension, Type II helmets have a pad liner, mostly made of foam materials. There is an advanced high-performance helmet (Kask safety helmet; KASK Inc, Chiuduno, Italy) on the market, it has an additional polymer shock absorption pad liner between the strip-type suspension and shell. High performance industrial helmets will pass EN14052 [16] tests, which are more stringent than the Type I and Type II tests in ANSI Z89.1 [14]. Since the suspension system plays an essential role in absorbing impact shocks in a helmet, the research and development efforts of helmets have mainly been focused on the improvement of the suspension system [17,18]. None of the current industrial helmet designs used air-bubble cushions in the suspension system.

Comparing with other conventional shock absorption materials, such as rubbers and polymers, air-bubble cushions have the advantages of being light weight, low cost, and unique mechanical performance attributes. Air-bubble cushions have been widely used in scenarios where humans interact with the equipment or environment, for example, shoes, shock-absorption gloves, seat cushions, and air bed mattresses. Air cushioned soles have been used in shoes to improve shock absorption performance and comfort for decades [19]. In air-cushioned gloves, finger segments are cushioned by separated air bubbles to absorb the vibrations transmitted to the hand [20]. The vibration absorption performances of air-cushioned gloves were found to be dependent on the vibration frequencies and grip forces [21]. The dependence of the contact stiffness of an air-cushioned glove on the air pressure and bubble sheet materials have been analyzed theoretically [22]. Air bubble buffers have been used in hip protectors to protect the elderly from hip fractures [23,24]. Air cushion seats have been applied to improve the interface contact pressure distributions on the human body [25]. Air bubble cushions have been used in football helmets to provide an additional layer of padding while increasing comfort and the fit of the helmet [26]. In all these scenarios, the air-bubble cushions have been used to reduce contact stress or to absorb small impact force in the contact interface between the human and equipment. It is not known if the air-bubble cushions would also be effective in absorbing large impact forces, such as those observed with the industrial helmets.

Air-bubble cushions have also been widely used in the packaging industry [27]. An air-bubble wrap sheet – a common packing material in industries – consists of two low-density polyethylene (LDPE) films, with one bubble-shaped film being bonded to a flat film to form air bubbles. The pressure of the initial inflation air may be varied in accordance with the sheet material properties and requirements of the package contents to be protected. Air bubble wrapping sheets are commercially available in different thicknesses, bubble sizes, and bubble densities. The air bubble size can be as small as 3/16″ (6 mm), to as large as 1″ (25 mm) in diameter. The most commonly used air-bubble wrapping sheet has an air bubble diameter of 10 mm [28]. Compared to other packing materials, air-bubble wrapping sheet has the advantages of excellent shock absorption characteristics, light weight, insensitive to climate conditions (e.g., temperature and humidity), and high flexibility [28]. Malasri et al. [29] showed that the impact acceleration in the contents packed with 3/16″ (5 mm) and 5/16″ (8 mm) bubble wrapping is about 34% less than that packed with viscoelastic foam wrapping.

Despite widespread adoption of air-bubble cushions in ergonomic designs and in commercial packaging as shock absorption materials, they have never been used in industrial helmets. The purpose of the current study was to test if air-bubble cushions can be used to improve the shock absorption performance in Type I industrial helmets. Our hypotheses were that the air-bubble cushioning would help improve the shock absorption for industrial helmets and that the effect of the air-bubble cushioning in shock absorption would be dependent on the magnitude of the impact force. In the current study, we used air-bubble wrapping sheets as air-bubble cushioning liner in helmet impact tests, since these air-bubble wrapping sheets are commercially available in different sizes for our purposes. A representative Type I industrial helmet model and air-bubble wrapping sheets were selected for use in the study. Top impact tests were performed at different drop heights with an impactor mass of 3.6 kg. The knowledge obtained in our study would help optimize helmet design to improve impact performance, thereby improving workers' safety.

2. Method

2.1. Experimental setup

The experimental set-up is similar to those in our previous studies [30,31]. A commercial drop tower test machine (HP. White Laboratory, MD, USA) was used for the helmet drop impact tests (Fig. 2A). Helmet impact tests were performed according to the Type I helmet impact protocol in ANSI Z89.1 standard (ANSI/ISEA Z89.1, 2014). The impactor had a mass of 3.6 kg and was free-dropped from heights ranging from 2.00 ft (0.61 m) to 6.34 ft (1.93 m), which resulted in impact velocities ranging from 3.45 m/s to 6.15 m/s, estimated at a frictionless condition. The transmitted impact forces were measured via a force sensor (Model 925M113, Kistler, Amherst, NY, USA) installed between the base plate and the headform. The accelerations of the impactor were collected via a single axial accelerometer (Model 357B03, PCB Electronics, Depew, NY, USA) installed near the mass center within the impactor. Force and acceleration data were collected simultaneously (synchronized) at a sampling rate of 25 kHz. The velocity of the impactor immediately before impact was measured via an optical sensor built into the system.

2.2. Test procedure

Typical off-the-shelf Type I basic industrial helmets from a manufacturer (Fig. 1) were used in the study. The helmets were randomly assigned to one of two test groups. Helmets tested in Group I were unmodified and served as the control group. Helmets in Group II were equipped with an air-bubble cushioning liner. The effect of air-bubble cushioning on the helmets' shock absorption performance was evaluated by comparing two test groups (Fig. 2B and 2C). Commercially available air-bubble cushioning wrap sheets (Blue Hawk, Gilbert, AZ) were used for the cushioning liner. The air-bubble cushioning had dimensions of 30.5 × 30.5 cm (1′ × 1′), as illustrated in Fig. 2D. In a natural, undeformed state, an individual air bubble had a diameter of approximately 9 mm and a height of approximately 4 mm. The air-bubble cushioning liner was made of two layers of air-bubble cushioning wrap sheets, with their bubble sides placed against each other. The air-bubble cushioning liner had a thickness of approximately 5 mm in an undeformed state. The air-bubble cushioning liner was first put on the top of the headform, and the helmet was then placed onto the partially wrapped headform, such that the impact force would be transmitted to the headform through the air-bubble cushioning liner. The air-bubble cushioning sheet covered the entire suspension system, but not the entire headform.

Drop impact tests were performed at six drop heights: 0.61, 1.52, 1.63, 1.73, 1.83, and 1.93 m. Four replications were performed for each of the tests in both Group I and II. A total of 48 helmet drop impact trials were performed in the study. The sequence of the drop heights is randomized in the tests. Each of the trials started with a new untested helmet and each helmet sample was impacted only once.

Before data collection, each of the helmets was pre-conditioned [31] by being placed on the headform, as in the impact test, and impacting three times with the impactor at a drop height about 10 cm. The pre-conditioning would make the helmet to reach a "steady state" before the data collection and would make the measurements of the transmitted force more repeatable.

2.3. Data processing

Before data collection, the drop tower system was calibrated to determine the system friction loss. The potential energy loss due to friction (ΔE) is estimated by the difference between the initial potential energy (mgh) and the kinetic energy involved in the impact ($\frac{1}{2}mv^2$):

$$\Delta E = mgh - \frac{1}{2}mv^2 \tag{1}$$

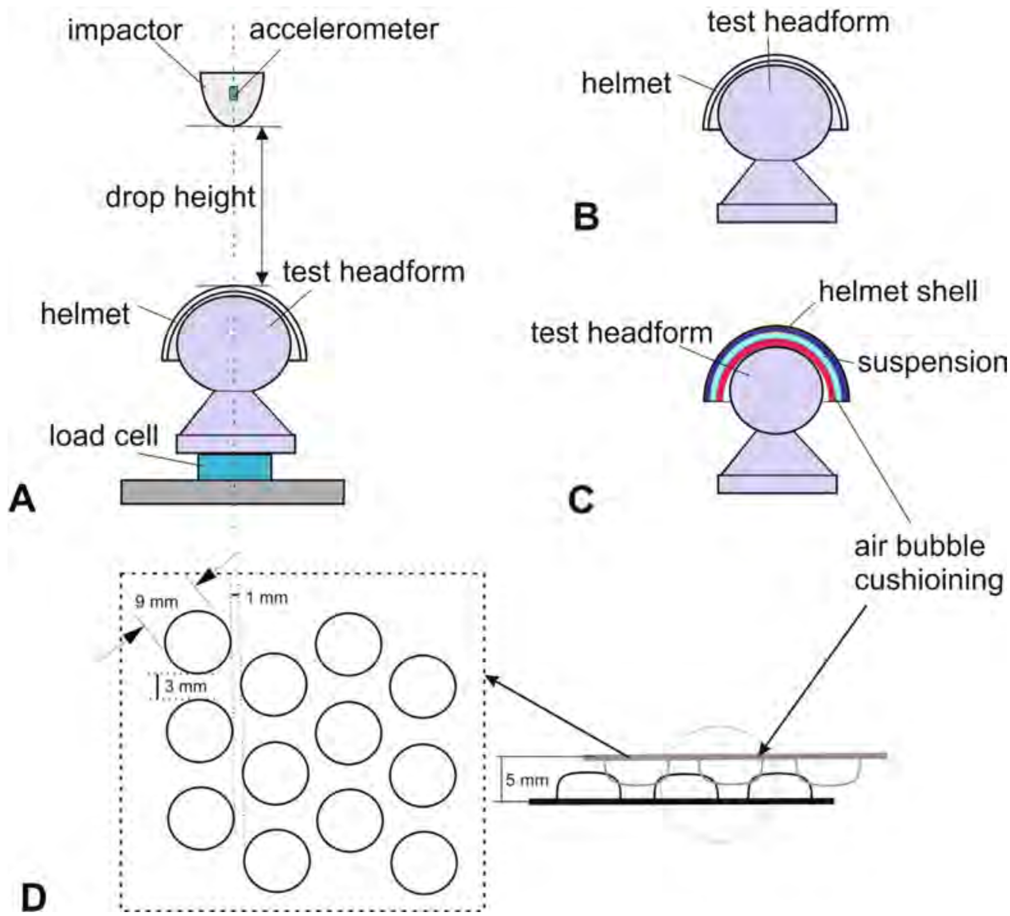

Fig. 2. Experimental set-up. (A) The control parameter was the drop height; the acceleration of the impactor and the transmitted force at the base of the headform were measured. (B) Test Group I consists of off-the-shelf type I helmets. (C) Test Group II consists of type I helmets equipped with an air-bubble cushioning liner between the suspension and headform. (D) Air bubble cushioning structure. The air-bubble cushioning liner consists of two layers of commercially available air-bubble packing sheet (1-foot width), with their bubble-sides being placed against each other. The air-bubble cushioning liner has a thickness of 5 mm at an undeformed state. A basic type I industrial helmet model was selected for the drop impact tests.

where m (3.6 kg) and g (9.8 m/s^2) are the impactor mass and gravitational acceleration, respectively.

The relative energy loss, δ, was estimated by comparing ΔE to the potential energy:

$$\delta = \frac{\Delta E}{mgh} \times 100\%. \tag{2}$$

The raw time-history data of the transmitted force and acceleration were processed using a MATLAB program to find the maximal peaks. The dependence of peak transmitted force and peak acceleration on the drop height was analyzed. The effect of the air-bubble cushioning liners on the peak transmitted force of helmets at six different drop heights was analyzed using a two-way analysis of variance (ANOVA). Furthermore, in order to evaluate the contribution of the air-bubble cushioning liner to the helmet's shock absorption performance, an impact force reduction coefficient is defined:

$$\eta = \left(1 - \frac{F_{max,air}}{F_{max,no-air}}\right) \times 100\% \tag{3}$$

where $F_{max,no-air}$ and $F_{max,air}$ are the mean peak forces for test Group I and Group II, respectively.

Since the data collected from the test Group I are independent of those collected from test Group II, the standard deviation of the impact force reduction coefficient, S_η, is estimated by the Taylor approximation [32]:

$$S_\eta = \frac{F_{max,air}}{F_{max,no-air}} \sqrt{\left(\frac{S_{max,no-air}}{F_{max,no-air}}\right)^2 + \left(\frac{S_{max,air}}{F_{max,air}}\right)^2} \tag{4}$$

where $S_{max,no-air}$ and $S_{max,air}$ are the standard deviations of the test Group I and Group II, respectively.

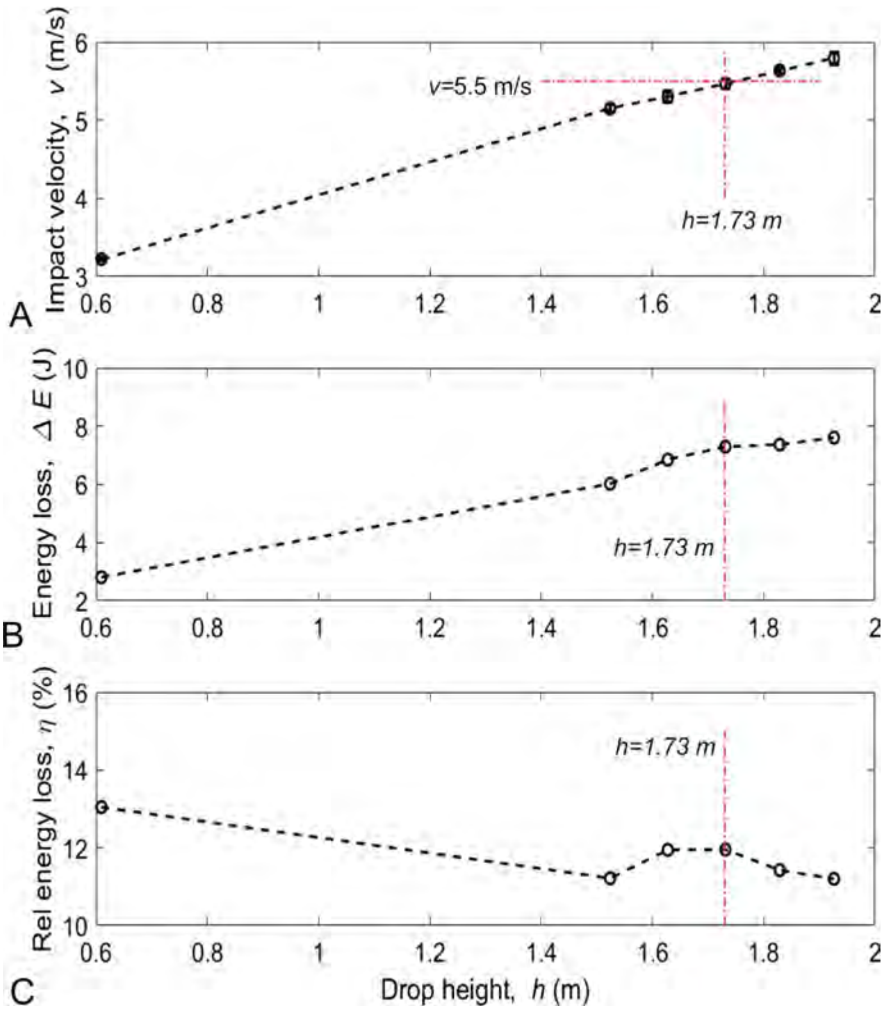

Fig. 3. Calibration of the frictional loss of the drop tower system. (A) Impact velocity (v) as a function of the drop height (h). (B) Kinetic energy loss of the system (ΔE) as a function of drop height (h). (C) Relative kinetic energy loss (δ) of the system as a function of drop height (h). ANSI Z89.1 standards requires the tests to be performed at a impact velocity of 5.5 m/s just before the impactor contact the helmet, which is equivalent to a drop height of 1.73 m for the current drop tower system.

3. Results

The impact velocity, v, as a function of the drop height, h, is shown in Fig. 3A. The ANSI Z89.1 standard requires an impact velocity of 5.5 m/s, which was achieved at a drop height of 1.73 m in our drop tower system. The frictional energy loss, ΔE, and the relative energy loss, δ, as a function of drop height are shown in Fig. 3B and C, respectively. It is seen that the frictional energy loss of the system is dependent on the drop height, and the system has a frictional loss of approximately 7 J or 12% at the impact velocity (5.5 m/s) specified by ANSI Z89.1.

The representative sample data of time-histories of the transmitted forces for test Group I and Group II are shown in Fig. 4A and B, respectively. Generally, the data show two peak forces, which are associated with the first and second impacts between the impactor and the helmet shell (Fig. 4). In the current study, we were only interested in the first impact, which resulted in the maximal peak impact force, because it is related to potential traumatic brain injury [34,35]. Our results show that adding an air-bubble cushioning liner (Fig. 4B) to the helmet (Fig. 4A) makes the appearance of the second impact sooner, but does not alter the general characteristics of the impact time histories.

Typical sample data of time histories of the transmitted forces around the first impact of helmets in Group I are compared to those in Group II for drop heights 0.61 m, 1.52 m, 1.63 m, 1.73 m, 1.83 m, and 1.93 m, in Fig. 5A, B, C, D, E, and F, respectively. Fig. 5 shows that, for both Group I and Group II tests, the impact duration (i.e., the time that the impactor is in contact with the helmet shell, or the impact force is greater than zero), is approximately 22 ms, and it is nearly independent of the drop height and the addition of the air-bubble cushioning liner. By closely examining the characteristics of the impact force patterns (Fig. 5), for the helmets from Group I, when $h \leqslant 1.73$ m (Figs. 5A-D), the force impulses have a nearly unchanged base width, and their peaks increase

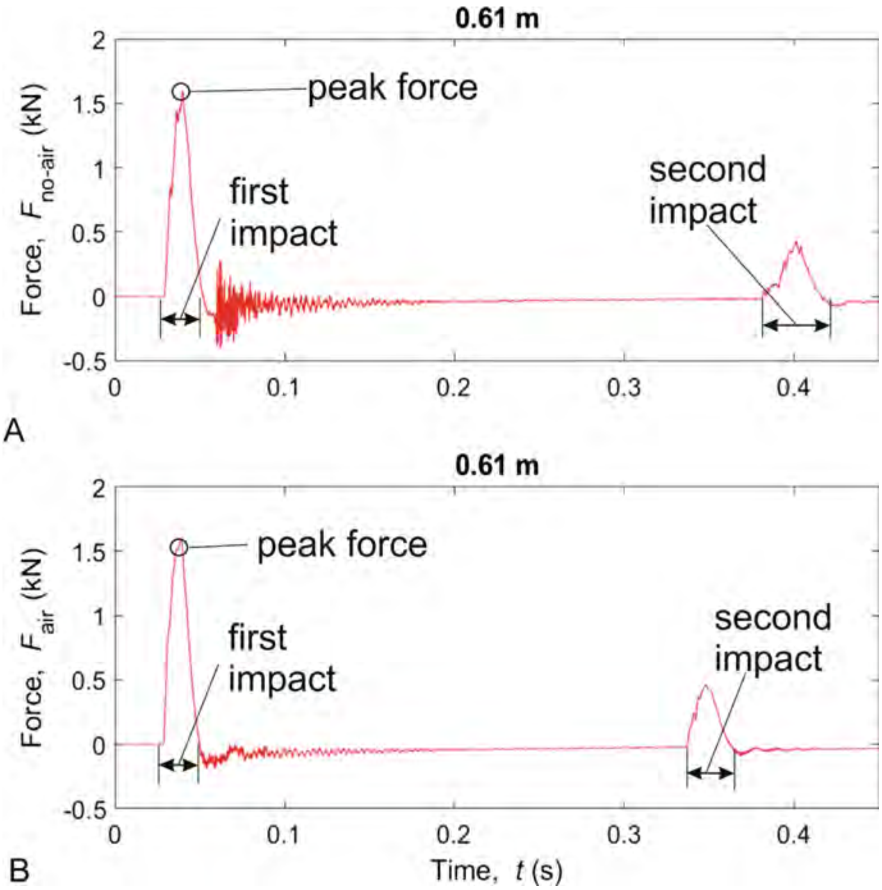

Fig. 4. The representative sample data for the time-histories of the transmitted forces for a drop impact test ($h = 0.61$ m). (A) The results for a off-the-shelf helmet (Group I). (B) The results for a helmet equipped with an air-bubble cushioning liner (Group II). The time-histories of forces show two peaks, corresponding to the first and second impacts between the impactor and the helmet shell.

gradually with increasing drop height. When $h \geqslant 1.83$ m (Figs. 5E-F), an additional sharp peak appears on the top of the base force impulse. This sharp force peak was very narrow (duration approximately 1 ms) and had a magnitude that increased dramatically with increasing drop height. For helmets in test Group II, there was no sharp force impulse for the entire range of drop heights.

Representative sample data of time histories of the accelerations of the impactor around the first impacts of Group I tests are compared with those of Group II tests for six different drop heights (Fig. 6). The magnitude of the peak acceleration for both test groups increased gradually from 50 G to 80 G, when the drop height increased from 0.61 m to 1.74 m (Figs. 6A-D). In this drop height range, the air-bubble cushioning had little effect on the acceleration patterns. Consistent with the variations of the transmitted forces (Figs. 5), the acceleration patterns for test Group I showed a sudden change around drop height from 1.73 to 1.83 m (Fig. 6D-E), where a narrow, sharp peak appeared on the top of the base pattern. At a drop height of 1.93 m, the magnitude of the peak acceleration reached as great as 370 G (Fig. 6F) for Group I tests. The acceleration results for the helmets equipped with an air-bubble cushioning liner (Group II) did not have these sharp acceleration peaks for the entire range of drop heights.

For each of the force-time curves, the peak transmitted forces have been evaluated. The ANOVA analysis found significant effects of air-bubble cushioning ($p < 0.0001$) and drop heights ($p < 0.0001$), and a significant interaction effect of air-bubble cushioning and drop heights ($p < 0.0001$). Table 1 shows the differences of mean peak transmitted forces (F_{max}) between test Groups I (helmet without air-bubble cushioning) and II (helmet with air-bubble cushioning) at different drop heights and their associated p-values. The peak transmitted forces between the two test groups were significantly different when the drop heights were at 1.83 m ($p = 0.0015$) and 1.93 m ($p < 0.0001$).

The mean peak impact forces for test Group I ($F_{max,no-air}$) and Group II ($F_{max,air}$), and the impact force reduction coefficient (η), together with their standard deviations, for six different drop heights are listed in Table 1. The mean peak transmitted forces presented in the table, for test Group I ($F_{max,no-air}$) and Group II ($F_{max,air}$), are plotted as a function of the drop height in Fig. 7A. With increasing drop height, the peak force values for helmets in Group I ($F_{max,no-air}$) increased gradually for $h \leqslant 1.73$ m and then increased dramatically for $h \geqslant 1.83$ m. In comparison, the peak force values for helmets in Group II ($F_{max,air}$) increased gradually with increasing drop height for the entire range of drop heights. The effects of the air cushioning liner on shock absorption are more clearly demonstrated in Fig. 7B, in which the impact force reduction coefficient (η) is plotted as a function of drop height. For lower drop

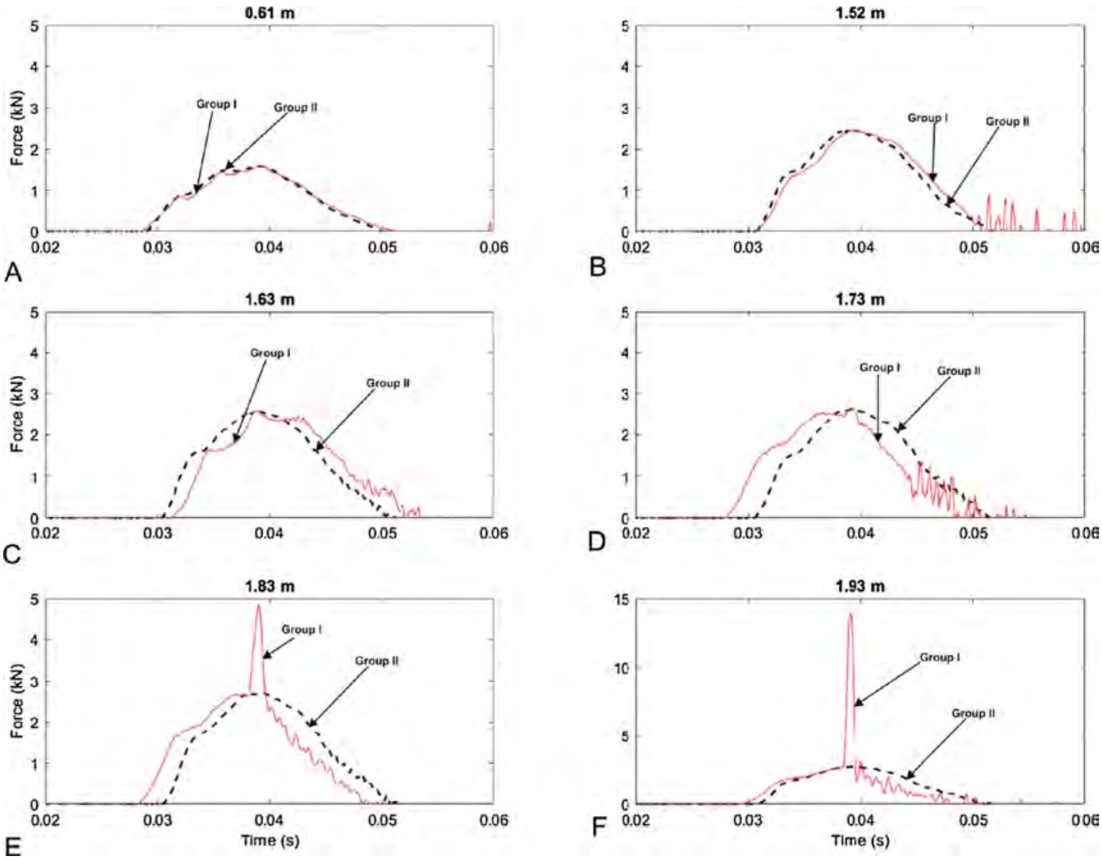

Fig. 5. The representative sample data for the time-histories of the transmitted force for six different drop heights (h) from 0.61 m (2 ft) to 1.93 m (6.34 ft) around the first impacts. (A) h = 0.61 m. (B) h = 1.52 m. (C) h = 1.63 m. (D) h = 1.73 m. (E) h = 1.83 m. (F) h = 1.93 m. The red solid lines and black dashed lines represent the results of the off-the-shelf helmets (Group I) and the helmets with air-bubble cushioning liner (Group II), respectively. The failure of the native helmets starts between h = 1.73 m (D) and h = 1.83 m (E), where a narrow, sharp force impulse appears on the top of the base force impulse. The helmets with air-bubble cushioning liner do not show any sign of failure for the entire drop height range. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

heights ($h \leqslant 1.73$ m), the air cushioning liner had little effect (η is close to 0%); whereas its shock absorption effects increased substantially (i.e., η increases) with increasing drop height for higher impact force ($h > 1.73$ m).

Visual examinations of the tested helmets showed that, for the helmets without an air-bubble cushioning, the conjunction sites between the suspension bands and hard shell were damaged after the high impact tests. For the helmets with air-bubble cushioning liners, the air-bubble cushioning liners were found to be damaged (air bubbles deflated), but no structural damages were observed in helmet shells or suspension systems. For all tested helmets, no external cracks were observed on the helmet shells.

4. Discussion and conclusion

Despite the outstanding shock absorption performances of air cushions in many applications, such as air beds, shoes, seat cushions, and other applications, air-bubble cushioning has not been used in industrial helmets. The current study represents the first to test the shock absorption performance of air-bubble cushioning in industrial helmets. Our results consistently show that the effects of shock absorption of air-bubble cushioning in industrial helmets are dependent on the impact magnitude. At lower drop heights ($h < 1.63$ m), adding an air-bubble cushion liner did not reduce the impact force for a typical industrial helmet with a strip-type suspension system. The effects of the air-bubble cushioning liner on the shock absorption was only seen at higher drop height ($h \geqslant 1.73$ m). At a drop height of 1.93 m (impact potential energy 68 J) – the highest drop height tested in the current study, adding the air cushioning liner to a typical Type I industrial helmet reduced the peak impact force magnitude by over 80%. Our results are consistent with a previous theoretical analysis, in which the air bubble was found not to vary the magnitude of force for low impacts [22].

Our finding that the air-bubble cushions significantly reduced impact force magnitudes transmitted through the helmets at higher impact forces suggests that including an air-bubble cushion into a typical Type I helmet will help improve the helmet's protection performance for top impacts. It is well accepted that the peak acceleration, associated with the peak impact force, causes the traumatic brain injury or concussion [33]. Previous studies indicated that a sudden high acceleration, even for only a few

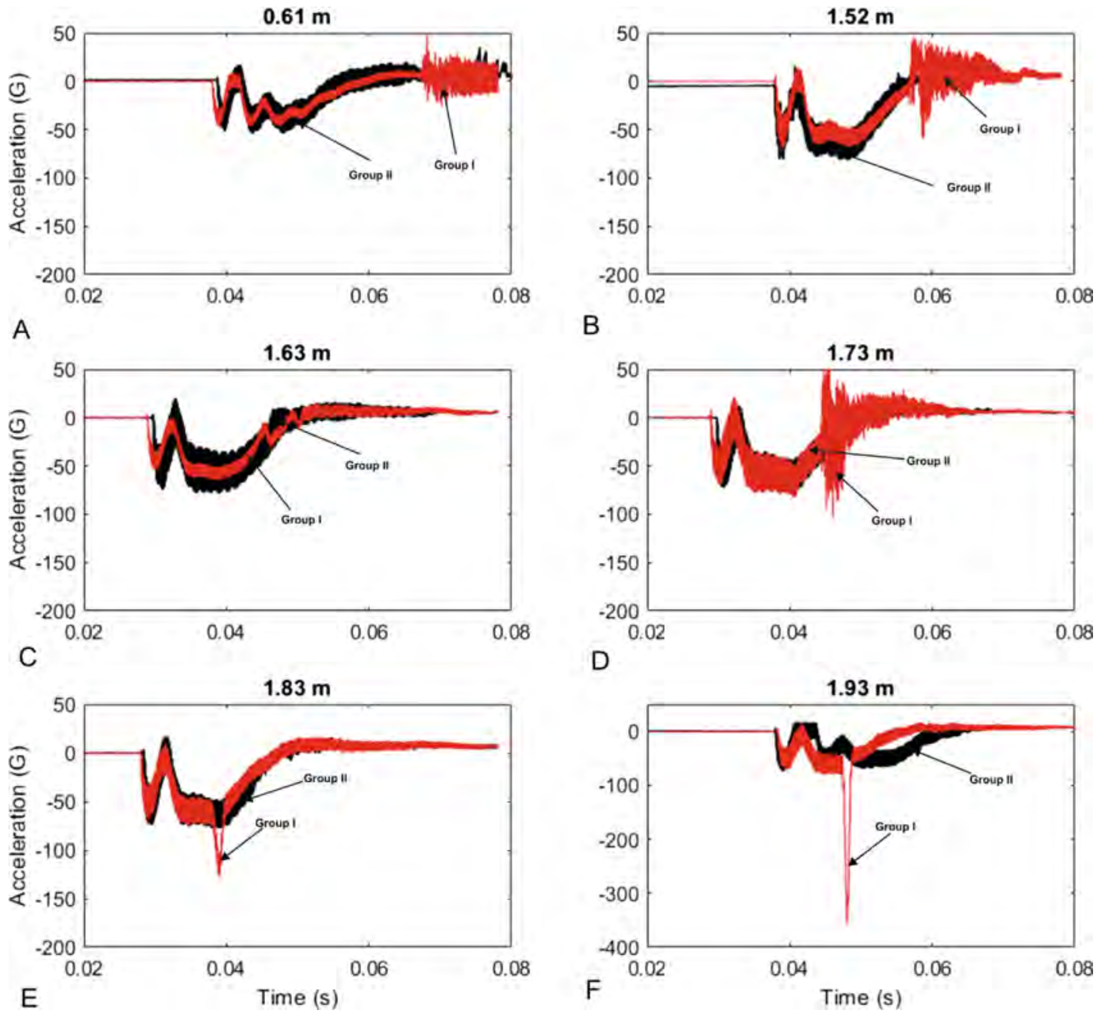

Fig. 6. The representative sample data for the time-histories of the impactor accelerations for six different drop heights (h) from 0.61 m (2 ft) to 1.93 m (6.34 ft) around the first impacts. (A) $h = 0.61$ m. (B) $h = 1.52$ m. (C) $h = 1.63$ m. (D) $h = 1.73$ m. (E) $h = 1.83$ m. (F) $h = 1.93$ m. The red and black lines represent the results of the off-the-shelf helmets (Group I) and the helmets with air-bubble cushioning liner (Group II), respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Mean peak transmitted forces (F_{max}) for test Groups I (original helmets) and II (helmets with air-bubble cushioning liners) and the impact force reduction coefficient (η) at six difference drop heights. The difference between the test Groups I and II is analyzed using a two-way analysis of variance (ANOVA). The data shown are the mean of four replication tests.

Drop height	Group I		Group II		Mean force difference		Force reduct coeff	
h (m)	$F_{max,no-air}$ Mean, (kN)	STD	$F_{max,air}$ Mean, (kN)	STD	$(F_{max,no-air} - F_{max,air})$ (kN)	p-value* (–)	η (%)	STD
0.610	1.588	0.03	1.584	0.03	0.004	1.000	0.3	2.7
1.524	2.480	0.03	2.515	0.05	-0.035	1.000	−1.4	2.5
1.628	2.645	0.24	2.541	0.02	0.104	1.000	3.9	8.7
1.731	2.942	0.66	2.596	0.02	0.347	1.000	11.8	19.7
1.829	7.329	3.87	2.687	0.03	4.642	0.002	63.3	19.4
1.926	14.405	2.51	2.521	0.22	11.884	<0.0001	82.5	3.4

* Bonferroni adjusted p-values

milliseconds, will result in a permanent brain injury [33]. The well-known Head Injury Criteria (HIC) is based on measurements of peak accelerations to determine probability of head injury occurring from impacts [34,35]. HIC is widely accepted in the automobile industry and in biomechanical analysis in sports. However, it is technically not convenient for helmet manufacture engineers to

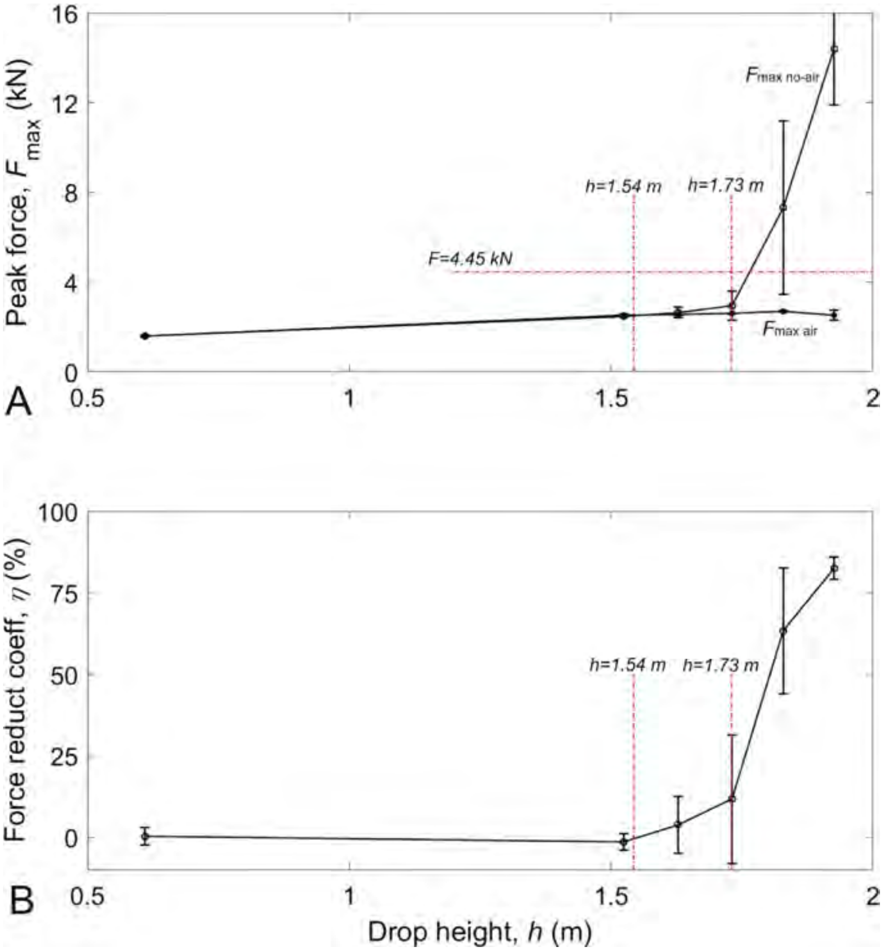

Fig. 7. The mean peak transmitted forces (F_{max}) as a function of drop height for test Groups I and II. (A) The peak transmitted forces as a function of drop height for Group I (the off-the-shelf helmets) and Group II (the helmets with air-bubble cushioning liner). B: The impact force reduction coefficient (η) as a function of drop height. The drop height designated in ANSI Z89.1 is 1.54 m and 1.73 m, respectively, for a frictionless condition and for the current system including the frictional loss. The maximal acceptable transmitted force magnitude in ANSI Z89.1 is 4.45 kN. The data shown are the mean of four replication tests.

obtain a reliable measure of HIC in a commercial drop tower. That is one of the reasons that the peak transmitted impact force, instead of the HIC measurement, is used to evaluated industrial helmets' shock absorption performance in the helmet test standards (e.g. ANSI Z89.1 and EN379). The magnitude of the maximal peak impact force is accepted as the most important measurement for an industrial helmet's protection performance.

Theoretically, there are three possible places that an air-bubble cushion can be attached onto an industrial helmet (Fig. 1): placing it externally on the top of helmet shell, inserting it into the space between the helmet shell and suspension, and attaching it onto the helmet suspension between head and helmet harness. The first setup is unpractical and structurally not reasonable, because the exposed air bubbles can easily be damaged by the striking objects and because the externally placed cushions will cause the helmet user inconvenience in some work applications. In the second setup, only a portion of the impact force will be carried by the air-bubble cushion during an impact. In addition, it cannot be guaranteed that the air bubble cushion will fit the same way into helmets of different manufacturers. In other words, using this setup, we cannot establish a uniform test condition for helmets of different designs and by different manufacturers. We choose the third setup in the study, because we are sure that the entire impact force will be transmitted through the air-bubble cushions in the impact tests and because we can use the same air-bubble cushions for helmets by different manufacturers without modifying their original suspension designs.

Our results demonstrate that damage to off-the-shelf helmets (Group I) starts around drop heights from 1.73 to 1.83 m (Fig. 5D-E). In order to elucidate the failure mechanism of the helmet, the time-histories of the impact force around these "critical" drop heights were closely re-examined (Fig. 8). The failure of the off-the-shelf helmet starts when a sharp narrow impulse (red solid lines in Fig. 8B) appears on the top of the base force impulse. The appearance of the sharp peaks in impact forces are likely due to the failure of the suspension system, causing a direct contact between the helmet shell and headform. The air-bubble cushioning liner helped prevent the helmet from premature failure; there was no sharp narrow impulse for the tests with the same drop height (black dashed

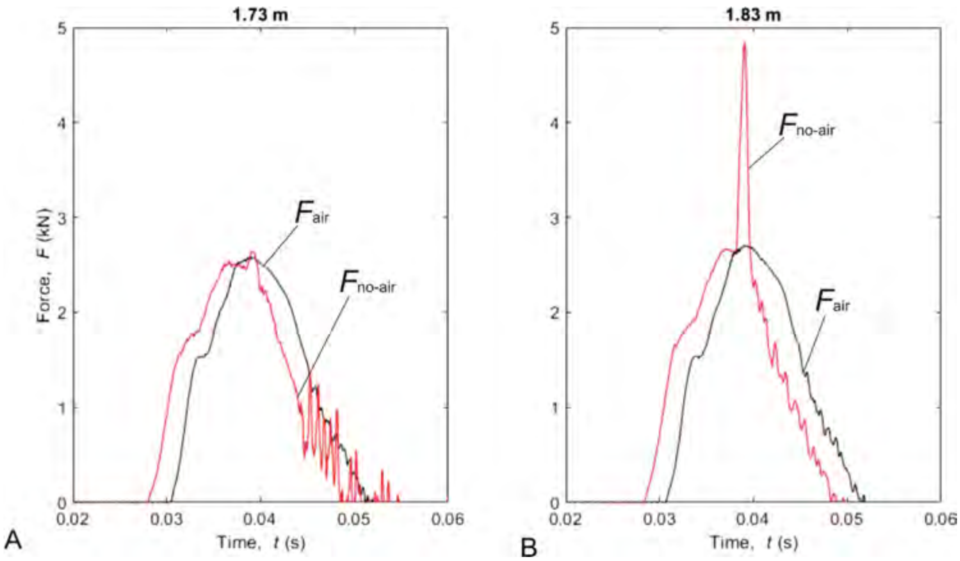

Fig. 8. Analysis of the variations of the transmitted force responses around the failure of the helmets. (A) Drop height 1.73 m. (B) Drop height 1.83 m. The red lines and black lines are representative sample data of the off-the-shelf helmets (Group I) and the helmets with air-bubble cushioning liner (Group II), respectively. The high frequency vibrations were likely caused by the impulsive tensions in the woven fabric strips and the air-bubble cushioning liner helped damp these system vibrations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

lines in Fig. 8B).

The high-frequency vibrations observed in the tests (Fig. 8) are likely the internal frictional vibration in fibers within the woven fabric strips in the suspension system caused by the impulsive tensions. Mechanically, the synthetic woven fabric strips in the suspension are comparable to a wire rope in structure [36,37]. Previous studies [36,37] found that impulsive stretching in synthetic or steel wire ropes caused high-frequency vibrations, which are very like to those observed in our tests. When a wire rope is stretched, the helix angles of wires/strands and the external overall diameter will vary depending on the magnitude of the tension, causing relative movements and sliding between the wires and/or strands and inducing torsional vibrations. It is seen that adding air-bubble cushioning liner in the helmet helped eliminate the high frequency vibrations of the suspension system (Fig. 8). These observations are comparable to a previous study of the vibration mitigation performance of air-bubble gloves [21], in which the air-bubble gloves were found to be effective in absorbing high frequency vibrations transmitted to the fingers, whereas they were ineffective for mitigating low frequency vibrations.

The reason that we presented time-histories of both impact force and acceleration (Figs. 5 and 6) for the same tests was to elucidate the mechanism of the helmet failure during the impacts. We demonstrated that the failure of the helmet starts when a sharp narrow impulse appears on the top of the base force impulse (Fig. 5). The measurement of the accelerations (Fig. 6) was used to further qualitatively check the observations of the peak impact forces, to confirm if they are associated with the failure of the suspension system. The nature of the acceleration measurements (Fig. 6) is noisy, because the tensions of the synthetic woven fabric strips in the suspension were accompanied by high frequency vibrations. That is one of the reasons that all standardized tests for industrial helmets rely on the measurements of the impact force.

Before the impact, the helmet suspension system was in a relaxed state and was only statically loaded by the helmet's weight. The first small peak in the time-histories of the acceleration measurements (Fig. 6) was caused by the initial contact between the impactor and the helmet shell. After the initial contact, the impactor bounced back from a small impact reaction force from the helmet due to the helmet's initially loose suspension. After the initial contact, the helmet moved towards the headform and the suspension system was tightened. The impactor and the helmet shell then came into a second contact – the major impact, which was the major peak in acceleration (Fig. 6). The major impact resulted in a large impulse wave of the acceleration.

ANSI Z89.1 standard requires a top impact dropping with an impactor of 3.6 kg at a velocity of 5.5 m/s, which is approximately equivalent to a drop height of 1.73 m for our drop tower tester (Fig. 3A). The drop height that is compliant with the ANSI Z89.1 standard is approximately 12% higher than the theoretical estimations due to the frictional loss of the system. The frictional loss of the testing system does not affect the effects of the air cushions on helmets' shock absorption performance – the problem we are studying. Our results show that the off-the-shelf helmet model selected in the current study passes ANSI Z89.1, which requires the transmitted peak force to be less than 4.45 kN. However, the selected helmet model would not likely pass EN14052 – European standard for high-performance industrial helmets, in which the helmet will be tested with an impactor of 5.0 kg from a drop height of 2.04 m (impact potential energy 100 J); the maximal force transmitted to the helmet shall be less than 5.0 kN. The peak impact force of the off-the-shelve helmet exceeds 5.0 kN when $h > 1.75$ m, which is equivalent to an impact potential energy of 68 J (Fig. 7A). Therefore, it is obvious that the off-the-shelve helmet does not pass EN14052 standardized test. Our results demonstrate that adding an air-bubble cushioning liner to a basic Type I industrial helmet would substantially increase the shock absorption performance at high impact forces, providing better protection and making it possibly pass more stringent test standards.

It is interesting to observe that the helmets show a narrow scattering (lower standard deviation values) in the peak transmitted force data when the shock absorption performance is in the stable range (i.e., $h < 1.73$ m) (Fig. 7). The scattering in the peak transmitted force test data becomes substantially larger (higher standard deviation values) once the drop height is above 1.73 m, reflecting unstable mechanical characteristics of the suspension system. The peak transmitted force data for the helmets with the air-bubble cushioning liner show a narrow scattering for the entire drop height range, indicating stable mechanical characteristics of the suspension system for the entire test range.

Helmets are used to protect repeated head impacts in many sports activities. Previous studies show that the shock absorption performance will get worse during repeated impacts for many sports helmets, such as baseball helmets [38], equestrian helmets [39], and hockey helmets [40]. In our previous study [31], type I industrial helmets were found to experience cumulative structural damage, resulting in a degradation of shock absorption performance during the repeated impacts. It is not known if adding air-bubble cushioning liner to a industrial helmet will increase its endurance for repeated impacts.

Temperature is a factor that may affect the shock absorption of air-bubble sheets in the helmets. The air-bubble cushioning sheets are made of thermal plastics (polyethylene or polypropylene). The mechanical properties of the thermal plastics are known to be temperature dependent. In addition, the environmental temperature also affects the thermal dynamic status of the air enclosed in the air bubbles. Therefore, the temperature will likely affect the shock absorption performance of the helmets. In the current study, all impact test were performed at a room temperature (21 °C). The effect of the temperature on helmets' shock absorption has not yet been investigated and it will be a topic for our future study.

The current study is for the purpose of proof of concept. When the proposed approach is accepted by engineers and is applied in the helmet design, there are many aspects that the air-bubble cushioning liners need be improved. First, the air bubble cushioning liners will be custom-made to take on a shape and size to just wrap the suspension system, as only the portion of the air-bubble cushioning sheet within the range of the suspension system is mechanically effective. Secondly, the air-bubble cushioning will be made of durable materials, such as high-density polyethylene (HDPE) and polypropylene (PP). The helmets' shock absorption performances would be improved more if custom-made air-bubble cushioning with durable and high strength membranes were used. In addition, ventilation holes or gaps will be considered in the custom-made air-bubble cushioning sheets to improve the thermal dissipations of the helmet.

A further limitation of the current study is that we tested only one selected helmet model from a manufacturer. The shock absorbtion performance of the air-bubble cushioning liner may be different for different helmets if tested using the proposed approach. In addition, we tested the helmets only in top impacts, since Type I helmet is not required to be tested for lateral impacts according to current test standards [14,16,15]. However, if the proposed method is applied to Type II helmet models, the shock absorption performances for lateral impacts should be evaluated. The shock absorption mechanisms for Type I and Type II helmets are different. For Type I helmets, the shock impact is mainly absorbed by the strip-type suspension system, whereas the shock impact is mainly absorbed by the foam liner materials in Type II helmets [41]. It is not known if adding air-bubble cushioning liner will improve the shock absorption performance for Type II helmets. The proposed test methodology needs to be further verified using Type I and II helmets from different manufacturers.

In summary, in the current study we found that adding an air-bubble cushioning liner to a basic Type I industrial helmet will substantially increase the shock absorption performance for large impacts. The current study represents the first to use air-bubble cushioning in the helmet suspension systems. Our findings may help manufacturers improve helmet designs, thereby reducing the potential for WrTBI. The concept of the air-bubble cushioning may not only be used for industrial helmets, but also be used for sports helmets to increase the shock absorption performance.

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.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.engfailanal.2020.104921.

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