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Climbing style safety helmets do not improve impact protection over type II hard hats

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A R T I C L E I N F O

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A B S T R A C T

Safety helmets are promoted as safer alternatives to traditional hard hats, but few data on impact performance exist. Conversely, traditional hard hats have evolved to include Type II models that have liners for lateral impact protection. This study employed standardized test methods to determine if safety helmets outperform traditional hard hats.

Seven safety helmet models and four Type II hard hat models were tested for their ability to absorb crown and lateral impacts according to standards EN 12492 and ANSI Z89.1, respectively. Three Type I hard hats were included for baseline comparison. For crown impacts, a hemispherical striker was dropped onto the helmet crown at 98 J impact energy and the resulting force transmission F_{CROWN} was measured. For lateral impacts, helmeted headforms were dropped onto a hemispherical anvil with 31 J impact energy. The linear acceleration a_Z was captured for front, side and rear impacts.

For crown impacts, at least half of the helmet models in all three helmet categories exceeded the 10 kN threshold specified in EN 12492. For lateral impacts, all Type I hard hats and all safety helmets exceeded the 150 g threshold specified in ANSI Z89.1,while all Type II hard hats remained below the 150 g threshold. Safety helmets exhibited on average 1.9 times higher head accelerations from lateral impacts compared to Type II hard hats.

For best head protection, helmet should be selected based on their ability to meet both, EN 12492 and ANSI Type II, and not based on a particular helmet style.

1. Introduction

A 2021 systematic review found that despite a decrease in overall work-related injury claims, the proportion of claims from work-related TBIs have increased. (Toccalino et al., 2021). Helmets are the most effective intervention to reduce the incidence and severity of work-related head injury. (Gilchrist and Mills, 1987) This suggests that selecting the most effective helmet is critical to address the costly and debilitating TBI epidemic among the work force. (Gilchrist and Mills, 1987).

Most recently, climbing-style safety helmets are being promoted as a safer alternative to traditional hard hats that have been used since over 80 years. (King, 2022; Pardon, 2022; Rolfsen, 2022) These modern safety helmets are derived from mountaineering helmets that have a hard thermoplastic shell for penetration protection, a soft inner liner made of expanded polystyrene (EPS) for impact absorption, and a chin strap for helmet retention. To accommodate this recent trend of safety helmet adoption, leading hard hat manufacturers, including Bullard, MSA, and 3M, have recently introduced climbing-style safety helmets. Some large general contractors in the USA, such as the Clark Construction Group, already require their employees to wear safety helmets instead of hard hats in order to provide enhanced head protection. (Pardon, 2022).

In collaboration with Clark, the American Society of Concrete Contractors started a Safety Helmet Initiative called “Hats to Helmets” with the strategic goal to transition 75% of society members from hard hats to safety helmets by 2023. (American Society of Concrete Contractors) Moreover, the Directorate of Construction of the Occupational Safety and Health Administration (OSHA) recently announced that OSHA inspectors may soon wear safety helmets instead of hard hats. (Rolfsen, 2022).

In an recent article titled “Why the Switch to Safety Helmets is a Good Decision”, the author suggests two reasons to promote modern safety helmets over traditional hard hats. (Pardon, 2022) First, safety

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helmets are believed to offer better protection in falls since they require chin straps for helmet retention during a fall. Second, the EPS liner inside safety helmets may provide absorption of impacts to the helmet sides, front, and back. This lateral impact protection is particularly critical during falls, which are responsible for 68% of all work-related TBI cases in the construction industry, while falling objects hitting the crown of a helmet cause only 12% of work-related TBI. (ISEA Z89.1-2014, 2014) However, little data exist to substantiate these potential benefits of modern safety helmets over hard hats. Additionally, hard hats have also evolved. Today, all leading hard hat manufacturers offer hard hat models that accommodate chin straps and that have an inner EPS liner for damping of lateral impacts to the front, sides, and back.

Measuring the impact performance of contemporary hard hats and climbing-style safety helmets is critical to guide the development and selection of helmet designs for prevention of work-related head injury. Impact protection provided by a helmet is assessed in the USA by the American National Standard for Industrial Head Protection, ANSI/ISEA Z89.1–2014. (ISEA Z89.1-2014, 2014) This standard describes two levels of impact protection. Type I helmets are intended to reduce the force of impact resulting from a blow only to the top of the head. Type II helmets are intended to reduce the force of impact resulting from a blow to the top or sides of the head. If supplied with a chin strap, Type II helmets must also be tested for chin strap retention. This standards is applicable for hard hats and climbing-style safety helmets. Many climbing-style safety helmets are also certified to the European Standard EN 12492 for "Helmets for Mountaineers". (In: EN 12492, 2012) This standard requires chin straps. Similar to the ANSI Z89.1 standard, it also requires impact testing to the helmet crown and sides. Crown impact testing is more stringent in EN 12492, which requires 98 J impact energy, compared to ANSI Z89.1, which requires only 55 J impact energy (Table 1). Lateral impact testing is more stringent in ANSI Z89.1 for three reasons. ANSI Z89.1 requires 31 J lateral impacts compared to 25 J in the EN 12492 standard. ANSI Z89.1 also prescribes a hemispherical impactor, which causes a more focused impact concentration compared to the flat impactor of EN 12492. Finally, lateral impacts in ANSI Z89.1 are conducted lower to the helmet brim compared to EN 12492. The most stringent helmet performance assessment is therefore provided by evaluating crown impacts according to EN 12492 and lateral impacts according to ANSI Z89.1.

These standardized test methods can readily be used to measure and compare the performance of contemporary hard hats and climbing-style safety helmets. We hypothesize that there is no difference in impact performance between Type II hard hats and safety helmets. Results of this study will be critical to determine whether the recent shift from hard hats toward safety helmets is substantiated by evidence of improved impact performance.

Table 1
Comparison of impact test requirements between ANSI Z89.1 and EN 12492 standards for testing of hard hats and safety helmets.

		ANSI Z89.1	EN12492
Crown Impact Testing	**Energy**	**55 J**	**98 J**
	Speed	5.5 m/s	6.3 m/s
	Mass	3.6 kg	5 kg
	Drop Height	1.5 m	2 m
	Anvil Shape	hemisphere, r = 48 mm	hemishere, r = 50 mm
	Threshold	≤ 4,459 N MAX, ≤ 3,780 AVG	≤ 10 kN
Lateral Impact Testing	**Energy**	**31 J**	**25 J**
	Speed	3.5 m/s	3.1 m/s
	Mass	5 kg	5 kg
	Drop Height	0.6 m	0.5 m
	Anvil Shape	hemispherical, r = 48 mm	flat
	Threshold	≤ 150 g	≤ 10 kN

2. Methods

Seven safety helmet designs and four Type II hard hat designs were tested for their ability to absorb crown impacts according to EN 12492 and lateral impacts according to ANSI Z89.1. In addition, three Type I hard hat designs were included to provide a baseline representing today's most frequently used helmets. All testing was conducted at the Helmet Impact Testing (HIT) facility of the Biomechanics Laboratory of Legacy Health System in Portland, Oregon, USA. Three helmets of each helmet design were tested to assess the average amount for impact force or acceleration transmitted to a standardized headform. Finally, the coverage of impact liners inside Type II hard hats and safety helmets was measured to identify underlying structural differences in helmet design that may affect impact performance.

2.1. Helmets

Helmets in three categories (Type I hard hats, Type II hard hats, safety helmets) were selected from leading manufacturers that offered helmets in all three categories when possible (Table 2). For baseline testing, three Type I hard hat helmets were selected, labeled H1a-H1c: H1a (Classic, Bullard, Cynthiana, KY); H1b (V-Gard 500, MSA, Cranberry, PA); and H1c (H-800, 3M, St Paul, MN). All Type I hard hats had a strap suspension (Fig. 1A). Four Type II hard hats available with chin straps were selected, labeled H2a-H2d: H2a (Bullard Vector); H2b (MSA Super-V); H2c (A89, Honeywell, Charlotte, NC); and H2d (T2 MAX, WaveCel, Wilsonville, OR). Three of the four Type II hard hats had a strap suspension combined with an EPS liner, and one hard hat had a WaveCel cellular Dome (Fig. 1B). Seven safety helmets were selected and labeled Sa-Sg: Sa (Cen10, Bullard); Sb (V-Gard H1, MSA); Sc (SecureFit, 3 M); Sd (Fibre Metal, Honeywell); Se (Vertex, Petzl, West Valley City, UT); Sf (Superplasma HD, Kask, Charlotte, NC); and Sg (Zenith X, Kask). Of the seven safety helmets, two had only a strap suspension (Sd, Se), three had only an EPS liner (Sa, Sf, Sg), and two had a combined strap suspension and EPS liner (Sb, Sc) (Fig. 1C).

Three helmets of each design were ordered for repeat testing, requiring a total of 42 helmets.

2.2. Crown impact testing

The shock absorption of impacts to the helmet crown was evaluated in accordance to standard EN 12492:2012, section 4.2.1.1. (In: EN 12492, 2012) For this test, helmets were seated on an ISO size J half headform (100_04_HMH, Cadex Inc., Quebec, Canada) made of magnesium that was mounted at the base of a vertical drop tower (Fig. 2A). The headform was attached to an impact force measurement system (DI-1000UHS, Loadstar Systems, Fremont, CA) to capture the impact force transmitted to the headform at a frequency of 10 kHz. A steel striker with a hemispherical face of 50 mm radius and a mass of 5 kg was released from a drop height of 2 m and guided with a mono-rail guide system to impact the crown of the helmet. The impact location coincided with the intersection of the central coronal and sagittal planes of the headform (Fig. 2B). Impact speed was measured with a timed light gate (#5012 Velocimeter, Cadex Inc., Quebec, CA) located 5 mm above the point of impact. All tests were performed at ambient room temperature. The impact energy E_{CROWN} was calculated based on the measured impact speed. The peak impact force F_{CROWN} was extracted after 600 Hz low pass filtering of the impact force signal, as required by EN 12492. In order to pass this standard, F_{CROWN} must remain below 10,000 N.

2.3. Lateral impact testing

Attenuation of lateral impacts to the front, side and back of the helmet were evaluated in accordance to standard ANSI/Z89.1–2014. (ISEA Z89.1-2014, 2014) An ISO size J headform with a Shore "D" durometer of 60 (SB070, Cadex Inc., Quebec, Canada) was mounted to

Table 2
Description of Type I and Type II hard hats and safety helmets, selected from leading manufacturers. None of the selected manufacturers offered a Type II rated safety helmet at the time of study initiation.

Category	Label	Model	Manufacturer	Suspension	Shell	Liner	Weight [g]	ANSI Rating	EU Rating
Type 1 Hard Hats	**H1a**	Classic	Bullard	6-point	HDPE	none	415	Type I	–
	H1b	V-Gard 500	MSA	4-point	HDPE	none	350**	Type I	–
	H1c	H-800	3M	4-point	HDPE	none	416	Type I	–
Type 2 Hard Hats	**H2a**	Vector	Bullard	4-point	HDPE	EPS, crown + lat.	437	Type II	–
	H2b	Super-V	MSA	4-point	HDPE	EPS, lateral	555	Type II	–
	H2c	A89	Honeywell	4-point	HDPE	EPS, lateral	499	Type II	–
	H2d	T2 Max	WaveCel	none	ABS	Cellular, crown + lat.	480	Type II	EN 12,492
Safety Helmets	**Sa**	Cen10	Bullard	none	PC/ABS	EPS, crown + lat.	501	Type I	–
	Sb	V-Gard H1	MSA	4-point	ABS	EPS, crown	500	Type I	–
	Sc	SecureFit	3M	6-point	PC/ABS	EPS, crown + lat.	478	Type I	–
	Sd	Fibre Metal	Honeywell	6-point	PC/ABS	none	577***	Type I	–
	Se	Vertex	Petzl	6-point	ABS	none	494	Type I	EN 12,492
	Sf	Superplasma HD	Kask	none	ABS	EPS, crown + lat.	448	Type I	EN 12,492*
	Sg	Zenith X	Kask	none	PP	EPS, crown + lat.	457	Type I	EN 12,492*

* partial EN 12492 compliance, excluding crown impact; **front brim only; ***includes built-in visor.

Fig. 1. Examples of helmet types in the three helmet categories: A) Type I hard hats had a strap suspension; B) Type II hard hats had a strap suspension combined with an EPS liner, or a cellular WaveCel dome; C) Safety helmets had either an EPS liner, or a strap suspension, or a combination of both. Images of the helmet inside are shown with the fit system and half of the comfort pad removed to better visualize strap suspensions and liners for impact mitigation.

the drop assembly of a vertical drop rail (Fig. 3A). The combined weight of the headform and drop assembly was 5.0 kg. A ball joint inside the headform allowed adjustment of headform orientation for apex, front, side and rear impacts. ANSI standard Z89.1 requires that the edge of the hemispherical anvil with 48 mm radius does not overlap with the Dynamic Test Line (DTL). Therefore, locations of front impacts (Fig. 3B), side impacts (Fig. 3C), and rear impacts (Fig. 3D) were marked to be 48 mm superior to the DTL. Marking of impact locations was performed with a laser level after helmets were firmly seated onto the ISO size J headform and loaded with a 50 N static force according to standard ANSI Z89.1–2014. For impact testing, helmeted headforms were subjected to guided freefall from a nominal drop height of 0.6 m to achieve an impact speed of 3.5 m/s, representing an impact energy of 31 J. Impact speed was again measured with the timed light gate located 5 mm above the point of impact. Drop tests were conducted onto a hemispherical anvil with 48 mm radius that was rigidly mounted on a steel base of 150 kg weight. Linear acceleration of the headform during impact was measured with a linear accelerometer (356B21, PCB, Depew, NY) mounted at the center of gravity of the headform, and oriented to capture acceleration along the impact direction. Three specimens of each helmet model were impacted in accordance with ANSI standard Z89.1–2012 at 3.5 m/s onto the front side, and rear, locations (Fig. 3) to derive a_{FRONT}, a_{SIDE}, and a_{REAR}, respectively. In order to conform to this standards, each peak liner acceleration recording must remain below 150g. Additionally, the overall lateral impact acceleration $a_{LATERAL}$ was calculated by averaging head accelerations a_{FRONT}, a_{SIDE}, and a_{REAR} for each helmet design. Furthermore, the Head Injury Criterion (HIC) was calculated, which represents an established head injury metric that accounts for both the magnitude and duration of linear acceleration: (Marjoux et al., 2008)

$$\mathrm{HIC} = (t_2 - t_1)\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a\,\mathrm{d}t\right]^{5/2}$$

where a is the linear acceleration signal, and whereby t_1 and t_2 are the initial and final times that span a 15 ms time window over which HIC is maximized. HIC was calculated from a_{FRONT}, a_{SIDE}, and a_{REAR} acceleration signals, and all HIC values from these lateral impacts were averaged to derive a single $HIC_{LATERAL}$ result per helmet. Finally, the coverage of EPS impact liners inside Type II hard hats and safety helmets was measured to identify underlying structural differences in helmet design that may affect impact performance. First, a series of 1 mm holes were drilled from the helmet inside along the boundary of the impact liner to allow accurate tracing of the liner boundary on the outer surface of the shell. Next, helmets were mounted on a full face headform (NOCSEA

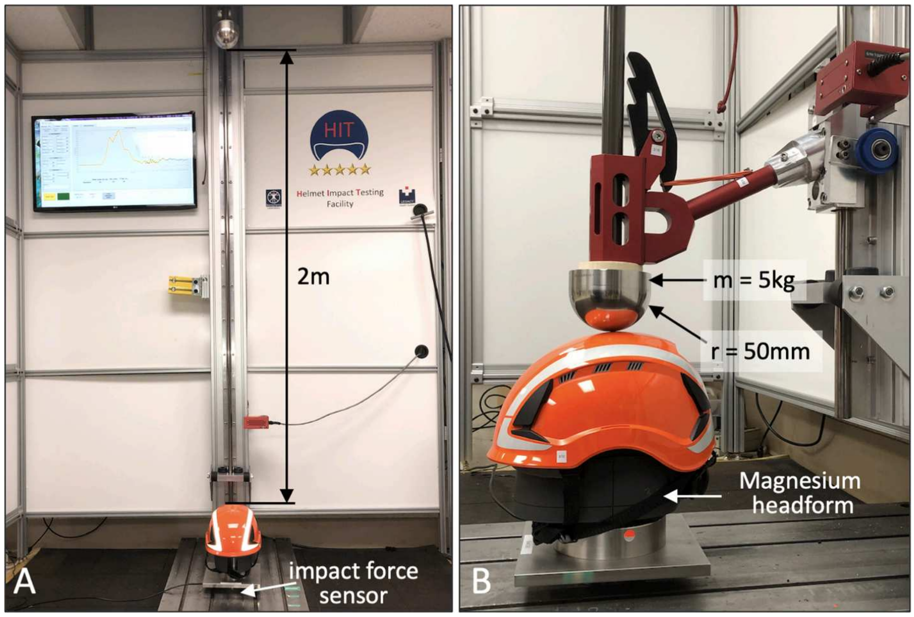

Fig. 2. Crown impact testing at 98 J impact energy according to EN 12492. A) A hemispherical impactor is release from 2 m height onto the crown of the helmet, with the impact force sensor being located under the square base plate. B) The impact force is measured at the base of the headform.

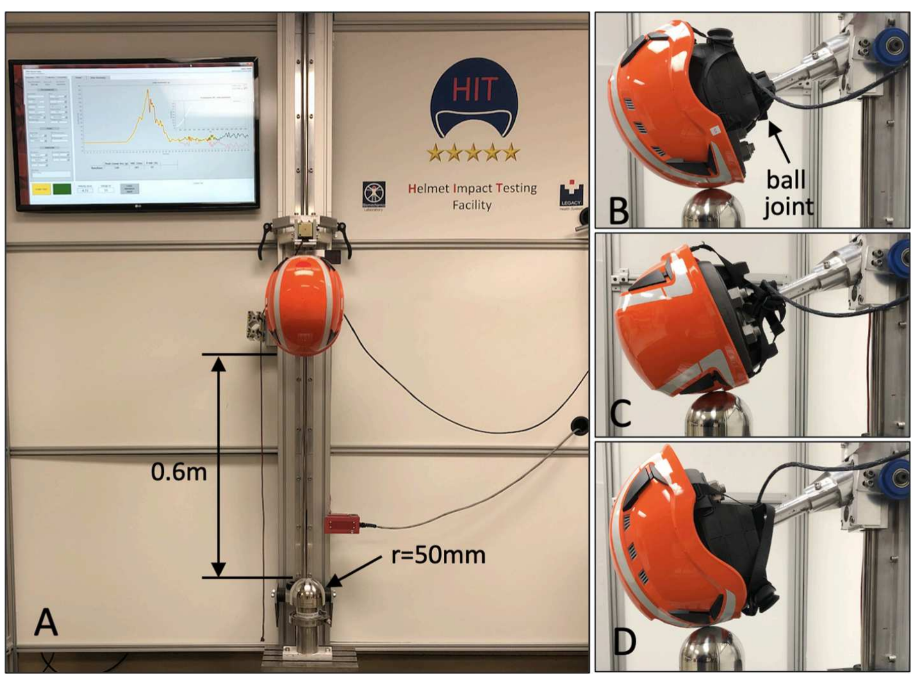

Fig. 3. Lateral impact testing at 31 J impact energy according to ANSI Z89.1. A) A helmeted headform is released from 0.6 m height onto a hemispherical impactor. The headform is rotated around a ball joint to achieve front (B), side (C), and rear (D) impacts.

RMM 367–9, Southern Impact Research Center, Rockford, TN) with an engraved basic plan which was used to reference the Dynamic Test Line (DTL) on the helmet surface according to ANSI standard Z89.1. Images of the helmeted headform were subsequently scaled and analyzed in ImageJ software (https://www.imagej.nih.gov) to calculate the head profile area above the DTL (A_{HEAD}), and the area of the impact liner (A_{LINER}) that covered the head profile. Dividing A_{LINER} by A_{HEAD} yielded the liner coverage, whereby a 100% liner coverage would indicate that the impact liner covered the entire lateral head profile above the DTL.

Rather than performing a statistical analysis of differences in outcome parameters F_{CROWN}, a_{FRONT}, a_{SIDE}, a_{REAR}, and $a_{LATERAL}$ between each helmet design, these outcome parameters were correlated to the thresholds of 150 g and 10 kN specified in ANSI standard Z89.1 and in the European standard 12482, respectively.

3. Results

For crown impact testing according to standard EN 12492, average impact speeds per group ranged from 6.28 ± 0.03 m/s to 6.31 ± 0.01 m/s, corresponding to impact energies E_{CROWN} ranging from 98.6 J to 99.5 J, respectively. For lateral impact testing to the front, side and rear of the helmet according to ANSI standard Z89.1, average impact speeds per group ranged from 3.48 ± 0.02 m/s to 3.52 ± 0.01 m/s, corresponding to impact energies ranging from 30.3 J to 31.0 J, respectively.

Crown impacts according to standard EN 12492 induced peak impact forces F_{CROWN} ranging from 7.0 ± 0.2 kN to 20.3 ± 1.5 kN for Type I hard hats, from 4.7 ± 0.2 kN to over 23.1 kN for Type II hard hats, and from 4.5 ± 0.2 kN to over 23.1 kN for safety helmets (Fig. 4). The 23.1 kN reports measured for one Type II hard hat and two safety helmets represents the maximum capacity of the load sensor, which was exceeded in these test. Peak impact forces exceeded the 10 kN threshold specified in EN 12492 in two out of three Type I hard hats, in two out of four Type II hard hats, and in four out of seven safety helmets.

Front impacts induced peak linear accelerations a_{FRONT} ranging from 204 ± 6 g to 283 ± 6 g for Type I hard hats, from 103 ± 21 g to 150 ± 3 g for Type II hard hats, and from 115 ± 19 g to 260 ± 6 g for safety helmets (Fig. 5). Linear acceleration exceeded the 150 g threshold specified in ANSI Z89.1 in all Type I hard hats and in six out of seven safety helmets, but not in any of the four Type II hard hats.

Side impacts induced peak linear accelerations a_{SIDE} ranging from 229 ± 17 g to 281 ± 22 g for Type I hard hats, from 72 ± 3 g to 122 ± 12 g for Type II hard hats, and from 115 ± 10 g to 266 ± 12 g for safety helmets (Fig. 6). Linear acceleration exceeded the 150 g threshold specified in ANSI Z89.1 in all Type I hard hats and in six out of seven safety helmets, but not in any of the four Type II hard hats.

Rear impacts induced peak linear accelerations a_{REAR} ranging from 217 ± 9 g to 286 ± 6 g for Type I hard hats, from 64 ± 7 g to 87 ± 15 g for Type II hard hats, and from 90 ± 11 g to 209 ± 22 g for safety helmets (Fig. 7). Linear acceleration exceeded the 150 g threshold specified in ANSI Z89.1 in all Type I hard hats and in four out of seven safety helmets, but not in any of the four Type II hard hats.

The overall lateral impact acceleration $a_{LATERAL}$ during front, side, and rear impacts ranged from 230 ± 21 g to 266 ± 30 g for Type I hard hats, from 68 ± 20 g to 113 ± 37 g for Type II hard hats, and from 123 ± 34 g to 242 ± 35 g for safety helmets (Fig. 8). Of the three Type I hard hats, all exceed the 150 g threshold for lateral impacts, and two also exceed the 10kN threshold for crown impacts. Of the four Type II hard hats, all remained below the 150 threshold for lateral impacts, but two exceed the 10kN threshold for crown impacts. Of the seven safety helmets, 5 exceed the 150 threshold for lateral impacts, and four also exceed the 10kN threshold for crown impacts. One safety helmet (Sa) and two Type II hard hats (H2b, H2d) reduced lateral accelerations below the 150 g threshold of ANSI Z89.1, and reduced crown forces below the 10kN threshold of EN 12482.

HIC values, averaged from frontal, side, and rear impacts, ranged from 169 ± 31 to 208 ± 48 for Type I hard hats, from 82 ± 8 to 98 ± 12 for Type II hard hats, and from 94 ± 9 to 186 ± 28 for safety helmets (Fig. 9).

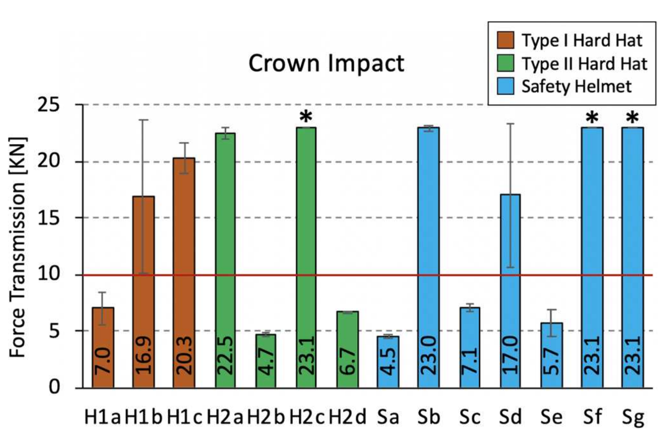

Fig. 4. Crown impact forces in correlation to the 10 kN threshold specified in EN 12492. Asterisks indicate force measurements in excess of the load sensor capacity.

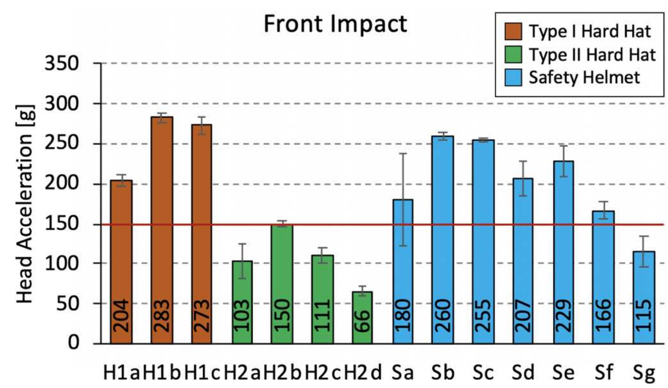

Fig. 5. Head accelerations from front impacts, shown in correlation to the 150 g threshold specified in ANSI Z89.1.

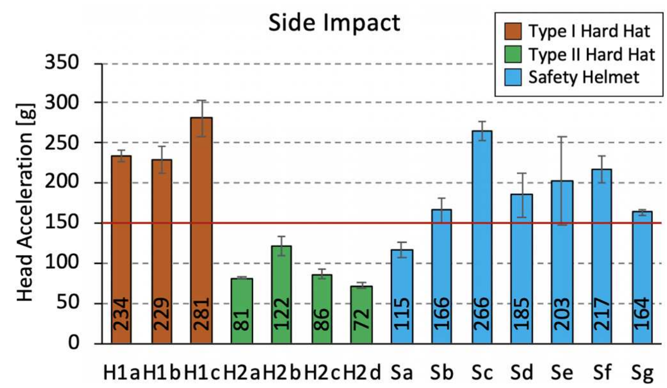

Fig. 6. Head accelerations from side impacts, shown in correlation to the 150 g threshold specified in ANSI Z89.1.

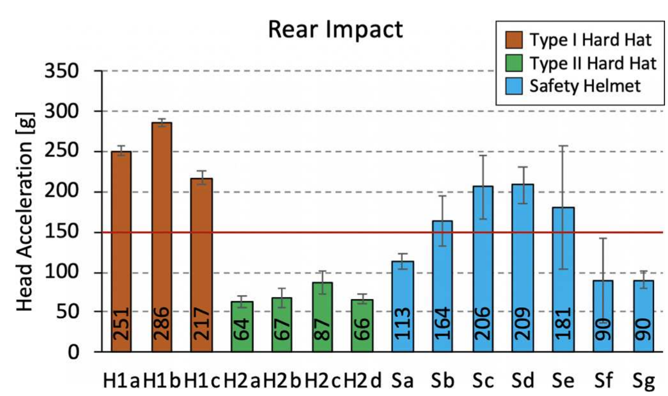

Fig. 7. Head accelerations from rear impacts, shown in correlation to the 150 g threshold specified in ANSI Z89.1.

Impact liners inside Type II hard hats covered 72–94% of the lateral head profile above the DTL. (Fig. 10). Of the seven safety helmets, two helmets had no impact liner (Sd, Se), one helmet had an impact liner that did not extended to the lateral head profile (Sb), and the remaining four safety helmet had impact liners that covered 25–38% of the lateral head profile above the DTL.

4. Discussion

Results of this study confirmed that Type I hard hats provide inadequate protection from lateral impacts since they do not have an impact absorbing liner in the helmet front, sides, and rear. This deficiency is

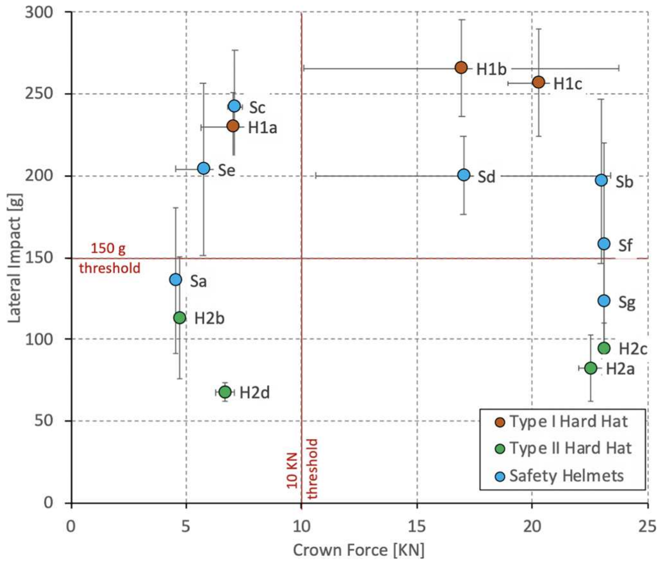

Fig. 8. Differences in lateral and crown impact performance exist between helmet groups (Type I, Type II, and Safety) and within helmet groups.

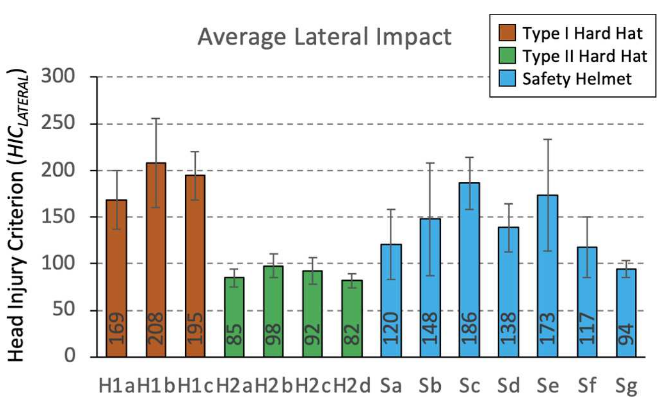

Fig. 9. Head Injury Criterion ($HIC_{LATERAL}$), calculated from acceleration signals of front, side, and rear impacts.

readily addressed by Type II hard hats with impact liners that reduced head accelerations from lateral impact on average by a factor of 2.7 compared to Type I hard hats in the present study.

Contrary to the widespread promotion of safety helmets as the safer alternative to hard hats, results of this study delivered quantitative experimental evidence that safety helmets may not provide improved impact protection compared to Type II hard hats. Specifically, results demonstrated that the range of popular safety helmets tested exhibited on average 1.9 times higher head accelerations from lateral impacts compared to Type II hard hats. Moreover, five of the seven safety helmets tested exceeded the 10 kN threshold for crown impacts of climbing helmet standard EN 12482 that is typically used to evaluate climbing-style safety helmets.

The large performance differences observed between safety helmets furthermore demonstrates that impact performance is not defined by the helmet style, but by the test standards a helmet can meet. None of the seven safety helmets tested met ANSI 89.1 Type II, which requires that all front, side, and rear impacts must remain below 150 g. This 150 g acceleration threshold of Z89.1 remains below the average head acceleration of 250 ± 65 g reported in a human cadaveric study that induced skull fracture by head impacts on a flat steel anvil. (Yoganandan and Pintar, 2004) To select a superior head protection, it is therefore important to not only evaluate if a helmet is ANSI 89.1 certified, but to ascertain that it is also Type II rated. At the time of study initiation in October of 2022, none of the major helmet manufacturers included in this study offered a climbing-style safety helmet with a ANSI/ISEA Z89.1 Type II rating. Lateral impact performance matters in real-world accidents since 52% − 62% of impacts occur to the helmet front and sides, and only a quarter to a thirds of impacts occur on the helmet crown. (Proctor and Rowland, 1986) The finding that safety helmets provided less protection from lateral impacts than Type II hard hats may be primarily attributed to deficient coverage of impact liners. Two safety helmets had no impact liner and only relied on a suspension system similar to a traditional Type I hard hat for impact attenuation. The remaining five safety helmets had on average less than 1/3 of lateral liner coverage compared to Type II hard hats. Moreover, impact liners were gradually thinning to accommodate the close-fitting safety helmet style. Since lateral impacts were located close to the impact liner edge, small variations in impact locations lead to considerable variations in impact performance, as can be seen by increase standard deviations in lateral impact tests of some safety helmets.

Lateral impact results of the present study are consistent with a

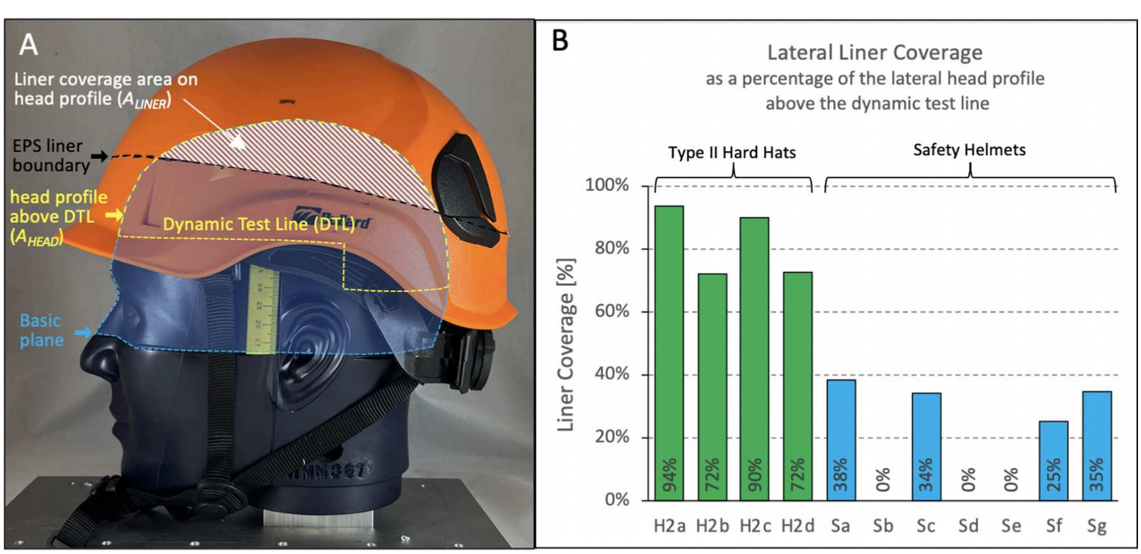

Fig. 10. A) Lateral coverage of impact liners inside Type II hard hats and safety helmets, calculated by dividing the area A_{LINER} (white) by A_{HEAD} (yellow border); B) Lateral coverage provided by impact liners, expressed as a percentage of the lateral head profile. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

recent publication that evaluated a range a different helmet design, including one Type II hard hat and two safety helmets. (Bottlang et al., 2022) They found that the Type II hard hat provided up to three times great mitigation of front and side impacts, and up to two times great mitigation of rear impacts compared to the safety helmets. The need for Type II certification was emphasized as early as 1987 in a study by Gilchrist and Mills, concluding that Type I hard hats are practically useless against side, front and rear impacts, making a redesign necessary. (Gilchrist and Mills, 1987) According to Canadian standard Z94.1–15 for protective headwear, Type I crown-only protective headwear has limited use and shall only be considered if it can be demonstrated that no lateral impact hazards exist. (Canadian Standard Association CSA).

All safety helmets came with chin straps, while two of three Type II hard hats required ordering chin straps as an accessory. To ensure helmet retention during slips, trips, and falls, chin straps should be included with every hard hat. Since safety helmets are always fitted with chin straps, they are particularly recommended when working at a height. However, their inconsistent protection from crown impacts runs counter to the notion that safety helmets provide better protection during a fall. Only three of the seven safety helmets met the crown impact requirement of the EN 12492 standard. One of the seven climbing-style safety helmets was EN 12492 certified (Vertex). Two additional safety helmets (Zenith X, Superplasma HD) stated compliance with EN 12492 but excluded clause 4.2.1.1 for crown shock absorption as tested in this study. This partial compliance statement may mislead safety officers into believing that these helmet are actually EN 12492 certified. Only two of the four Type II hard hats met the 10 kN crown impact requirement, one of which was EN 12492 certified. For superior protection from crown and lateral impact, helmets should meet EN 12492 and ANSI Type II impact requirements. The 10 kN impact force threshold of EN12492 is slightly higher than the average impact force of 8.4 ± 3.8 kN reported in a full-body human cadaveric study that induced skull fracture by head impacts on a flat steel anvil. (Yoganandan and Pintar, 2004) Since fracture force also depends on the contact area, the Society of Automotive Engineers (SAE) developed skull fracture tolerance data as a function of contact area. (Hodgson et al., 1970) In their SAE J1460 specification, impact areas of 300 mm^2 and 900 mm^2 require impact forces of 6 kN and 10 kN, respectively, to induce a skull fracture.

Force transmission results in response to crown impacts varied greatly between helmets of similar configuration (e.g., H2b, H2c), and between tests of the same helmet (H1b, Sd). In these helmets, highly elevated force transmission results were caused by the helmet shell bottoming out against the crown of the headform. The two helmet models that exhibited high standard deviations in force transmission results (H1b, Sd) performed so close their force absorption limits, that they bottomed out in some impacts but not in all. Given that testing was performed at room temperature, helmet will likely be more prone to bottoming out at elevated temperatures that soften the thermoplastic shell and thereby allow for greater deformation under impact.

This study only evaluated a subset of performance tests required by ANSI 89.1 and EN 12492 at ambient room temperature. It employed this limited set of standardized test methods to ensure reproducible and well-defined test parameters for assessment of relevant, relative performance differences between helmet styles. Standardized test methods, including the impact shock absorption test of EN 12492 and the impact energy attenuation test of ANSI Z89.1 employ simplified test conditions to facilitate reproducibility between test laboratories. Specifically, headforms are rigidly mounted to a base or a uni-axial drop mechanism that prevents rotational head motion. This over-constraint does not account for the anatomic degrees of freedom provided by a neck. Moreover, impacts are conducted along a linear axis through the center of gravity of the headform, which minimizes rotational moments. As such, these tests are limited to assess the risk of skull fracture in response to a linear impact force or acceleration. Since brain injury is primarily caused by rotational acceleration of the head, (Gennarelli, 1993; Gutierrez et al., 2001; King et al., 1995; Post and Blaine, 2015; Rowson and Duma, 2013; Gallant, 2022) these tests neither simulate nor assess the effectiveness of helmets to mitigation brain injury risk. A recent study demonstrated that hard hats with a dedicated rotation damping system can significantly improve protection of the brain from rotational forces and concussions. (Bottlang et al., 2022) Furthermore, each helmet in this study was subjected to three lateral impacts (front, side, and rear) and one crown impact. Subjecting a helmet to multiple impacts is consistent with test schedules in ANSI 89.1, and impact locations remained sufficiently separated to prevent adverse effects from prior impacts. Furthermore, lateral impacts were conducted before the crown impact, since they required less impact energy and less loading to the suspension mechanism. Future studies should focus on defining better test scenarios that account for real-world impact scenarios and injury mechanisms, and should evaluate the effectiveness of new helmet designs that feature advanced technology for mitigation of linear and rotational forces.

5. Conclusions

Helmets are the most effective strategy to reduce the incidence and severity of work-related head injury. Given the market-driven promotion of helmet styles, test data are essential to objectively guide safety officers and helmet developers toward the most effective helmet designs. Results of this study challenge the promotion of safety helmets as a safer alternative to Type II hard hats. Switching workers into safety helmets instead of Type II hard hats with chin straps will likely expose them to a higher risk of head injury from lateral impacts. Moreover, since crown impact performance varied greatly with all three helmet categories, safety officers seeking the best head protection should select helmets that are Type II rated and fully compliant with EN 12492. More research and testing will be required to ensure that investment in improved head protection is guided by evidence from physical testing or numerical simulation.

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Some of the authors (MB, SM) have a financial interest in WaveCel, a helmet manufacturer. None of the authors received any money or in-kind contribution for this work.

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