Smart Materials and Structures

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To cite this article: Mark Begonia *et al* 2023 *Smart Mater. Struct.* **32** 034003

OPEN ACCESS
IOP Publishing
Smart Materials and Structures
Smart Mater. Struct. **32** (2023) 034003 (6pp)
https://doi.org/10.1088/1361-665X/acb6ea

Laboratory evaluation of climbing helmets: assessment of linear acceleration

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Received 21 July 2022, revised 6 December 2022
Accepted for publication 28 January 2023
Published 6 February 2023

Abstract

This study utilized a guided free-fall drop tower and standard test headform to measure the peak linear acceleration (PLA) generated by different climbing helmet models that were impacted at various speeds (2–6 m s^{-1}) and locations (top, front, rear, side). Wide-ranging impact performance was observed for the climbing helmet models selected. Helmets that produced lower PLAs were composed of protective materials, such as expanded polystyrene (EPS) or expanded polypropylene, which were integrated throughout multiple helmet regions including the front, rear and side. Climbing helmets that produced the highest PLAs consisted of a chinstrap, a suspension system, an acrylontrile butadiene styrene (ABS) outer shell, and an EPS inner layer, which was applied only to the top location. Variation in impact protection was attributed not only to helmet model but also impact location. Although head acceleration measurements were fairly similar between helmet models at the top location, impacts to the front, rear, and side led to larger changes in PLA. A 300 g cutoff for PLA was chosen due to its use as a pass/fail threshold in other helmet safety standards, and because it represents a high risk of severe head injury. All seven helmet models had the lowest acceleration values at the top location with PLAs below 300 g at speeds as high as 6 m s^{-1}. Impact performance varied more substantially at the front, rear, and side locations, with some models generating PLAs above 300 g at speeds as low as 3 m s^{-1}. These differences in impact performance represent opportunities for improved helmet design to better protect climbers across a broader range of impact scenarios in the event of a fall or other collision. An understanding of how current climbing helmets attenuate head acceleration could allow manufacturers to enhance next-generation models with innovative and more robust safety features including smart materials.

Keywords: climbing, helmet, head injury, linear acceleration

(Some figures may appear in colour only in the online journal)

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1. Introduction

Climbing-based sports have gained worldwide popularity in recent years with over 4.5 million participants in the United States alone [1]. Sub-disciplines of these sports include sport climbing, bouldering, traditional climbing (i.e. alpine climbing), indoor climbing, and ice climbing, with each requiring different skillsets for climbers and posing different types of injury risk based on various environmental hazards. Although climbing-based sports have been generally classified as high-risk, overall injury rates are relatively low compared to other popular global sports such as rugby, ice hockey, and soccer [2, 3]. Sport and indoor climbing are generally considered to be safe for the youth population, especially under guided supervision, but younger climbers are still susceptible to head injuries from falls and hand or finger injuries from repetitive use without proper training [4, 5]. Despite the emphasis on head protection in other sports, helmet use in climbing-based sports varies drastically. One study examined injury patterns in rock climbers using online surveys, with over 1500 respondents answering survey questions pertaining to safety. The surveys revealed that only 36% of climbers wore helmets most or all the time and 19% never wore a helmet [6].

Climbing helmets must adhere to standards established by the European Committee for Standardization (EN 12492) or the International Climbing and Mountaineering Federation (UIAA 106) [7, 8]. Both standards specify laboratory testing procedures for assessing factors such as helmet slippage and chinstrap strength. These helmet standards also address blunt impact performance through laboratory tests in which a representative mass is dropped onto a helmeted headform with a load cell attached to the base of the head. Two of these tests assess protection against blunt trauma whereas the third test focuses on penetration. For blunt impacts to the top of the helmet, a 5 kg mass is dropped at a speed of 6.3 m s^{-1} (2 m height), and the impact force cannot exceed 10 000 N according to EN 12 492 or 8000 N according to UIAA 106. A similar approach and performance criteria are required for alternative impact locations to the front, side, and back of the helmet at 60 degrees relative to the vertical axis, but the 5 kg mass is instead dropped at a speed of 3.1 m s^{-1} (0.5 m height). For the penetration test, a 3 kg cone-shaped mass is dropped at a speed of 4.4 m s^{-1} (1 m height) and its tip is not allowed to penetrate the top of the helmet or come in contact with the headform [8].

There is limited published research on the head protection used in climbing but a few notable studies exist. In 2000, the British Mountaineering Council (BMC) released the results from their testing program in which they evaluated helmets according to the EN 12 492 and UIAA 106 standards. The BMC selected a total of 15 helmet models from seven different helmet manufacturers with the majority of the helmets classified as lightweight (i.e. less than 400 g). The BMC found that several helmets did not pass the EN 12 492 standard and that several more helmets did not pass the more stringent UIAA 106 standard. Exact force measurements were not reported but general observations could be made at each impact location using the information published by the BMC. Two helmets were near the 8000 N limit specified in the UIAA 106 standard when subjected to front impacts, and none of the helmets produced forces near the 8000 N limit when subjected to either rear or side impacts. For top impacts, five helmets exceeded the 8000 N limit with two of those helmets also exceeding the 10 000 N limit specified in the less stringent EN 12 492 standard [9]. Yamaguchi *et al* [10] used an instrumented whole-body Hybrid III dummy to evaluate the impact performance of three styles of climbing helmets (i.e. suspension, foam, and hybrid foam/suspension). Drop and pendulum tests were used to impact the front, crown, upper parietal, and occipital regions of each helmet. Yamaguchi *et al* measured head kinematics and computed injury parameters such as head injury criterion [10].

Current test standards for climbing helmets were developed to ensure adequate head protection against various environmental hazards including impacts from falling debris. These standards also require multiple helmet locations to be impacted, but the top is the only helmet location that must comply with both blunt impact and penetration-based test criteria. This may partially explain why the energy absorbing materials in many climbing helmets tend to be integrated toward the top region of the helmet compared to other locations. It should also be noted that the most common head injuries to climbers are concussion or closed head injury, with 75% of injuries resulting from falls and only 8% resulting from falling objects [11]. Because head injury risk is associated with head acceleration, helmets that reduce head acceleration will likely have a lower risk of head injury [12]. Due to the lack of head acceleration-based criteria in current test standards for climbing helmets, the purpose of this study was to evaluate the impact performance of representative helmet models by assessing their ability to attenuate peak head acceleration at different impact locations. The head acceleration-based results could also be useful for manufacturers that may require additional lab performance metrics to optimize next-generation climbing helmets with advanced safety features such as smart materials.

2. Methods

Climbing helmet models were selected from various manufacturers and with prices ranging from $55 to $120 (table 1). Each helmet model was composed of different materials such as expanded polystyrene (EPS), expanded polypropylene (EPP), and acrylontrile butadiene styrene (ABS) (figure 1). Each model also complied with EN 12 492 and/or UIAA 106 performance standards for climbing helmets (table 2).

A twin-wire guided free-fall drop tower was used for laboratory evaluation of climbing helmets. Drop tests were conducted using an International Organization for Standardization (ISO) headform (Size J) instrumented with an accelerometer (Endevco 7264B-2000, measurement range ±2000 g, uncertainty of ±1% of reading, PCB Piezotronics of North Carolina, Inc.) mounted at its center of gravity. The carriage, headform, and connectors had a total mass of 5 kg. Each helmet model was impacted at four locations with up to five impact speeds using a flat anvil (figure 2). A digital inclinometer and custom

Table 1. Climbing helmets selected for impact testing.

Helmet Model	Price	Size	Mass (Avg ± SD)
A	$59.95	54–61 cm	453 ± 4 g
B	$54.95	M/L	364 ± 2 g
C	$59.99	54–61 cm	453 ± 4 g
D	$109.95	54–62 cm	211 ± 6 g
E	$119.95	56–61 cm	235 ± 5 g
F	$59.95	M/L	305 ± 4 g
G	$109.95	M/L	175 ± 2 g

Figure 1. Inner materials and construction for several representative climbing helmet models.

laser array, which was attached to the center of the anvil, were used to achieve a consistent headform orientation for each of the four impact locations. At each location, a representative helmet was used to identify an appropriate headform orientation. Once an orientation was set, the digital inclinometer was placed along the bottom surface of the headform and an angle measurement was recorded. The laser array was then used to shine three dots on the headform surface so that three markers could be applied. This procedure was repeated for the other three impact locations so that the headform orientation could remain consistent despite variations in helmet geometry. Digital inclinometer readings were within ±0.1° of predetermined angle measurements at each of the four impact locations. Drop tests started at 2 m s^{-1} and progressed at 1 m s^{-1} increments up to 6 m s^{-1} to cover a wide range of head accelerations and to evaluate the upper limits of helmet performance within the range of impact speeds specified under the EN 12 492 and UIAA 106 standards. Measured drop heights were within ±5 mm of each target height, and measured impact speeds were within ±0.1 m s^{-1} of each target speed. One sample of each helmet model was impacted once at each test configuration (i.e. location and speed) until the peak linear acceleration (PLA) exceeded a limit of 300 g. A 300 g cutoff was chosen due to its use as a peak head acceleration-based threshold in other helmet safety standards, and because it correlates with risk of severe head injury [12, 13]. This drop test procedure was repeated to ensure that two PLA measurements were recorded at each test configuration. Linear acceleration data were sampled at 20 000 Hz and filtered using a four-pole Butterworth low pass filter with a channel frequency class of 1000, or cutoff frequency of 1650 Hz, in accordance with Society of Automotive Engineers (SAE) J211 standards [14].

3. Results

PLA was compared by impact location and speed for each climbing helmet model (figure 3). A cutoff PLA of 300 g was used to indicate risk of severe head injury (e.g. skull fracture) [12]. All seven helmet models had the lowest acceleration values at the top location with PLAs below 300 g at speeds as high as 6 m s^{-1}, which corresponds to a theoretical drop height of 1.8 m (6 ft). For 6 m s^{-1} impacts to the top location, Helmet C generated the lowest PLA (156 g) while Helmet B generated the highest PLA (204 g). Impact performance, however, varied more substantially at the front, rear, and side locations, with some models generating PLAs above 300 g at speeds as low as 3 m s^{-1} (46 cm or 1.5 ft drop height).

Helmets B, D, E, and G generated PLAs less than 300 g at the front location across all impact speeds. Helmet F also generated PLAs below 300 g at the front location for most speeds except at 6 m s^{-1} (492 g). Helmet C had a higher front impact response (464 g) at 3 m s^{-1}, and Helmet A had the highest overall front impact response (622 g) at 4 m s^{-1}.

Helmet D produced PLAs that were below 300 g at every impact speed at the rear location. Helmets B, G, E, and F generated PLAs below 300 g at most impact speeds except for 6 m s^{-1}, which produced PLAs of 330 g, 354 g, 370 g, and 512 g, respectively. Helmets C and Helmet A exceeded the 300 g threshold at 4 m s^{-1} with PLAs of 662 g and 742 g, respectively.

Helmet D produced PLAs that were below 300 g at every impact speed at the side location except for 6 m s^{-1} (361 g). Helmets F, E, and G kept PLAs below the 300 g limit until they experienced side impacts at 5 m s^{-1}, which produced PLAs of 424 g, 498 g, and 503 g, respectively. Helmets B, C, and A exceeded the 300 g limit at side impacts of only 3 m s^{-1}, which generated PLAs of 316 g, 384 g, and 514 g, respectively.

4. Discussion

The current study demonstrated through drop testing of representative climbing helmets that the corresponding head accelerations are influenced by helmet model and impact location. Although this observation is intuitive, it should be emphasized that current impact performance standards for climbing helmets specify pass/fail criteria in the context of force measured at the bottom of a helmeted headform as opposed to acceleration measured at the center of gravity for a helmeted headform. Peak head acceleration thresholds and/or head acceleration-based injury parameters are already utilized in various sports helmet certifications [13, 15, 16] and helmet rating systems [17–20], which means that a similar approach could be adopted to further evaluate the impact performance of climbing helmets.

It was difficult to identify a clearcut top-performing helmet model due to the mixture of test speeds and impact locations for each helmet model that generated PLAs above 300 g.

Table 2. Summary of climbing helmet features and certifications.

Helmet Model	Features	Certification
A	ABS outer shell, EPS inner layer, suspended inner liner with buckle, multiple vents	EN 12 492
B	Co-molded EPS foam, low-profile ABS outer shell, low-profile suspension system with adjustment dial	EN 12 492, UIAA 106
C	ABS outer shell, EPS inner layer, suspended inner liner with buckle, multiple vents	EN 12 492
D	EPS inner layer, polycarbonate outer layer, top and side protection	EN 12 492, UIAA 106
E	EPP core combined with partial ABS shell, large ventilation openings, light weight adjustment system	EN 12 492
F	ABS crown, EPP and EPS foam liner, top and side impact protection	EN 12 492, UIAA 106
G	EPP foam shell, EPS foam and polycarbonate at crown, top and side protection	EN 12 492, UIAA 106

Figure 2. Representative climbing helmet oriented to show impact locations at the (a) top, (b) front, (c) rear, and (d) side on the drop tower.

Helmet A and Helmet C, however, did not attenuate head acceleration as effectively as the other helmet models. One explanation could be the overall helmet design for these two models compared to the others. Helmet A and Helmet C consisted of a chinstrap, a suspension system, an ABS outer shell, and an EPS inner layer, which was applied only to the top location. The lack of EPS, EPP, or comparable protective material at other areas of these two helmets would explain why PLAs exceeded the 300 g limit at impact speeds of 4 m s^{-1} and lower. The other five models utilized alternatives to an ABS-only outer shell or integrated protective material throughout much larger areas of the available inner helmet surface by contrast (figure 1). These design strategies were likely associated with the other five models outperforming Helmet A and Helmet C at the front, rear, and side impact locations.

PLAs were generally lower for the top location compared to other impact locations. This could be attributed to all helmet models complying with EN 12 492 and/or UIAA 106 certifications. Both certifications specify impact performance requirements against simulated blunt force trauma at the front, rear, side, and top locations, but the top location also requires protection from simulated helmet penetration from falling debris with sharp geometries. It is possible that design strategies intended to protect climbers against both blunt and penetration-based head injuries also leads to increased protection to the top location of climbing helmets regardless of model.

A few notable studies in the literature could be used for comparisons with the current study. The testing program by the BMC in 2000 revealed a wide range of climbing helmet performance across impact locations although it should be noted that the results were presented in the context of forces measured below the helmeted headform instead of head acceleration [9]. Force is not an ideal or comparative metric to acceleration. A lower mass helmet could generate lower headform forces in a drop test and seemingly outperform a higher mass helmet subjected to the same test. Under the same impact force, however, the higher mass helmet is more likely to reduce headform acceleration and injury risk. In 2014, Yamaguchi *et al* [10] utilized a fully instrumented Hybrid III dummy to evaluate the performance of different climbing helmets at various impact locations, and they reported average peak accelerations that exceeded 500 g. The PLAs reported by Yamaguchi *et al* were on the same order of magnitude as the PLAs observed in the current study despite notable differences in study approaches, including whole-body versus head-only testing, impact location, impact speed, and helmet model selection [10]. This is promising for the potential development of a climbing helmet test procedure that utilizes head acceleration-based performance criteria but is also less technically challenging compared to testing involving an entire Hybrid III dummy.

There are some limitations to this study that should be noted. A total of seven helmet models from six different manufacturers were selected for this work but these specific models may not be fully representative of every model available for use in climbing sports. Two trials were performed at each impact location and speed for each helmet model, which meant that some helmet samples were impacted up to four times. Although climbing helmets are designed for a single impact, the centers of the four impact zones were spaced apart by at least 120 mm to avoid any overlapping of damage profiles [13]. Impact performance of each helmet model was assessed through measurements of headform linear acceleration, which are used to indicate risk of severe head injury such as skull fracture. Additional testing with a methodology that introduces rotational head kinematics would also be recommended to determine the risk of concussion under similar impact conditions.

Another consideration for the future development of climbing helmets is the integration of smart materials. The models selected for this work are primarily composed of ABS, EPS, and/or EPP with variation in the amount and distribution

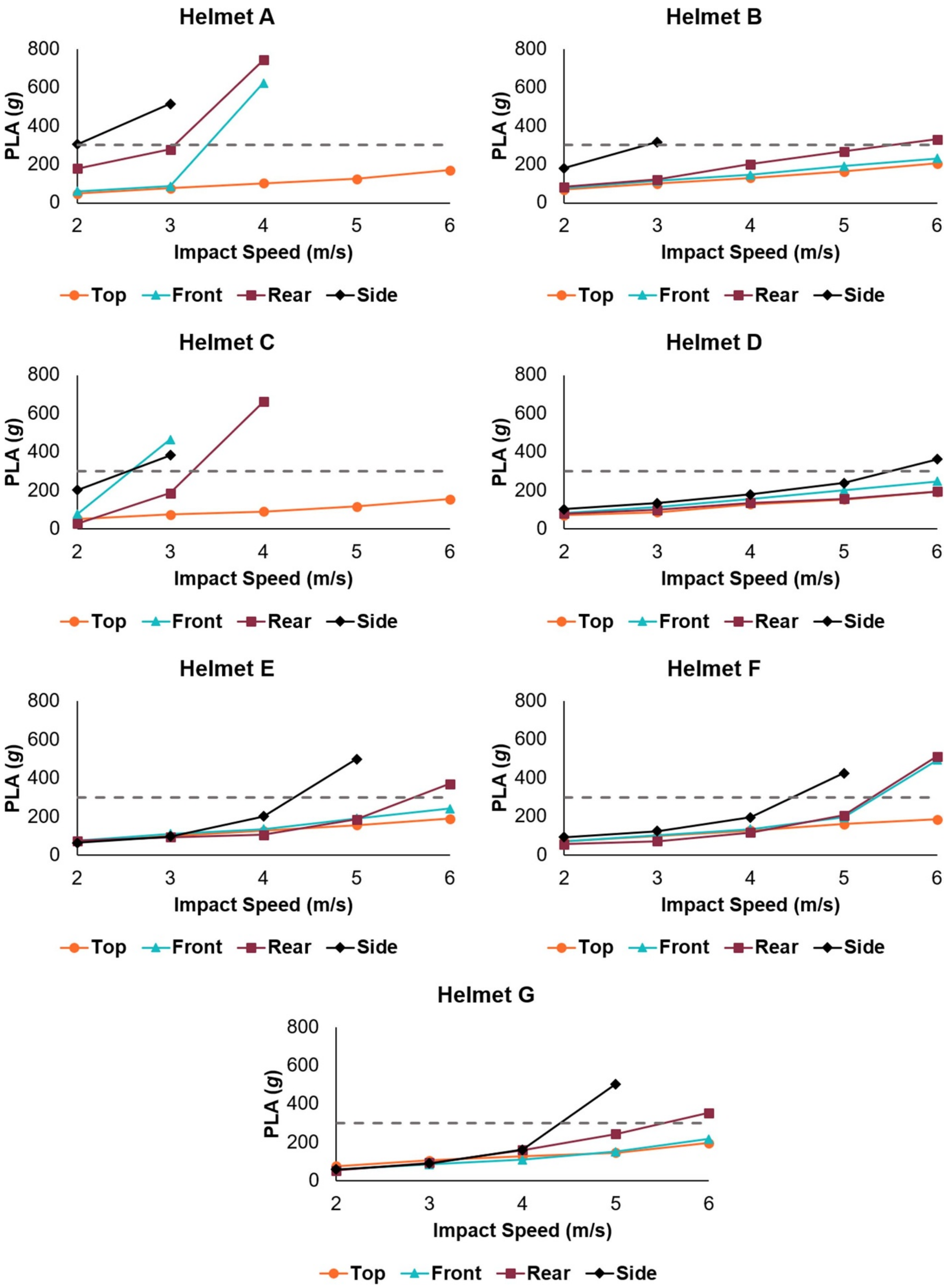

Figure 3. Comparison of peak linear acceleration (PLA) by impact location and speed.

of the protective materials based on the helmet brand and model (table 2). These materials are integrated into many helmet types (e.g. American football, cycling, equestrian, and construction) for increased protection at the outer and/or inner shell. Helmets are typically designed for multiple loading environments and in the case of climbing helmets, it would be advantageous for next-generation models to adopt smart materials that adapt to various external stimuli (e.g.

penetration versus blunt trauma) rather than utilizing a combination of ABS and EPS/EPP to address those two impact scenarios separately. Use of smart materials could also facilitate the minimizing of helmet mass and maximizing of head protection throughout the entire helmet rather than selected locations specified in certification tests. For multiple models evaluated in the current study, the side impact location could be improved with smart materials such as rate sensitive polymer foams. Compared to conventional helmet materials such as EPS, rate sensitive polymer foams fully recover after impact and can be optimized for lower density and higher energy absorption [21]. Laboratory drop tests of American football helmets and motorcycle helmets lined with rate sensitive polymer foams also led to a 22% reduction in peak head acceleration and 25% reduction in head injury criteria [22].

5. Conclusions

Current test standards for climbing helmets do not consider head acceleration, which has been shown to correlate with risk of severe head injuries (e.g. skull fracture) and risk of milder head injuries (e.g. concussion). This study utilized a guided free-fall drop tower and ISO headform to determine the extent to which representative climbing helmets could attenuate head acceleration at various impact speeds and locations. Variation in impact protection was attributed not only to helmet model but also to impact location. Although head acceleration measurements were fairly similar between helmet models at the top location, impacts to the front, rear, and side led to larger changes in PLA. These differences in performance represent opportunities for improvements in helmet design using advanced technologies such as smart materials to better protect climbers across a broader range of impact scenarios in the event of a fall or other collision.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Acknowledgments

The authors would like to thank the Department of Physics at the University of Lynchburg, the Virginia Tech Helmet Lab, and the Institute for Critical Technology and Applied Science for their support. The authors wish to thank the referees whose comments and suggestions led to a final paper that was better than the initial submission.

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