Influence of helmet surface protrusions on youth bicycle helmet impact performance

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ABSTRACT

Youth bicycle helmet manufacturers often add shell protrusions to make helmets more attractive or fun for children, yet the safety implications of these features are not well understood. While prior work suggests protrusions may affect head impact kinematics, no study has evaluated their effectiveness in location-matched impacts between helmets with and without protrusions. Twelve youth bicycle helmet models, with protrusions intact and removed, underwent matched oblique impacts at three locations and 4.2 m/s to capture resulting peak linear acceleration (PLA) and peak rotational acceleration (PRA). A linear mixed model was used to quantify the effect of protrusion presence on PLA, PRA, and impact duration. The youth bicycle helmet models produced a wide range of kinematics. Protrusion presence had a strong effect on PLA, PRA, and impact duration. PLA averaged 103.0 ± 22.8 g for helmets with protrusions compared to 143.9 ± 21.4 g for helmets without protrusions, while PRA averaged 4432 ± 1570 rad/s^2 for helmets with protrusions and 5177 ± 2110 rad/s^2 for helmets without protrusions. These findings suggest that helmet protrusions can reduce peak head accelerations in youth bicycle helmet impacts.

INTRODUCTION

In 2024, 56% of children aged 3 to 17 rode a bicycle at least once during the year (People for Bikes, 2025). Bicycle accidents were also identified as the fifth leading cause of concussion in children aged 14 and under (U.S. Consumer Product Safety Commission, 2025). However, this figure is based on emergency department visits, meaning the true occurrence of concussions is likely greater. Broader population-based research indicates that pediatric cyclists continue to face substantial risk for head injury, especially in areas without helmet laws, highlighting the importance of consistent helmet use and age-appropriate protective measures (Kaushik et al., 2015).

To reduce the risk of severe outcomes such as skull fractures, traumatic brain injuries, and death, the Consumer Product Safety Commission (CPSC) requires that bicycle helmets marketed for children over the age of 5 meet the same safety standard as those designed for adults. Certification testing uses a series of guided drop tests with different anvils and impact speeds, with

This paper is a student paper from the 21st Injury Biomechanics Symposium and is published in a special issue of SAE International Journal of Transportation Safety.

helmets required to keep peak linear acceleration (PLA) to below 300 g to mitigate the risk of catastrophic head injury (Gurdjian et al., 1961), (Lissner et al., 1960), (Patrick et al., 1963), (U.S. Consumer Product Safety Commission, 1998). However, concussions occur at much lower accelerations and result from both linear and rotational accelerations (Campolettano et al., 2020a), (Kleiven, 2013), (Meaney et al., 2011), (Rowson et al., 2012), (Rowson et al., 2013). Since current certification standards do not incorporate rotational kinematics, impact testing that measures rotational acceleration is necessary to better evaluate bicycle helmet performance (Bland et al., 2020b), (McIntosh et al., 1995).

Although bicycle helmets for children over age 5 and adults must meet the same safety standard, evidence suggests that these groups experience head injuries at different biomechanical thresholds (Campolettano et al., 2020a), (Figaji, 2017), (Margulies et al., 2013). Research on football head impacts has shown that youth athletes tend to experience lower-speed impacts compared to varsity-level athletes (Campolettano et al., 2020a), (Campolettano et al., 2020b). These differences contributed to the development of youth-specific helmet testing protocols designed to better reflect age-specific injury mechanics (Campolettano et al., 2020b), (Rowson et al., 2011). In a similar way, children riding bicycles are expected to encounter different impact conditions than adults due to factors such as lower rider height and reduced travel speeds. Although several testing protocols exist for evaluating adult bicycle helmets (Baker et al., 2024), (Bland et al., 2020b), (Mutuelle des Motards, 2018), (Transport for NSW, 2024), there is still limited research on youth bicycle helmet performance (Jung et al., 2025), (Klug et al., 2015), (Zhou et al., 2025).

We recently addressed this gap by testing 21 youth bicycle helmet models under youth-specific impact conditions (Jung et al., 2025). The results indicate that certain design features such as thicker expanded polystyrene (EPS) liners, thinner shells, and shell protrusions were associated with reductions in both PLA and peak rotational acceleration (PRA). These protrusions, often made of deformable thermoplastic rubber (TPR) and styled as mohawks or animal faces, are a distinctive characteristic of youth bicycle helmets. While protrusions were generally associated with lower PLA, their influence on PRA was less clear (Jung et al., 2025). However, it remains unclear whether protrusions could negatively affect impact performance under more oblique loading conditions, where they may snag on the impact surface in a way that increase rotational acceleration, since matched-location comparisons were not included in the previous study.

The present study builds on this work by directly comparing location-matched impacts between helmets with and without protrusions to evaluate how protrusions influence peak head kinematics and impact duration. Based on our previous findings, we hypothesize that protrusions will reduce peak head kinematics relative to matched impacts on helmets without protrusions. Understanding the protective capacity of protrusions may help consumers make more informed choices when selecting helmets and considering potential differences in safety performance. In addition, these results may allow manufacturers to assess protrusions not only as aesthetic elements, but also as features that could be intentionally designed to improve impact performance and enhance protective function.

METHODS

Helmet Selection

Helmet models were selected based on availability from major nationwide retailers and inclusion of externally affixed protrusions. The goal was to compare a representative range of protrusion designs available in the consumer market. Twelve CPSC-certified bicycle helmet models were selected for testing (Figure 1). All helmets were sized using the small National Operating Committee on Standards for Athletic Equipment (NOCSAE) head circumference (53.4 cm), and three manufacturers were represented. At the time of purchase, manufacturer suggested retail prices (MSRP) ranged from $20-$35. The selected helmets featured a variety of protrusion styles, such as mohawk and animal-face designs, to reflect the diversity of commercially available configurations. Internal helmet components were re-secured between tests as necessary to maintain consistent fit and structural integrity.

Figure 1: Youth bicycle helmet models selected for testing. The two columns on the left include helmets with mohawk protrusions. The two columns on the right include helmets with animal protrusions. Under each model name, the left image is the helmet with protrusions intact, and the right image is the matched helmet with protrusions removed.

Impact Testing

Impact testing was performed using an oblique drop tower. A helmeted small NOCSAE headform (NOCSAE, Overland Park, KS) was dropped onto a 25-degree steel anvil relative to the horizontal. The anvil surface was covered with 80-grit sandpaper to simulate road surface roughness (Baker et al., 2024), (Bland et al., 2020b), (Stark et al., 2024b), and the sandpaper was replaced after every four tests. Helmet position was standardized using the NOCSAE nose gauge, positioning the lower front edge of the helmet approximately 2 cm above the brow line (U.S. Consumer Product Safety Commission, 1998). Retention straps were tightened to a near-taut condition per the manufacturer's guidance. The midsagittal line of the headform was used to ensure consistent helmet alignment relative to the midsagittal plane.

Matched impact testing was performed across helmet models. Each of the twelve helmet models (Figure 1) was tested using four samples: two with protrusions intact and two with protrusions removed. Impact locations were selected individually for each helmet model such that, for protrusion-intact samples, the protrusion would be the first point of contact with the anvil. Because protrusion geometry varied between models, impact locations were adjusted to ensure consistent first-contact conditions (Figure 2). For non-protrusion samples, identical impact locations from the protrusion samples were used, resulting in direct helmet shell contact at locations where protrusions had been removed (Figure 2). Both more direct and more oblique impact orientations were included to evaluate whether protrusions influenced rotational acceleration through deformation, deflection, or snagging effects. Three impact locations were defined per helmet model, spaced at least 120 mm apart in accordance with CPSC guidelines to prevent overlap of damage regions (U.S. Consumer Product Safety Commission, 1998). Headform positioning in x-, y-, and z-orientations was controlled using a tri-axis inclinometer (WT9011DCL-BT50, WitMotion, Shenzhen, China) and a support ring marked in 5-degree increments.

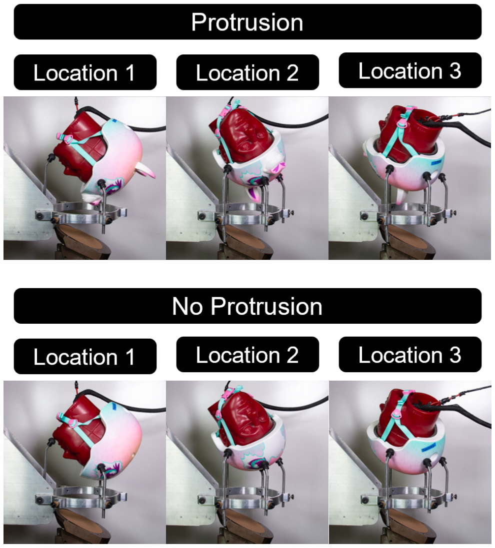

Figure 2: Impact locations selected for the Raskullz Llama helmet; note that these locations differ from those used for the other helmet models included in this study.

Impact velocity was set to a target drop speed of 4.2 m/s, based on the average resultant velocities used in a prior study (Jung et al., 2025). Each helmet sample was impacted three times, with one impact per location at 4.2 m/s (Figure 2). Each unique combination of impact location and protrusion condition was treated as an impact configuration. Two trials were conducted per configuration, resulting in twelve total impacts per helmet model (six with protrusions and six without), and 144 total tests across all helmets. All impacts were recorded using a high-speed camera (Phantom MIRO LC321S, Vision Research, Wayne, NJ) with a Nikon AF Nikkor 35 mm f/2D lens (Nikon, Melville, NY). Videos were captured at 1600 frames per second with a resolution of 1600 x 1200.

Linear and rotational head kinematics were recorded at 20 kHz using a six degree-of-freedom sensor package mounted at the headform center of gravity. The system included three linear accelerometers (Endevco 7264B-2000, PCB Piezotronics, Charlotte, NC) and a tri-axis angular rate sensor (ARS3 PRO-18k, DTS, Seal Beach, CA). Signals were filtered using a 4-pole, phaseless Butterworth low-pass filter in accordance with SAE J211 standards (Society of Automotive Engineers, 2022). Cutoff frequencies were set to 1650 Hz (channel frequency class [CFC] 1000) for linear acceleration and 300 Hz (CFC 180) for angular rate. Rotational acceleration was calculated using the 5-point central-difference method in accordance with SAE J1727 (Society of Automotive Engineers, 2021).

Impact duration was derived from filtered linear acceleration signals. The resultant acceleration magnitude was computed from the three orthogonal axes, and the time of peak resultant acceleration was identified. Signals were then rotated so that one axis aligned with the resultant direction at peak loading. Impact onset and offset were defined as the first points before and after the peak where the rotated acceleration dropped below 5 g. Impact duration was calculated as the time difference between onset and offset, reported in milliseconds based on sampling rate.

Statistical Analysis

Statistical analysis was performed in R (Version 4.4.0, RStudio, Boston, MA). Linear mixed-effects regression models were used to evaluate differences in PLA, PRA, and impact duration (Kuznetsova et al., 2017). A significance level of $\alpha < 0.05$ was used for all analyses. Separate models were constructed for PLA, PRA, and impact duration. In each case, protrusion presence was treated as a fixed effect, while the helmet model and location nested within the helmet model were included as a random effect.

RESULTS

The presence of shell protrusions at the impact location had an effect on head kinematics. Across all tests, protrusions reduced PLA by 40.9 g (confidence interval [CI]: 36.1 – 45.6 g, $p < 0.001$) and reduced PRA by 745 rad/s^2 (CI: 459 – 1031 rad/s^2, $p < 0.001$). In addition to lowering acceleration magnitudes, protrusions increased impact duration by 4.4 ms (CI: 3.9 – 5.0 ms, $p < 0.001$), indicating a longer energy transfer period during impact.

PLA and PRA responses varied across the 12 helmet models (Figure 3). For helmets with protrusions, PLA ranged from 54.4 to 171.6 g, with a mean of 103.0 ± 22.8 g. PRA values ranged from 1883 to 7668 rad/s^2, with a mean of 4432 ± 1570 rad/s^2. For helmets without protrusions, PLA ranged from 113.6 to 198.3 g, with a mean of 143.9 ± 21.4 g, while PRA ranged from 1146 to 8374 rad/s^2, with a mean of 5177 ± 2110 rad/s^2. The magnitude of PLA and PRA reduction also varied by helmet model (Figure 4). Compared to matched helmets without protrusions, helmets with protrusions showed PLA reductions ranging from 22.7 to 53.4 g. PRA reductions ranged from -269 to 1501 rad/s^2, indicating that while most models showed decreases in rotational acceleration, some exhibited small increases.

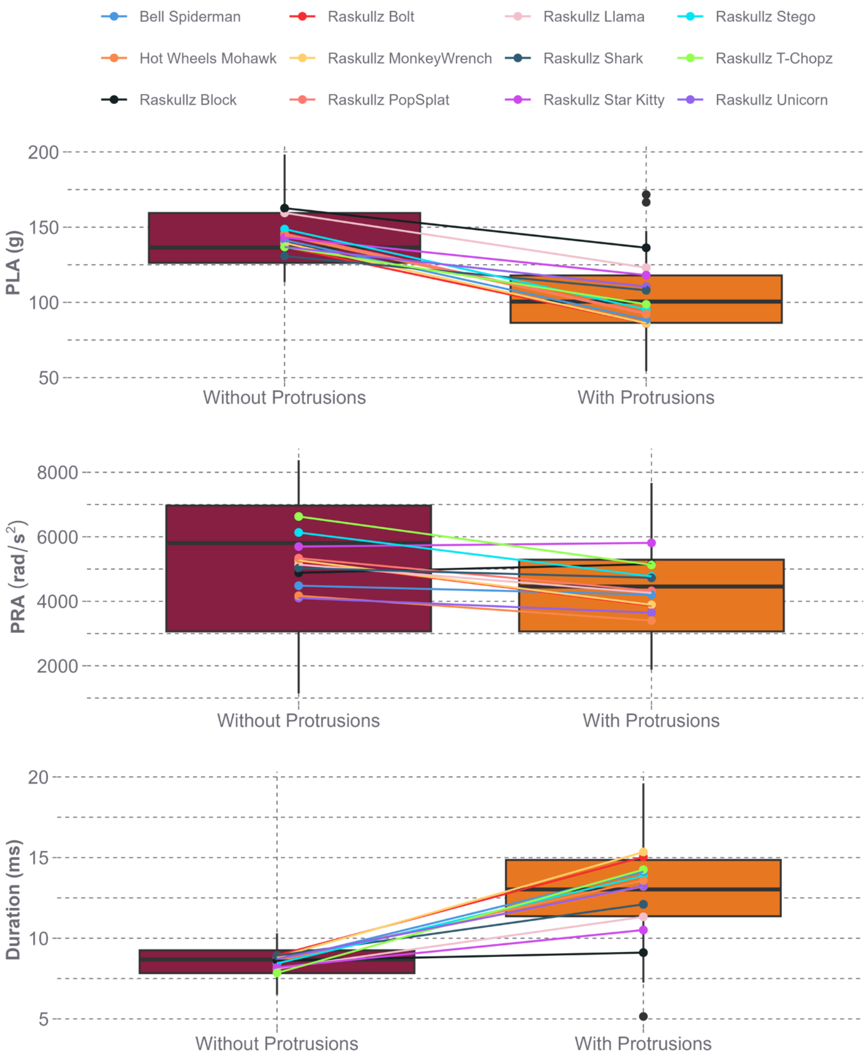

Figure 3: Distribution of PLA, PRA, and impact duration across the twelve helmet models and three locations for samples with and without protrusions. Points represent the average PLA, PRA, and impact duration for each model across impact locations, and lines connect the boxplots to show the change across protrusion level.

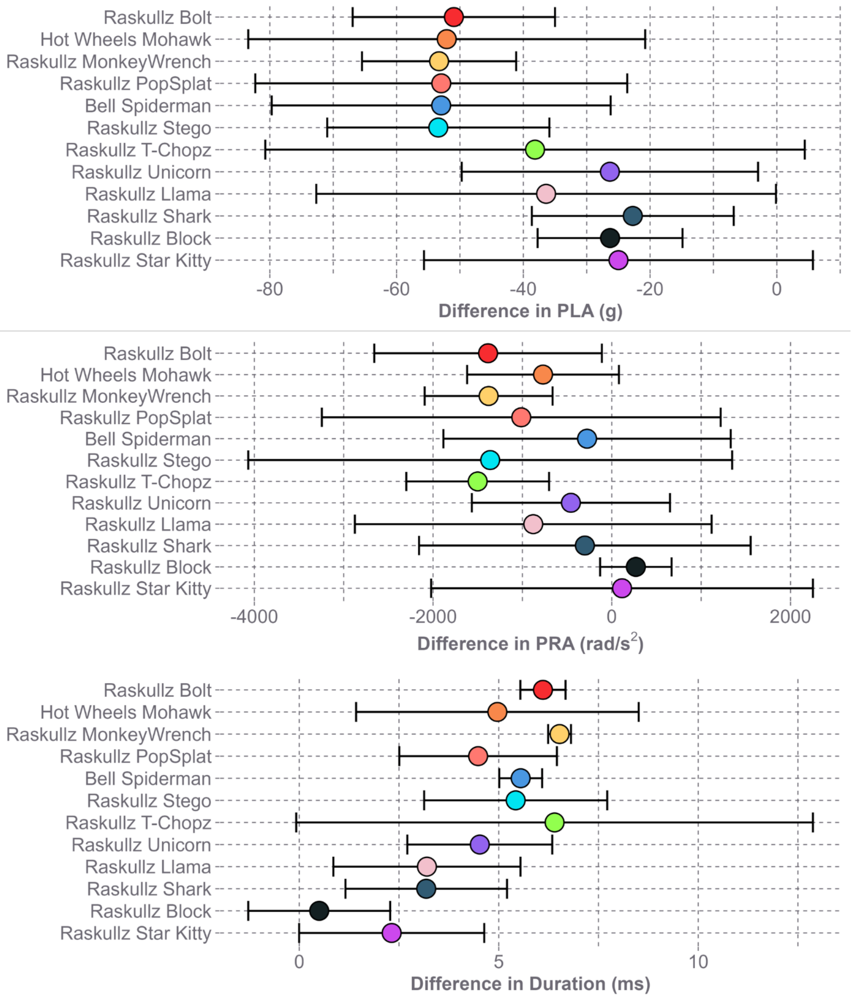

Figure 4: Mean differences between helmets with and without protrusions across impact locations, with 95% CI.

DISCUSSION

The purpose of this study was to evaluate whether commercially available youth bicycle helmets with external protrusions influence impact performance under controlled, location-matched conditions. Specifically, we aimed to determine whether protrusions could either worsen impact outcomes or provide protective benefits. All helmet models met the CPSC requirement of maintaining PLA below 300 g; however, notable variability was observed in both PLA and PRA across the 12 models tested (Figure 3).

Within-model comparisons between helmets tested with and without protrusions showed that the magnitude of PLA and PRA reduction varied by helmet (Figure 4). The relatively wide confidence intervals in Figure 4 reflect averaging across multiple impact locations and indicate that performance differs depending on where the helmet is struck. This pattern suggests that even among helmets that meet safety standards, protective performance is not consistent across all regions of the helmet. As a result, design features such as protrusions may enhance protection in certain impact locations while offering more limited benefit in others.

Differences in PRA reductions across helmet models (-269 to 1501 rad/s^2) can be partly explained by the experimental conditions. A 25-degree anvil angle and reduced impact speed were used to better represent youth-specific crash scenarios; however, these conditions also decrease tangential loading and rotational motion compared to adult testing protocols that use steeper anvil angles and higher speeds (Baker et al., 2024), (Bland et al., 2020b). As a result, baseline PRA values were lower under these conditions, which may reduce the apparent magnitude of differences between helmet configuration. Variation in PRA response may also be influenced by protrusion geometry. Helmets with sharper-edged protrusions, such as the Raskullz Block and Raskullz Star Kitty, may alter the direction of the impact force at the point of contact. This redirection can increase the tangential component of the applied force and potentially increase rotational motion compared to smoother helmet surfaces (Stark et al., 2024a). This mechanism may explain why some helmet models exhibited smaller reduction or slight increases in PRA.

The observed reduction in head kinematics with protrusions appears consistent with a "crumple zone" effect. Upon impact, the protrusions deform first, absorbing energy before the EPS liner in engaged. As shown in Figure 5, this creates a staged deformation process in which helmets with protrusions remain in contact with the anvil for a longer period than helmets without protrusions. This extended impact duration corresponds with increased energy dissipation over time and is consistent with the reductions in PLA and PRA (Figure 3, Figure 4). By prolonging the impact event, protrusions appear to lower peak accelerations by distributing energy more gradually, whereas helmets without protrusions rely solely on EPS compression.

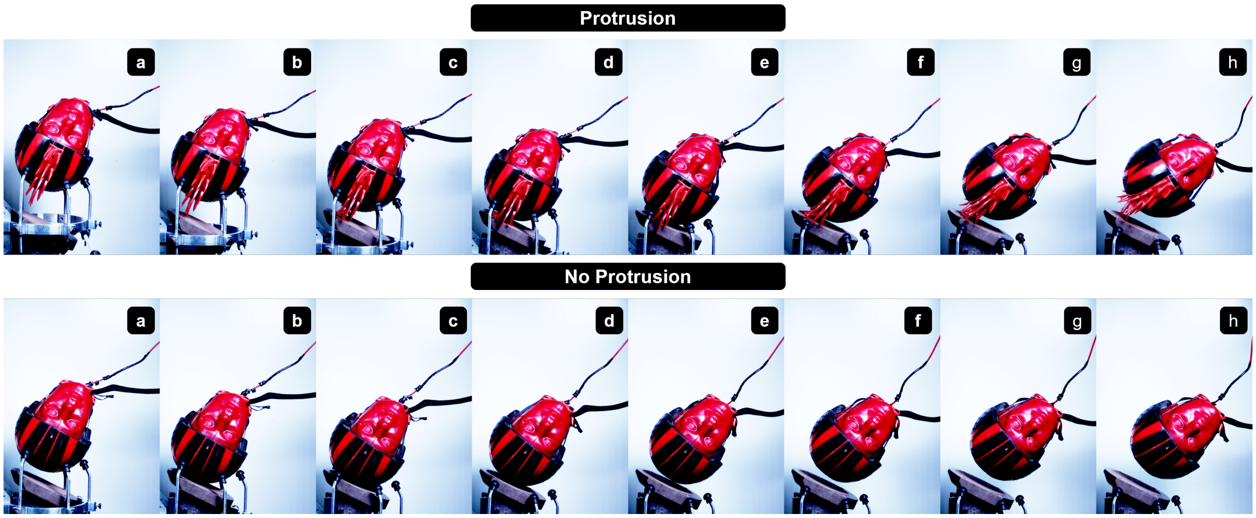

Figure 5: Sequential still images (a to h) obtained from representative high-speed videos. The top two rows illustrate the temporal progression of the impact event for a helmet with protrusions, while the bottom two rows illustrate the progression for a matched helmet without protrusions. Frame (a) corresponds to 10 frames before impact, frame (b) represents the moment of initial contact, and frames (c) through (h) occur at intervals of 10 frames after the preceding frame.

Several limitations should be considered when interpreting the results. First, only 12 helmet models were evaluated, which may not fully represent the range of protrusion designs available. However, the selected models were sourced from multiple major retailers to capture a range of commonly available products. Second, the impact locations were specifically chosen to isolate the effects of protrusions under location-matched conditions, which means they may not fully reflect typical real-world impact locations. Some test locations, such as the crown, are less frequently observed in actual bicycle crashes. Prior analysis of 24 youth bicycle crash videos found that impacts most often occur to the front of the head, with fewer impacts to the sides and rear (Jung et al., 2025). Although location-matched testing was necessary to examine protrusion effects in a controlled manner, it limits direct generalization to real-world scenarios. Third, the selected impact speed used in this study (4.2 m/s) was derived from previous work estimating fall speeds in children (Jung et al., 2025). This speed corresponds to approximately 80% of the energy associated with a free fall from the average standing height of a 6-year-old. While representative, this may not capture the full range of possible real-world impact severities.

Future work should focus on improving the understanding of real-world head impacts in youth cycling. This could involve collecting head kinematic data using wearable sensors and analyzing bicycle crash footage to better characterize common impact conditions experienced by children. In addition, reconstructing real-world helmet damage in laboratory settings would help identify the most relevant impact scenarios for youth cyclists. Similar approaches have been used in studies of adult bicycle impacts (Bland et al., 2020a), (Harlos et al., 2021).

CONCLUSIONS

This study indicates that externally affixed helmet protrusions can improve impact performance in youth bicycle helmets by increasing deformation at the point of contact, extending impact duration, and reducing peak linear and rotational head accelerations. This behavior suggests a staged energy absorption mechanism, in which protrusions engage before the EPS liner, allowing impact forces to be distributed over a longer period and reducing overall impact severity. Importantly, these benefits were achieved without a consistent increase in rotational response, indicating that protrusions do not adversely affect head rotation under the tested conditions. Although the magnitude of the effect varied across helmet models and impact locations, the overall results support the conclusion that protrusions can provide a protective benefit and may be a useful design feature for enhancing energy management in youth bicycle helmets.

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