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Evaluation of protective performance of children helmets via biomechanical modelling

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Abstract

Purpose: The purpose of the current study is to compare the protective performance of helmet designs with different sizes and cushion materials for skull and brain injuries in children.

Methods: A 6-year-old child head finite element (FE) model with high biofidelity was used to conduct impact simulations under the protection of helmets with different sizes (small, medium and large) and cushion materials (EPS-expanded polystyrene, PU-polyurethane and airbag) according to the testing conditions specified by the standard. Then the protective performance of different helmet designs was evaluated by assessing skull and brain injury risk calculated based on the kinematic and biomechanical response of the child head model.

Results: The skull fracture risk of children under the protection of airbag helmets is lower than that of EPS and PU helmets by more than 50%. Large-sized helmets, with thicker padding, show better protective capability for skull injury compared to small-sized helmets. The risk of brain injury under airbag helmet protection is significantly lower than EPS and PU helmet under 4.8m/s sharp drill impact test condition, and small sized helmet could generally reduce brain injury risk under the 6.2m/s flat drill impact test condition. However, no obvious effect has been found of helmet size and material to brain injury risk in the impact scenarios at 6.2m/s.

Conclusions: The size and cushion material of the helmet have a significant influence on its skull injury protection performance, but their effect pattern on brain injury protection capability is not obvious. The use of airbag helmets with larger buffering stroke can effectively reduce both the risk of skull and brain injuries under relatively low impact loads.

Keywords: Children helmet, Human body model, Biomechanics, FE simulation, Injury risk

1. Introduction

Traffic safety has become a globally issue, and within the entire transportation system, vulnerable road users (VRUs) such as pedestrians and cyclists face extremely high risks of injury. According to the World Health Organization (WHO) report, 1.19 million people died in traffic accidents in 2021, of which about 35% were two/three wheeler riders [22]. In China, two wheeler and three wheeler riders account for 35% of total road traffic fatalities [15]. In urban traffic scenarios, the accident rate involving all cyclists remains high, with an average of 40% serious accidents related to cyclists [24]. At the same time, a large amount of traffic accident data analysis shows that head injuries are the most common cause of death and serious injuries for two wheeler riders [4] [9] [21]. In the United States, approximately 26,000 children seek emergency treatment for head injuries caused by cycling each year, with traumatic brain injury being the most common cause of death [9]. Therefore, research on head injury protection for two wheeled cyclists deserves special attention.

As early as the 1980s, researchers began to pay attention to the design of helmets for two wheeled vehicles [18], the focuses are mainly on helmet structure design and material selection [6] [8] [13] [25]. and the mainstream methods used include drop tests based on regulatory conditions and finite element (FE) simulation analysis [2] [23]. For example, Fahlstedt et al. studied the impact of bicycle helmet design and materials on the risk of head injury in accidents and found that appropriate helmet design and materials can significantly reduce the risk of head injury for cyclists, especially in reducing skull strain [5]. Recently, Mathon et al. proposed a novel air-filled bicycle helmet and found that the air-filled helmet significantly reduced the maximal linear acceleration when compared to an traditional EPS (expanded polystyrene) helmet [11]. Though, the protective effects of helmet on head injuries are well known, current helmets still show limitations. Han et al. studied the protective performance of helmets for electric two wheeler riders in accidents and found that helmets can effectively reduce the risk of skull fractures under normal impacts, but the effect is not good under severe impacts, and the protective effect on diffuse axonal injury and concussion is limited [6]. Wang et al. used computational biomechanics modeling to evaluate the protective effect of bicycle helmets in accidents and found that helmets can reduce the risk of skull fractures, but the protective effect on brain injuries varies depending on the helmet and impact scenario [20-21]. Existing researches have emphasized the important role of helmets in reducing skull fractures and brain injuries, and providing a wealth of reference for helmet design. However, previous studies have mostly focused on adult helmets, with little attention paid to the design of children's helmets. As a special and vulnerable part of VRUs, school-age children are the main group of passengers in China's two wheeled vehicles, and their head injury protection issues have not received sufficient attention [17]. A large number of children suffer from head injuries caused by cycling, among which head injuries are one of the important causes of death and disability in cycling accidents [4].

Therefore, the current study intends to analyze the influence of different helmet designs on the risk of head injury in children from the perspectives of size and cushion materials. Specifically, a 6-year-old child's head finite element model with high biofidelity was used as the evaluation tool to conduct impact simulations under helmet protection with different sizes and cushion materials according to the testing conditions specified by a Chinese National Standard GB 24429-2009 (the helmet assessment regulation) [1]. Then the dynamic and biomechanical responses output from the child's head model were extracted to compare and analyze the protective performance of different helmet designs on skull and brain injuries.

2. Methods and Materials

2.1 Pediatric head model

The head model extracted from the THUMS 6YO (6-year-old) Version 4 human body model was employed to simulate the mechanical responses of a child head during collisions. The THUMS 6YO head model features a comprehensive structure that encompasses numerous human head components, including the scalp, skull, cerebral white matter, cerebral gray matter, lateral ventricles, and the third ventricle, as depicted in Figure 1. During the modeling process, high-resolution CT scan data from the University of Michigan were utilized to precisely construct the geometric [19]. For mesh generation, appropriate element types were chosen based on the distinct tissue characteristics, and strict size control was implemented. Specifically, the brain region was simulated using tetrahedral elements, with the element length regulated within the range of 0.75-4.2 mm [19]. When defining the material properties, the mechanical behaviors of each tissue were thoroughly considered. For instance, damage materials were used to simulate the skull, while incompressible and viscoelastic materials were selected for the brain [19].

To guarantee the reliability of the THUMS 6YO head model was subjected to extensive validation through simulated biomechanical tests which include lateral head compression, drop tests in various directions, and neck axial loading tests [19]. The validation results indicated that there were discrepancies between the 6YO and 10YO head models in terms of parameters such as force and acceleration, however the trends of change were reasonable. Moreover, the simulation results of the 10YO head model showed well agreements with the experimental data. This strongly suggests that the THUMS 6YO model is highly accurate in representing the head impact mechanical responses of children at this age and reliable for in-depth investigations into the head injury mechanisms of children during vehicle collisions.

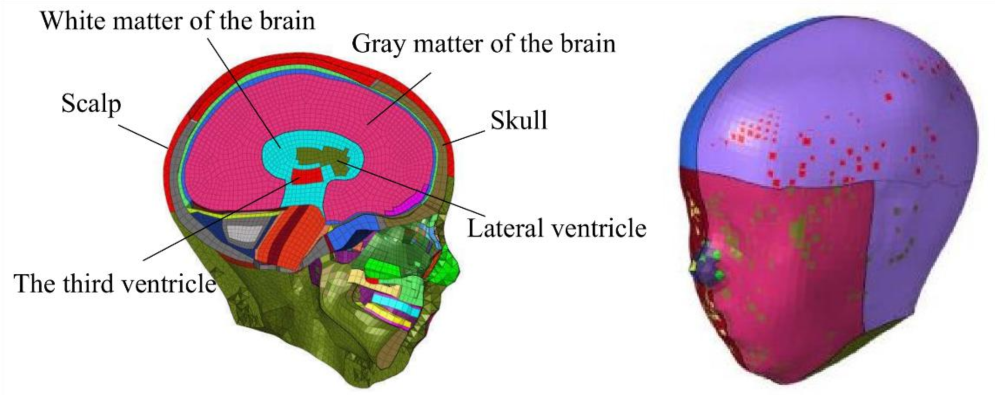

Figure 1. The THUMS 6YO head model.

2.2 Helmet models

To comprehensively assess the protective performance of various helmet designs, this study developed helmet models featuring two distinct energy-absorbing cushion designs: expanded polystyrene (EPS) foam cushion, polyurethane (PU) foam cushion and airbag cushion. The geometry of the helmet model was sourced from geometric point-cloud data of a half-face helmet acquired through laser scanning technology in the earlier stage. Based on this data, corresponding FE models of the shell and cushion surface were established using 2D elements. Then the space between the shell and cushion surface was filled with solid elements for the EPS and PU foam model (Figure 2a), while for the airbag helmet model this space was set as multiple small chambers with a pressure of 0.6 Mpa (Figure 2b). The selected half face helmet is the most popular helmet type in China for child passengers on electric two wheelers, while EPS and PU are the main materials for helmet liner. The selection of airbag pressure was from preliminary analysis of the authors, where the constant pressure of 0.6 MPa showed better protective capability. It is worth noting that the three different helmets have the same volume of the energy absorbing part and the innermost layer of all helmet models was simulated using shell elements to represent the comfort liner for contact with the head.

The material properties of each component of the helmet were defined under the LS-DYNA software environment according to the data from the literature. Particularly, the material parameters of the acrylonitrile-butadiene-styrene (ABS) of the helmet shell (represented by the elastoplastic material model) and EPS foam cushion (simulated using the crushable foam material model) were sourced from the reference [21], the PU foam was simulated using the Fu-Chang foam material model according to the reference [10]. and the airbag skin material was defined as a sealed woven fabric material model [3]. The stress-strain curves for the EPS (adapted from [21]) and PU (adapted from [10]) foam are shown in Figure 2c, which were obtained from quasi-static compression tests. It should be noted that the FE model of the EPS helmet was previously validated against impact test data [21], Figure 2d shows the validation results in one of the loading conditions.

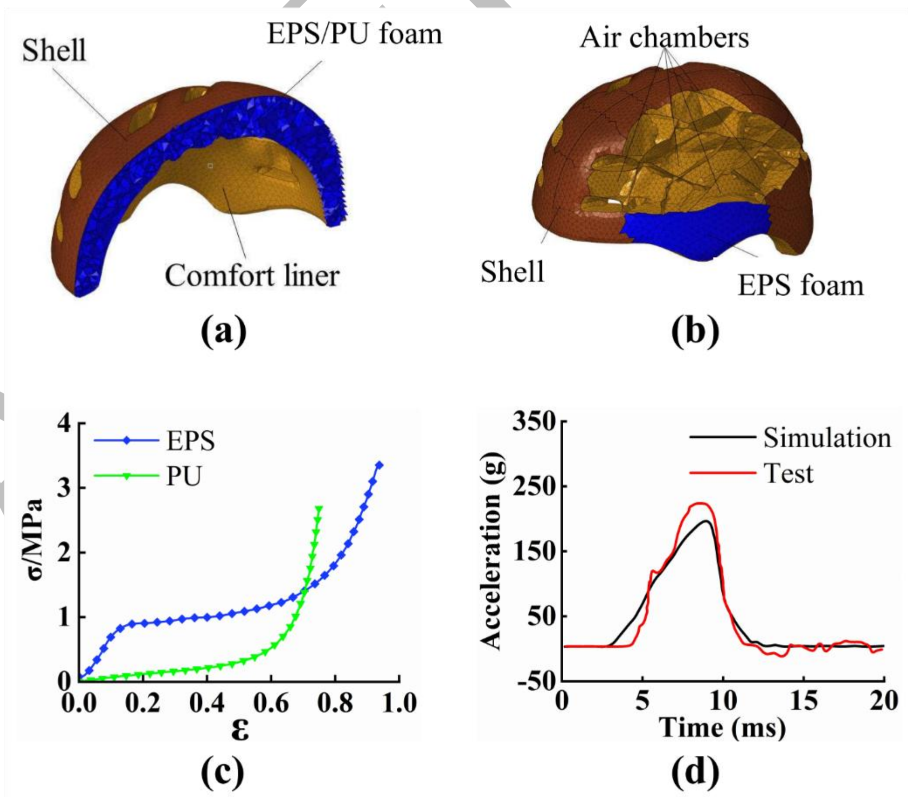

Figure 2. The FE modes of the EPS/PU (a) and airbag (b) helmet, the stress-strain curves of EPS and PU material (c) and the validation result of the EPS helmet model (d).

2.3 Simulation matrix

Given that the size classification of children's helmets has a relatively wide range (e.g., for children aged 6-12 years), and there may be cases where the helmet size does not match the head circumference during usage, the original helmet model of each cushion design was scaled to three different sizes (small, medium and large) to mimic different levels of tightness when children wear helmets in real-world situations. Figure 3a shows the dimensions of the helmets in different sizes, where the small and large sized helmets were generated with scaling ratios of 0.95 and 1.05 from the medium-sized helmet, respectively. The large size represents a loose fit, the small size represents a tight fit, and the medium size represents a normal fit. To cover different impact locations on the helmet, four drop-impact simulation models corresponding to different test conditions stipulated in China National Standard GB 24429-2009 [1]. The impact scenarios are illustrated in Figure 3b, where the impact velocity of the helmet (together with the head model) against the flat anvil (Scenario A and B) was set at 6.2 m/s, while the velocity against the pointed anvil (Scenario C and D) was set at 4.8 m/s. Taking the above factors into account, a total of 36 (3 sizes * 3 cushion types * 4 scenarios) simulations were conducted in this study. In all simulations, the anvil was fixed at six degrees of freedom and an initial velocity was applied to the helmet and head model freely. Similar to previous studies [20-21], the friction coefficient between the head model and the cushion was set as 0.3, and the friction coefficient between the helmet and the steel anvil was set as 0.4.

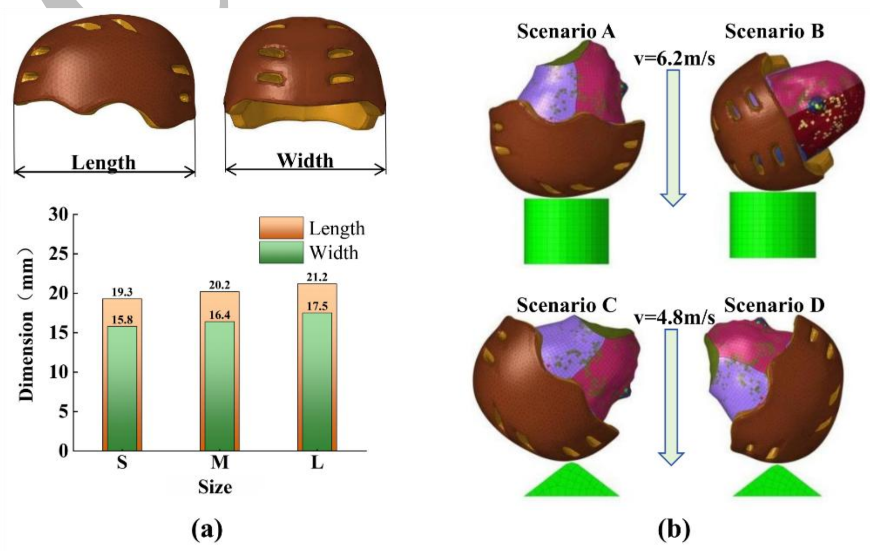

Figure 3. The dimensions of the helmets in different sizes (a) and the impact scenarios (b).

2.4 Injury risk assessment parameters

To assess the protective performance of different helmets, the parameters of HIC (Head Injury Criterion) and maximum principal strain (MPS) were used as the predictors for skull fracture and brain injury, respectively. HIC was proposed for skull fracture assessment, which accounts for both the peak and duration of the head linear acceleration [12]. The formula for HIC calculation is given by Eq. 1, where at represents head resultant linear acceleration, and t2-t1 is 15 ms. The skull fracture risk curve as a function of HIC developed from cadaver test data [12] and the AIS2+ brain injury risk curve as a function of MPS proposed from reconstruction of sports and vehicle crash injuries [16] were employed to quantify the protective performance of different helmets, as these are the main injury types observed in real-world accidents [4][6]. It should be noted that the resultant linear acceleration was captured at the center of gravity of the head model, the MPS was output from the gray matter, white matter and lateral ventricle of the brain.

$$HIC = \left\{ \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a_t dt \right]^{2.5} (t_2 - t_1) \right\}_{max} \quad (1)$$

3. Results

3.1 Protective performance for skull injury

Figure 4 shows the head linear acceleration time histories of all the 36 impact simulations. The peak linear acceleration (PLA) values of the head wearing airbag helmets are lower than those of the EPS and PU helmets in all scenarios, while the head PLA values under the protection of the PU and EPS helmets are quite close. In most instances, the head PLA value in cases of airbag helmet is merely 60% of that of the EPS and PU helmets. When the cushion material remains the same, variations in helmet size also exert a certain influence on the head PLA value. Generally, the head PLA value of a large-sized helmet is higher than that of a small-sized helmet with the same cushion material. Specifically, in test Scenario A, the head PLA value of the large-sized EPS helmet is 76.1 g lower than that of the small-sized EPS helmet.

According to the HIC data, for all scenarios, the HIC values of the airbag helmets are also significantly lower than those of the EPS and PU helmets, and the HIC value of the PU helmet is notably higher than that of the EPS helmet. Quantitatively, in most cases, the HIC value of the airbag helmet is approximately 30%-40% of that of the EPS and PU helmets. Helmet size also shows certain influence on the HIC value, the HIC values of large-sized helmets under all scenarios are generally smaller than those of small-sized helmets with the same cushion, and the maximum difference in HIC values resulting from helmet size exceeds 400 (for the PU helmet).

Figure 5 illustrates the risk of skull fracture (Rf) calculated based on the HIC values and the injury risk curve reported in the literature [12]. It is evident that the risk of skull fracture for the airbag helmets are lower than that of the EPS and PU helmets across three different sizes and four operating conditions, and all Rf values are below 40%. Quantitatively, for large-sized helmets, in test Scenario A, the average risk of skull fracture for the airbag helmets is 22.9%, while this value is 67.3% and 97.9% for EPS and PU helmets, respectively. In test Scenario B, the average risk of skull fracture for the airbag helmets is 21.3%, which is also significantly lower than that of the EPS (51.3%) and PU helmets (60.95%). Under these two scenarios, the risk of skull fracture when protected by the airbag helmets is relatively reduced by more than 60% compared to that protected by the EPS and PU helmets. Since the risk of skull fracture in test Scenario C and D is lower than 10%, it will not be elaborated upon here. However, the airbag helmet has a significantly greater advantage in protecting against skull skull compared to the EPS and PU helmets in Scenario C and D.

In terms of the influence of helmet size, as the helmet size increases from small to large, the risk of skull fracture generally exhibits a downward trend. In test Scenario A, the risk for the airbag helmet decreases from 26.70% to 22.90%, the EPS helmet decreases from 80.3% to 67.30%, and the PU helmet decreases from 99.4% to 97.90%. In test Scenario B, when the helmet size increases from small to large, the skull fracture risks for airbag, EPS, and PU helmets show decreases of 14.8%, 15.1%, and 20.5%, respectively. It can be observed that a large-sized helmet with the same cushion material can reduce the risk of skull injury by nearly 50% at most compared to a small-sized helmet (the airbag helmet in Scenario B). Scenario C and D will not be analyzed either.

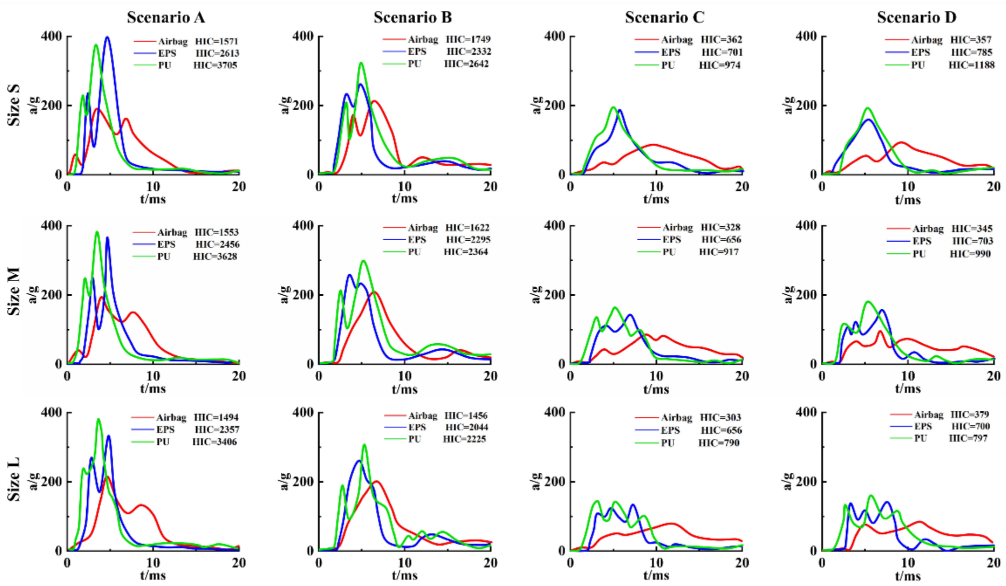

Figure 4. The predicted head linear acceleration curves and HIC values of all impact simulations.

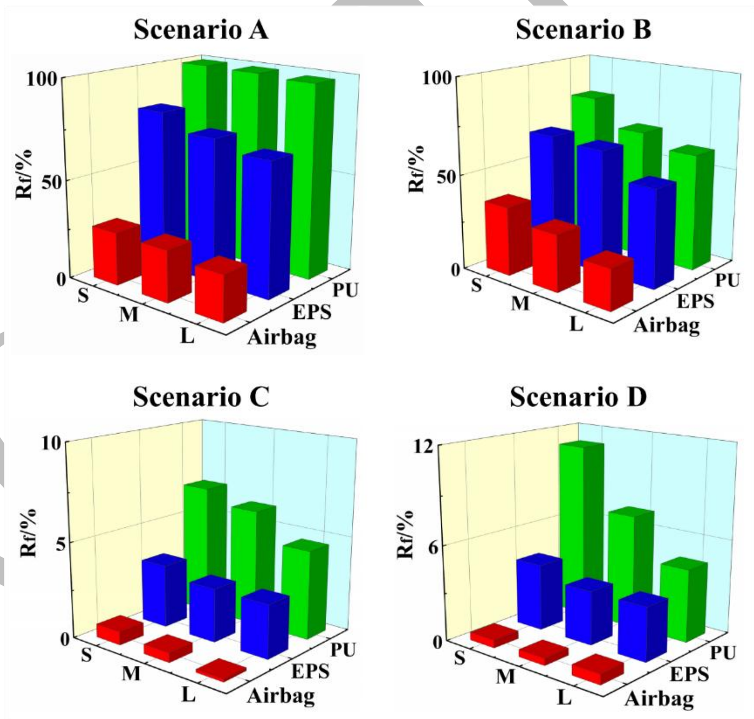

Figure 5. The calculated skull fracture risk of all impact simulations.

3.2 Protective performance for brain injury

Figure 6 depicts the strain contour map of brain tissue and the MPS under each simulated impact. Among the four scenarios, in most cases, the maximum strain is observed at the junction of the white matter of the left and right cerebral hemispheres. In test Scenario A and

B, most of the brain MPS values fall within the range of 0.5-0.6. In test Scenario C and D, the brain MPS values are mostly fluctuate within the range of 0.2-0.4. When the helmet size is the same, the difference in the brain MPS protected by helmets with different cushions in test Scenario A and B is generally negligible. In contrast, in Scenario C and D, the strain MPS values protected by the airbag helmet are obviously lower. It can also be observed that in test Scenario B the white matter in both cerebral hemispheres undergoes significant deformation in all cases, while in test Scenario A, C, and D, brain deformation is not obvious.

Figure 7 illustrates the AIS2+ brain injury risk calculated based on the MPS values and reported in the literature [16]. The results indicate that: under test Scenario A and B, the AIS2+ brain injury risk for all helmets exceeds 50%, changes in helmet size and cushion material generally have a negligible effect on the brain injury risk, and the probability of AIS2+ brain injury when protected by the EPS helmet is slightly lower than that of the other two helmets. In test Scenario A, the AIS2+ brain injury risk of large-sized helmets is generally higher than that of small-sized helmets. Conversely, in test Scenario C and D, the risk values of AIS2+ brain injury when protected by the airbag helmets are all below 20%. The average AIS2+ brain injury risk for the airbag helmet cases (11.7%) is less than half of that of the EPS (26.0%) and gel (25.8%) helmets. However, the influence of helmet size on the brain injury risk varies depending on the cushion material.

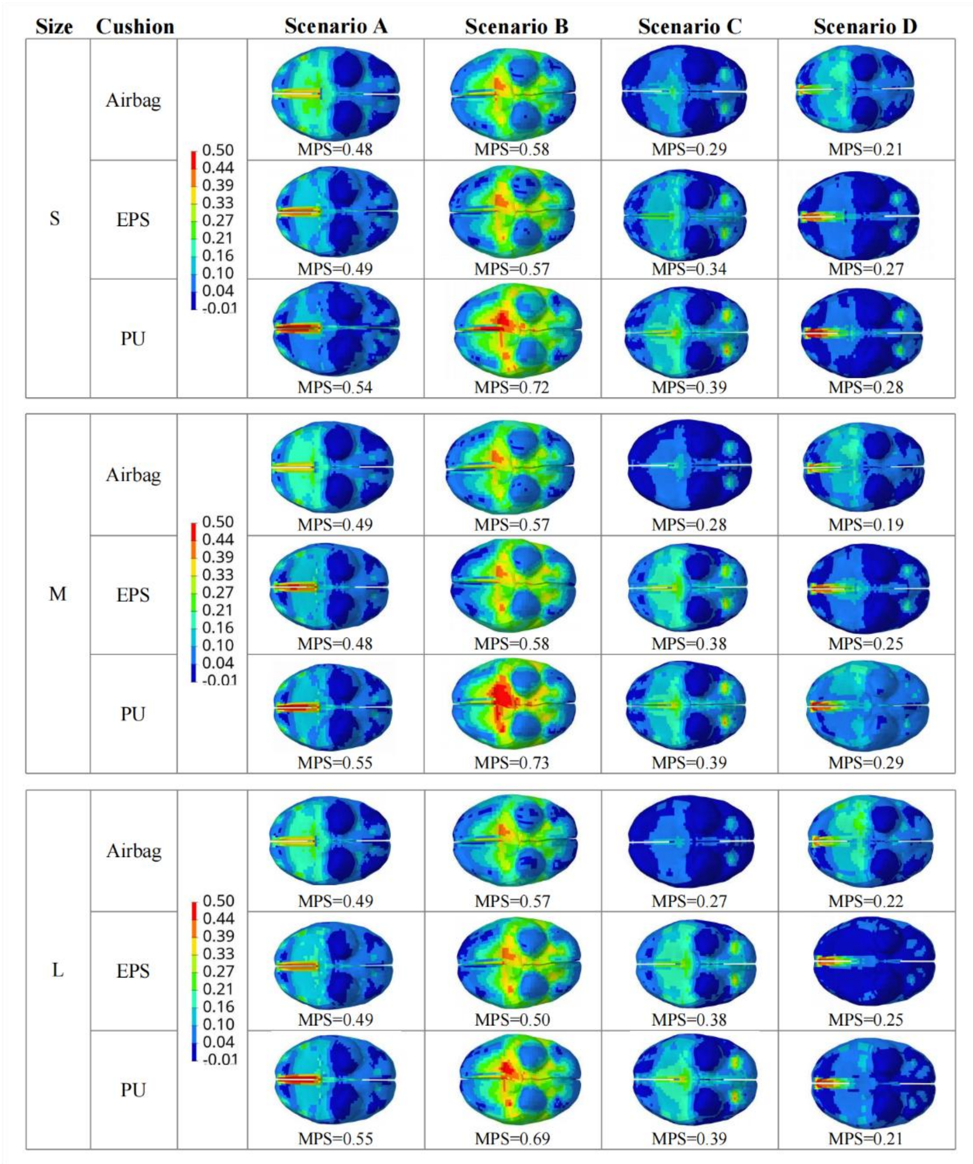

Figure 6. The predicted brain strain distribution and MPS values of all impact simulations.

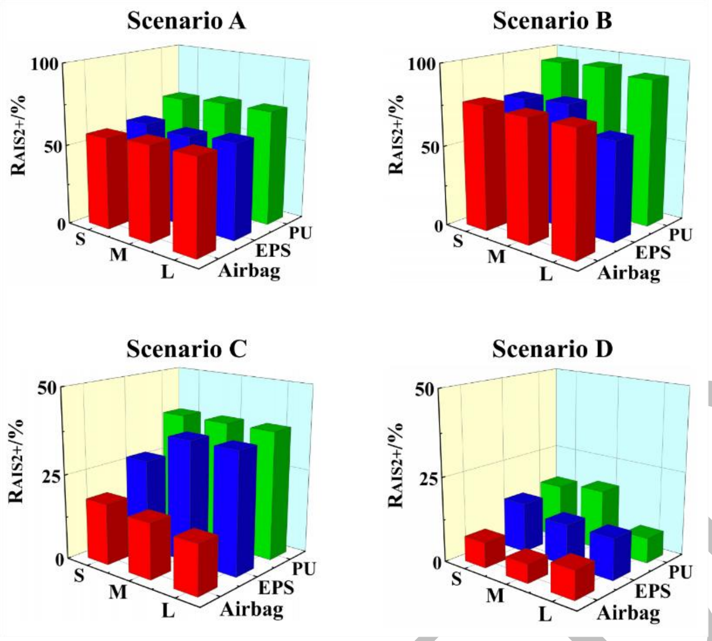

Figure 7. The calculated AIS2+ brain injury risk of all impact simulations.

4. Discussion

The current study compared the protective performance of different helmet designs for children head injuries with skull fracture risk and brain injury risk being distinguished, the following discussion aims to understand the trends observed in simulation results from a mechanical perspective.

In terms of the influence of the cushion material on the protective performance of helmets, altering the helmet cushion material can remarkably influence its protective capabilities, particularly having a most pronounced effect on reducing the risk of skull injury. Under all test scenarios, the airbag helmets demonstrate a better protective performance against skull injury than EPS and PU helmets. The advantage of the airbag helmets stems from the continuous buffering capacity provided by the constant pressure within the airbag [11], which reduces the peak head acceleration through an equal buffering stroke, whereas foam materials tend to harden during compression deformation and consequently lose their protective efficacy (see stress-strain curves in Figure 1c). The superiority of airbag helmets over EPS helmets has also been proved in a previous study [11], where the PLA recorded during the test on the airbag helmets was significantly lower than that of the EPS helmets. By comparing the stress-strain curves (Figure 1c) and protective performances of EPS and PU helmets (Figure 5), it is evident that EPS, with a higher stress plateau under the same strain conditions, offers superior protection against skull injury. However, both EPS and PU helmets show poor protection to skull injury in test Scenario A and B. That is largely due to the high impact speed, since many studies have proved that ordinary EPS helmets are still limited for protecting skull injuries in the scenarios with high collision loads [6] [21]. Additionally, the airbag helmet exhibits a distinct advantage in protecting against brain injury in test Scenario C and D (Figure 7). However, in test Scenario A and B, its brain injury protective performance is comparable to that of other helmets. This is primarily because that in test Scenario A and B, the impact energy is substantial, and the impact is from a flat anvil (resulting in minimal significant rotation of the helmet), the advantage of airbags in restraining the head cannot be fully demonstrated. These results imply that the protective capability of helmets for brain injuries is not sensitive to helmet design when the impact load is high, this finding is similar to that reported in previous studies of helmet protective capability in simulated accidents [6] [20-21].

Regarding the influence of helmet size on its protective performance, large-sized helmets exhibit a clear advantage in reducing the risk of skull fracture. Conversely, they show a slight drawback in protecting against brain injury. The superiority of large-sized helmets in safeguarding against skull fracture can be attributed to several factors. Firstly, the advantage of increased buffering space is pivotal [21]. A larger helmet provides more room for the buffering material, enabling it to more effectively absorb and disperse the impact force during a collision and preventing the buffering effect from being compromised due to excessive tightness. Secondly, there is a significant synergistic effect between material properties and size. For instance, the large-sized airbag helmet demonstrates a lower risk of skull fracture as it can more efficiently disperse the impact force. Finally, the physiological characteristics of children's heads necessitate more effective protection. A looser-fitting helmet can better conform to the shape of a child's head, reducing local pressure concentration and thereby enhancing the protective effect. Consequently, large-sized helmets can significantly mitigate the instantaneous high acceleration impact on the head. This characteristic is not only reflected in the smoother variation of the head PLA value but also corroborated by the reduction in the HIC value (Figure 4). This finding is consistent with that of reference [7], which indicates that helmets with thicker EPS perform better in reducing the peek linear acceleration. However, previous analysis indicates that better fitness of a helmet can enhance the fixation of it on the head, which could improve the protective effect [14]. This may imply that the fitness of a helmet could not be reflected only by the size, more detailed geometry needs to be discussed in further analysis. On the other hand, although large-sized helmets show significant advantages in reducing the risk of skull fracture, their ability to restrain head movement is relatively weak. Under specific test scenarios and cushioning designs, large-sized helmets may increase the rotational motion of the head during a collision, leading to relatively higher strains and injury risks in brain tissue. However, this negative impact does not manifest as a consistent pattern across all test scenarios (Figure 7).

The current study is still limited in the following aspects. Firstly, only one half-face helmet geometry was used, future study would focus on other styles of helmets (such as the full-face helmet). Secondly, only the test scenarios defined in a standard were simulated, future analysis would pay close attention to helmet protection capability in real-world accident collisions. Finally, only the 6-year-old child head model was used for assessment and the 6-year-old child head model was validated indirectly, it is necessary to conduct research on head protection for children of other age groups and future research needs to further improve the validation methods to enhance the accuracy and reliability of the human body model.

5. Conclusions

The current work compared the protection performance of helmets with different sizes and cushion materials based on assessment of the risk of skull fracture and brain injury using the predictions from a 6-year-old child head FE model. The results imply that both the size and cushion material have a significant influence on head injuries, especially the designed airbag helmets show remarkable advantages in protecting skull fractures at all tested scenarios and brain injuries in the cases with a relatively low impact load. For a given cushion material, the large-sized helmets, with a thicker pad, are better for protection of skull structure. However, the influence of helmet size and material on the risk of brain injury is less pronounced under high impact loads than under low impact loads.

Integrating the above analysis with the key conclusions from previous research on helmet design and protection, this study proposes that, on one hand, research into the design of the interior of helmets should simultaneously consider material and structural optimization to comprehensively enhance the helmet's protective performance against overall head injuries. On the other hand, given the significant disparities in the protective performance of helmets under different test conditions, real-world accident scenarios should be considered as extensively as possible when evaluating helmet performance.

Acknowledgements

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