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Article

# Validation of impact-absorbing football helmet facemask for head injury prevention with simulation

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## SUMMARY

**American football reports the highest rate of head injury in the United States. While football helmets have been developed to protect players and reduced severe head injuries, concussion incidents have not declined in the National Football League. A facemask is one of the helmet components mounted on the front opening of the helmet to protect the face, and it is the second most impacted location causing concussions. It is made of carbon steel or titanium and has high rigidity, which is effective at protecting the face from direct contact injury, but it is ineffective at absorbing impact. This study aimed to assess whether a facemask contributes to head injury prevention against front impact. We hypothesized that if a facemask absorbs impact, it would drop the concussion risk. We conducted a ram impact test and a helmet-to-helmet collision test to validate a facemask using numerical simulation. For the front ram impact test simulation, highly ductile polycarbonate plastic was applied to the facemask to cushion the impact. Various polycarbonate facemask designs reduced the head acceleration from the impact by more than 46% versus the titanium facemask. For severe helmet-to-helmet collision simulation with an angled front impact, a hybrid facemask composed of polycarbonate frame and steel wire decreased translational and rotational acceleration of the struck head and dropped concussion risk by approximately 50%. This study indicated that a facemask played a significant role in lowering concussion risk if it was designed to absorb impact.**

## INTRODUCTION

American football is the most popular sport in the United States, but unfortunately, it causes the highest rate of head injuries each year (1). In high schools, 4,183 concussions were reported in American football from 2013 to 2018, and it was the highest among the 20 common high school sports (2). Football players wear helmets for head protection, and the helmet consists of an outer shell, padding, clips, a chinstrap, and a facemask (**Figure 1**). While the helmet mitigates the risk of severe head injuries such as skull fracture by using thick and impact energy-absorbing padding on the side, back, and around the ears, the concussion incident rate remains as high as 0.3-0.4 per game in National Football League (NFL) since 2015 (3). The facemask of the helmet, which is for face protection, is the second most impacted location causing concussions, followed by the side of the helmet, according to NFL (**Figure 2**) (4).

Numerical simulations have been crucial for the development of impact mitigation structures in automotive and other industries. Still, these simulations have not historically been widely utilized in the development of football helmets (10). Moreover, little research has been done on the facemask for head injury prevention, while padding structure and material have been studied to improve impact-absorbing performance. Modern facemasks are currently made of metal such as carbon steel or titanium and are very stiff. High stiffness or rigidity suppresses the deformation of the facemask, increasing its effectiveness in protecting the face from direct contact damage, but reducing its impact absorption. The study aimed to investigate the relationship between the rigidity of a face-

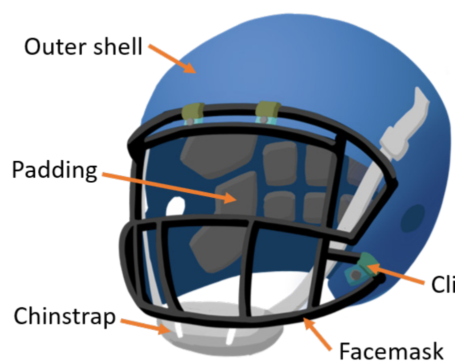


**Figure 1: American football helmet.** Facemask is mounted on the front and made of steel or titanium. Outer shell, chin strap, and clips are plastics. Padding is soft foam or rubber.

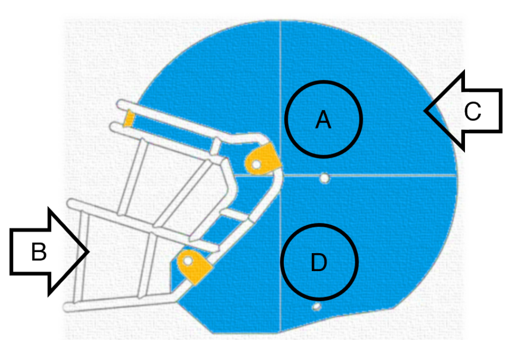


**Figure 2: Major impact locations of concussed players.** (A) Side upper. (B) Facemask center. (C) Rear upper. (D) Side lower.

mask and concussion risk. We hypothesized that if a facemask absorbs impact like a padding component, it will reduce the concussion risk.

The study used Fusion 360™ software to design the neck-head model with a football helmet and to simulate ram impact test and helmet-to-helmet collision (**Figure 3**). A titanium facemask was selected as a baseline, and polycarbonate plastic was applied to the facemask to control the rigidity. Also, different facemask designs with polycarbonate plastic were simulated to study how the design affected the concussion risk. The resultant head acceleration by the impact on the facemask was used to assess concussion risk. The polycarbonate facemask reduced head acceleration notably versus the titanium facemask, and head acceleration varied with the designs of different rigidity. This supports our hypothesis that impact-absorbing facemask will lower the risk of concussion.

## RESULTS

### Facemask models

The baseline facemask was a titanium facemask, and the polycarbonate facemask 1 (PC1) has the same design as the titanium facemask (**Figure 4A**). The polycarbonate facemask 2 (PC2) served as the reinforced model of PC1 due to having more vertical and transverse bars and higher stiffness and strength than PC1 (**Figure 4B**). The hybrid facemasks were the polycarbonate facemask (PC1) with steel wire inside to increase rigidity (**Figure 4C,D**). The hybrid facemask 1 (Hybrid1) included a steel wire of 4 mm diameter, and the hybrid facemask 2 (Hybrid2) had a steel wire of 4.8 mm diameter, making it stiffer than the Hybrid1. Since plastic is recommended to have more than 1.5 mm thickness to injection mold over the steel wire to make the hybrid facemask, 4 mm and 4.8 mm diameter were selected. Polycarbonate plastic is a highly ductile material, and it is currently used for the outer shell of the football helmet. It does not break until it is elongated by 120% in the tensile specimen test, and it does not fail in the unnotched Izod impact test of ASTM D4812 at 20°C and -30°C, which puts the impact in the mid of the specimen (5).

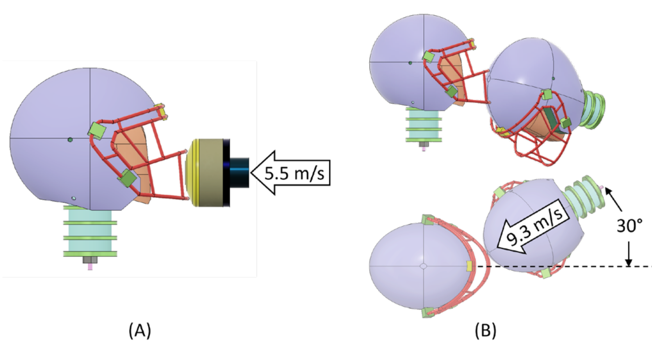


**Figure 3: Simulation condition.** (A) Ram impact test with a 5.5 m/s ram speed to the front of the helmet. (B) Helmet-to-helmet collision with a 9.3 m/s strike helmet speed with 30° attack angle.

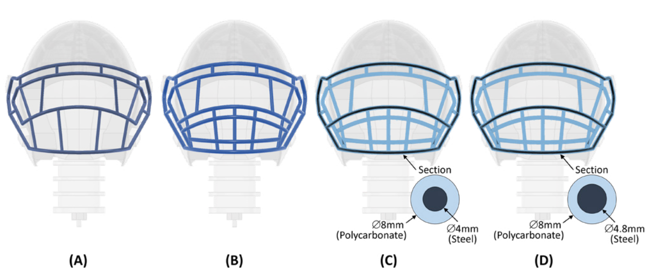


**Figure 4. Facemask designs.** (A) Titanium facemask and Polycarbonate facemask 1 (PC1). (B) Polycarbonate facemask 2 (PC2). (C) Hybrid facemask 1 (Hybrid1). (D) Hybrid facemask 2 (Hybrid2).

### Ram Impact Test Simulation

The NFL requires the test conditions of the National Operation Committee on Standards for Athletic Equipment (NOCSAE), and one of the test conditions is the pneumatic ram impact test (7, 15). The front ram impact position on a facemask and 5.5 m/s ram speed, average impact speed, were selected for the simulation (**Figure 3A**). A simulation with the titanium facemask was conducted first with a 0.03 s impact event time. Noticeable deformation of the facemask was not observed because of titanium's rigidity (**Figure 5A**). The ram impact on the facemask was almost directly transferred to the head, and head velocity increased until 0.012 s then decreased (**Figure 6A**). Since head velocity increased with fluctuations due to complex contact and damping control in the simulation, a linear regression of the velocity curve was used to average the head acceleration over 0.01 s. The head acceleration reached 244 $m/s^2$ (25 G) (**Figure 6B**). The same simulation was performed with PC1, and the facemask was deformed by the impact while protecting the face from the ram (**Figure 5B**). Head velocity increased more slowly than the titanium facemask, and head acceleration from the same linear regression approach was reduced from 244 $m/s^2$ to 39 $m/s^2$, an 84% reduction (**Figure 6B**). PC2 and Hybrid1 were also analyzed to determine the influence of the facemask design on head acceleration. Both facemasks absorbed the impact and were deformed like the PC1, and showed a lower level of head acceleration than the baseline, 81 $m/s^2$ and 131 $m/s^2$ respectively (**Figure 6B**).

### Helmet-to-Helmet Collision Simulation

The ram impact test evaluated the translation movement of the head along the ram impact direction; however, both blunt translation and rotation of the head cause concussion (6). Therefore, a helmet-to-helmet collision condition was

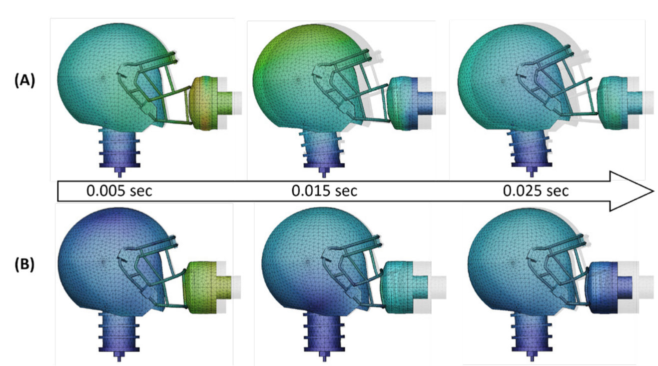


**Figure 5. Ram impact test simulation result.** (A) Titanium facemask. (B) PC1. PC1 shows less head translation by the ram impact with larger deformation. Countour shows velocity.

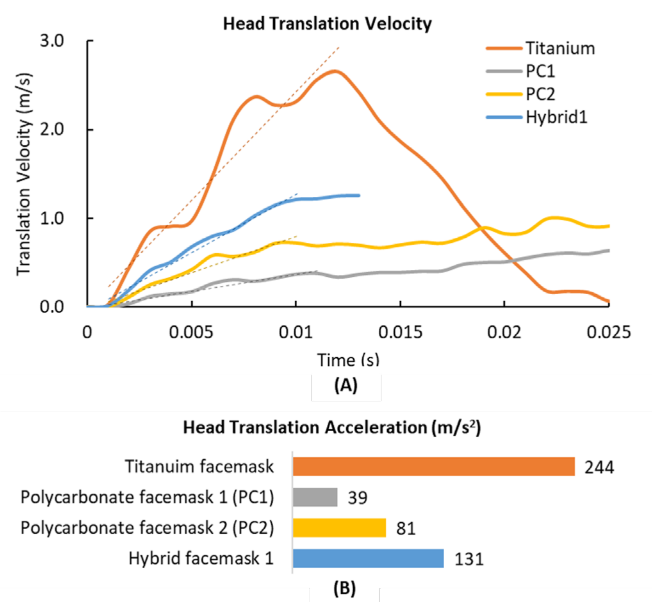


**Figure 6. Head velocity curves and head acceleration.** (A) Dashed lines show linear regressions of the head velocity over 0.01 s for each facemask. PC1, PC2, and Hybrid1 all show a slower increase of the head velocity than the Titanium facemask. (B) Head acceleration comparison.

designed to model a realistic concussion incident. The strike helmet had a 30° attack angle at a speed of 9.3 m/s, which is more severe than the standardized ram test (**Figure 3B**). The titanium facemask helmet showed a large translation and rotation of the head as predicted since the translational and rotational velocity of the head increased until 0.01 seconds, similar to the ram test (**Figure 7A, 8A,C**). Translational head acceleration went up to 647 m/s² (66 G), and rotational head acceleration reached 6,341 rad/s² (**Figure 8B,D**). For evaluating the severity of the result, concussion risk was estimated from the head acceleration results referencing the concussion risk prediction curve of Pellman *et al*. (7) and Zhang *et al*. (6). The concussion risk of the titanium facemask helmet was as high as 70% and 65% in translation and rotation of the head, respectively (**Table 1**). Using the same simulation Hybrid2 was deformed by the striker helmet protecting the struck player's face (**Figure 7B**). Impact event time was limited to 0.015 s due to a computing time constraint of 12 h for the software. As the translational and rotational velocity of the head increased more slowly than the titanium facemask, translational head acceleration was reduced from 647 m/s² (66 G) to 348 m/s² (35 G), and rotational head acceleration decreased from 6,341 rad/s² to 4,270 rad/s² (**Figure 8B,D**). Therefore, estimated concussion risk dropped from 70% to 25% in head translation and from 65% to 20% in head rotation according to the reference curve (**Table 1**). Hybrid1, having a thinner steel wire, showed lower accelerations than Hybrid2

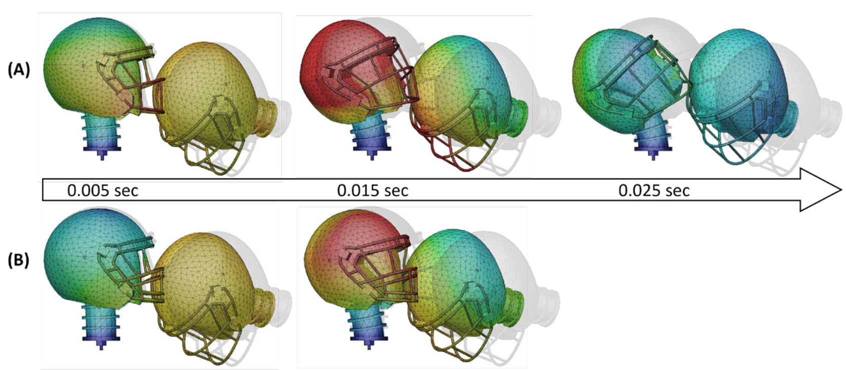


**Figure 7. Helmet-to-helmet collision simulation result.** (A) Titanium facemask. (B) Hybrid2. Hybrid2 facemask result is limited to 0.015 seconds due to a computational time constraint in the software. Angled attack generates both translation and rotation of the head. Hybrid2 facemask reduces the translation and rotation of the head. Coutour shows velocity.

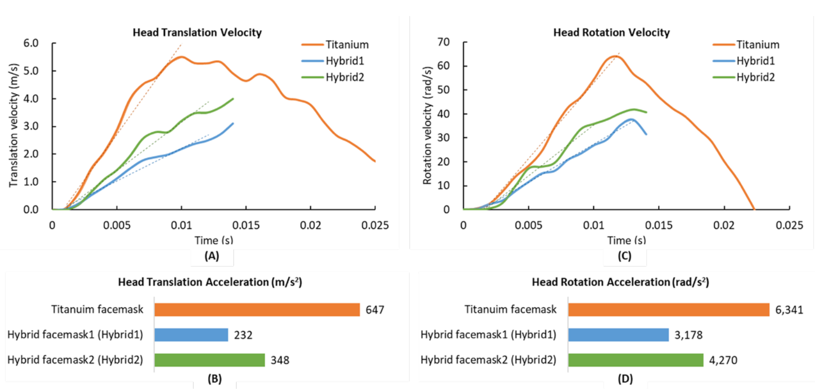


**Figure 8. Head velocity curves and head acceleration.** (A)(C) Dashed lines show linear regressions of the head velocity over 0.01 s. Hybrid1 and Hybrid2 show a slower increase of the head velocity than Titanium facemask for both the translational and rotational head velocities. (B)(D) Head acceleration comparison.

while it deformed more and slightly touched the face.

## DISCUSSION

The facemask of the football helmet is the second most impacted location causing concussions in football. We conducted extensive simulations on the facemask to evaluate solutions to mitigate the concussion risk. As the baseline facemask has a frame structure made of titanium, the deformation of the facemask by the impact was not observed in the ram impact test simulation. On the other hand, the polycarbonate plastic facemask was largely deformed, which resulted in a significant decrease in head acceleration. We also tested a reinforced polycarbonate facemask and a novel hybrid facemask. They had lower head accelerations than the titanium facemask, but the level of acceleration of the hybrid facemask was higher. We also conducted severe helmet-to-helmet collision simulations on the condition of the angled attack by strike helmet at a higher impact speed. The two hybrid facemasks reduced the concussion risk from translation and rotation of the head by being deformed more than the titanium facemask. The hybrid facemask with a thinner steel wire was more flexible and better than the other with a thicker wire as it showed lower acceleration.

This study indicated that the facemask has a strong relationship with head acceleration caused by impact, and the current titanium facemask is not effective in protecting the players from this response. Therefore, ductile and flexible polycarbonate facemasks have the potential to improve head injury prevention by absorbing impact forces. This flexible facemask would be more suitable for youth players who have lower collision speeds than adult players, and it would be more helpful for them because concussions may result in longer recovery times or even disrupt the natural maturation of the brain (9). Another advantage of the polycarbonate facemask is that it is designed to directly replace the current metal facemask using existing clips without any additional components.

Due to limitations in software capabilities and lack of material data in the software, assumptions were made in the simulation. Linear material property and linear tetrahedral elements were used to meet the computational time constraint, which has the potential to increase stiffness leading to higher acceleration response. Friction between the components was assumed to be zero since it was difficult to find specific friction coefficients for different materials. Zero friction may reduce transmission of the impact force and lower the acceleration response.

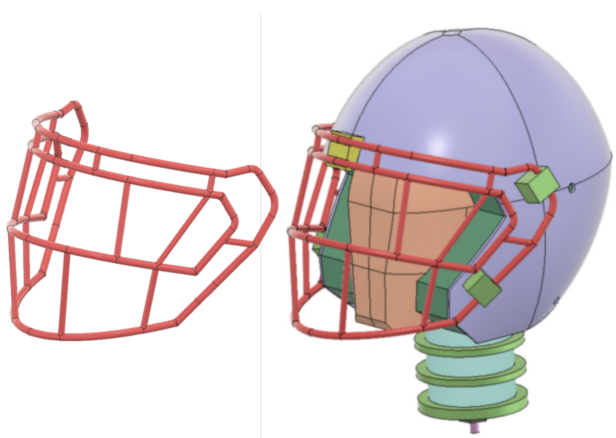

**Figure 9. Head-neck and football helmet model.** Fusion 360™ model: Facemask is 3-dimensionally modeled.

| | Translation acceleration Concussion risk (%) | Rotation acceleration Concussion risk (%) |
|---|---|---|
| Titanium facemask | 70 | 65 |
| Hybrid facemask 1 | 20 | 10 |
| Hybrid facemask 2 | 25 | 20 |

**Table 1: Estimated concussion risk.** Concussion risks based on the prediction curve of Pellman *et al.* (6) and Zhang *et al.* (5)

Research on facemasks is a new approach to study helmets. Simulations inevitably include assumptions, so a physical experiment would be essential to validate the polycarbonate facemask concept. In these physical experiments, the pneumatic ram impact test is a standardized test, and head acceleration data can be collected for various facemasks. Also, these tests can confirm if there is any serious break in the facemask caused by the ram, which the simulation was not able to identify due to theoretical limits and model simplification. Although the hybrid facemask concept came from research that shows a structure having an interface between two different parts or materials can improve the toughness of the system by preventing crack propagation, it was not possible to evaluate its failure mode at the interface in the simulation due to the linear material property (15, 16). Any failure can be examined in the physical impact test, enabling a more reliable and practical validation of the hybrid facemask. Head position is adjustable in the ram impact test, and different impact positions and angles can be set as the NFL test protocol. Thanks to recent 3D printing technology, polycarbonate plastic material is 3D printable (16), so the actual facemask part could be built easily for the initial testing. Once the test results of polycarbonate facemasks are available, they can tell any design issues and help improve the design with additional simulations. Furthermore, if the actual test result is positive, this study can be extended to other football helmets popular with professional players.

## MATERIALS AND METHODS

The NFL provides open-source simulation data of the head-neck and football helmet model (10-12). The data is for LS-Dyna software, which is not a design software but a simulation-only software. As Fusion 360™ is cloud-based design and simulation software, a new three-dimensional model was created with it using outline dimension data measured from the open-source data in LS-PrePost software which is free to use (**Figure 9**). The focus of this research was a facemask, and so it was designed in more detail while padding, neck, and a head joint were simplified. Chinstrap was included in the simulation using rigid body connectors, which is a one-dimensional element.

The material database is available in Fusion 360™, and material for each component was selected and assigned from the database. Rubber material was applied to head skin, soft neck discs, an inner ram impactor, and helmet padding. Steel was applied to a ram impactor, a neck cable, and a neck joint. Clips and solid neck discs had aluminum material, and an impactor front cap had Nylon 6/6 plastic material (10-12). Titanium or polycarbonate material was assigned to the facemask, and steel was applied to thin wires in the hybrid facemask. The default material properties were used, and those are linear. the skull was set to be rigid, which means no deformation is allowed.

The event simulation function of Fusion 360™ was used, and the event time was set to 0.03 s because of the computing time limit of the software. Interaction between components during the collision was treated with the automatic contact function of the software. The bottom of the neck was fixed, and the initial velocity was set to 5.5 m/s on the ram and 9.3 m/s on the striker model. The damping effect was included in the simulation, and the software provides Rayleigh damping control. The mass coefficient of Rayleigh damping was set to 80 based on the ram impact simulation with the head-neck model only. Head acceleration from 80 was compared with the actual test result from Bruneau *et al*. (13), and the selected coefficient value showed the best agreement. The linear tetrahedral mesh was used and generated automatically by the software. For the hybrid facemask simulation, impact event time was limited to 0.015 s because the maximum computing time for the software is 12 h. The hybrid facemask required computing time longer than 12 h to exceed a 0.015 s event time due to a large number of elements.

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