

Comparing the Performance of American Football Helmet Materials Using Finite Element Simulation

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ABSTRACT

Concussions remain a major safety concern in the NFL, where player-to-player and head-to-ground impacts can generate substantial head loading. Building on a prior video-analysis project that identified common concussion mechanisms and impact locations, this study used finite element simulations in Autodesk Fusion 360 to evaluate how helmet materials affected force transmission to a simplified headform. Expanded polypropylene (EPP) and expanded thermoplastic polyurethane (E-TPU) padding were compared under low-, medium-, and high-magnitude prescribed frontal, side, and rear loads. Polycarbonate (PC) and high-strength polycarbonate (HS-PC) shells were compared under frontal loading. Outputs included peak headform contact force, peak linear acceleration, and total padding displacement. Compared with EPP, E-TPU reduced peak headform contact force by 30–53% under frontal loading and 41–48% under side loading. The largest acceleration reduction (60%) occurred under high-magnitude side loading, accompanied by a 50% increase in padding displacement. The high-magnitude rear-impact E-TPU simulation did not converge due to excessive padding compression. PC and HS-PC produced nearly identical frontal-force results. Because the model used simplified geometry and constraints, omitted rotational motion, and lacked experimental validation, these findings represent relative material comparisons rather than concussion-risk predictions. The results support further testing of zoned or multilayer EPP/E-TPU padding systems to balance lower peak loading with controlled deformation.

KEYWORDS

concussion, EPP, E-TPU, finite element simulation, impact attenuation

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Abstract

Concussions remain a major safety concern in the NFL, where player-to-player and head-to-ground impacts can generate substantial head loading. Building on a prior video-analysis project that identified common concussion mechanisms and impact locations, this study used finite element simulations in Autodesk Fusion 360 to evaluate how helmet materials affected force transmission to a simplified headform. Expanded polypropylene (EPP) and expanded thermoplastic polyurethane (E-TPU) padding were compared under low-, medium-, and high-magnitude prescribed frontal, side, and rear loads. Polycarbonate (PC) and high-strength polycarbonate (HS-PC) shells were compared under frontal loading. Outputs included peak headform contact force, peak linear acceleration, and total padding displacement. Compared with EPP, E-TPU reduced peak headform contact force by 30–53% under frontal loading and 41–48% under side loading. The largest acceleration reduction (60%) occurred under high-magnitude side loading, accompanied by a 50% increase in padding displacement. The high-magnitude rear-impact E-TPU simulation did not converge due to excessive padding compression. PC and HS-PC produced nearly identical frontal-force results. Because the model used simplified geometry and constraints, omitted rotational motion, and lacked experimental validation, these findings represent relative material comparisons rather than concussion-risk predictions. The results support further testing of zoned or multilayer EPP/E-TPU padding systems to balance lower peak loading with controlled deformation.

Keywords: concussion, EPP, E-TPU, finite element simulation, impact attenuation

Comparing the Performance of American Football Helmet Materials Using Finite Element Simulation

As the NFL expands globally and football remains widely played across the United States, player safety is a continuing priority (Azzoni, 2025; National Football League [NFL], n.d.). Concussions remain a major safety concern in the NFL and in American football. The NFL reported 182 concussions during the 2024 season, approximately 14% below the average of the previous five seasons, but these injuries still occur frequently from both helmet-to-helmet and head-to-ground impacts (NFL, 2025a, 2025b). High-speed helmet impacts have also been reported as about 26 times more likely to result in a concussion than lower-speed impacts, highlighting the importance of impact mechanics and safety-equipment design (Carroll, 2025). Beyond the immediate injury, repeated head trauma can contribute to long-term neurological conditions such as chronic traumatic encephalopathy (CTE) (Centers for Disease Control and Prevention [CDC], 2024; McKee et al., 2016). For these reasons, reducing impact forces transmitted to the head is a critical goal.

A concussion is a form of mild traumatic brain injury caused by biomechanical forces. Symptoms can include confusion, blurred vision, nausea, memory problems, headache, and loss of consciousness (Mayo Clinic Staff, 2026b). Clinicians diagnose concussions primarily through clinical evaluation because CT and MRI scans generally identify structural injury rather than confirm a concussion (Mayo Clinic Staff, 2026a). Most athletes recover, although symptoms can persist in some cases. Long-term exposure to repeated head impacts is associated with chronic traumatic encephalopathy (CTE) (CDC, 2024; McKee et al., 2016). CTE was identified in 345 of 376 donated brains from former NFL players in one study sample; however, because the donors were not randomly selected, this percentage should not be interpreted as the prevalence of CTE

among all former NFL players (Boston University Chobanian & Avedisian School of Medicine, 2023).

Football helmets reduce transmitted loading by distributing contact through the outer shell and deforming the internal padding. As helmet performance standards and testing methods improve, evaluating the materials responsible for load distribution and impact attenuation remains an important design question (NFL, 2025b; National Operating Committee on Standards for Athletic Equipment [NOCSAE], n.d.). This study evaluates relative changes in modeled force, acceleration, and displacement; it does not directly predict concussion probability.

A prior video-analysis project classified NFL concussion events by impact type, impact location, and player position (Sayde, 2024). Related research has examined positional differences in impact biomechanics in Canadian collegiate football (D’Amario et al., 2025). The present study used the prior video-analysis project only to prioritize frontal, side, and rear loading regions, along with the shape of the magnitude curve. This paper did not reanalyze the video data, so the conclusions are based on the simulation results.

Objective, Scientific Question, and Hypothesis

The objective of this project was to compare how helmet shell and padding materials affected force transmission to a headform under controlled prescribed loading. The scientific question was: How do EPP and E-TPU padding materials affect peak headform force, linear acceleration, and padding displacement under frontal, side, and rear prescribed loads, and how do PC and HS-PC shells compare under frontal loading? The hypothesis was that E-TPU padding would reduce peak headform force and linear acceleration relative to EPP by permitting greater deformation, while PC and HS-PC shells would produce smaller differences when geometry and padding were held constant.

Methods

Study Design and Variables

This study used a finite element simulation design. The independent variables were padding material (EPP or E-TPU), shell material (PC or HS-PC), loading direction (frontal, side, or rear), and prescribed load magnitude (low, medium, or high). The dependent outputs were peak headform force, peak linear headform acceleration, and total padding displacement. Controlled factors included the headform, helmet geometry, simulation software, time scale, boundary conditions, contact settings, and load-time history.

Autodesk Fusion version 2605.1.52 arm64 (Student License) was used with Dynamic Event Simulation. Fusion 360 was used to import the helmet and headform geometries, assign materials, define contacts and constraints, apply the prescribed load-time histories, generate the mesh, and extract the modeled outputs.

The base football-helmet model was obtained from the Autodesk Community Gallery (jgavinOTC, 2017). The helmet dimensions were 176.341 mm × 219.799 mm × 233.294 mm, with a shell thickness of 4.990 mm and padding thickness of 12.141 mm. The shell and padding were treated as separate components. The headform model was a 50th-percentile male head scan obtained from Thingiverse (PearlGreyMusic, 2021), with dimensions of 178.429 mm × 225.000 mm × 287.357 mm. Because only one head size and geometry were used, the model does not represent the full range of football-player head sizes and helmet fits.

Materials, Contacts, and Constraints

The shell materials were standard polycarbonate and high-strength polycarbonate. The padding materials were expanded polypropylene and expanded thermoplastic polyurethane. EPP

and E-TPU were modeled with nonlinear behavior so that material stiffness could change with strain and pressure. Material properties are summarized in Table 1.

Table 1

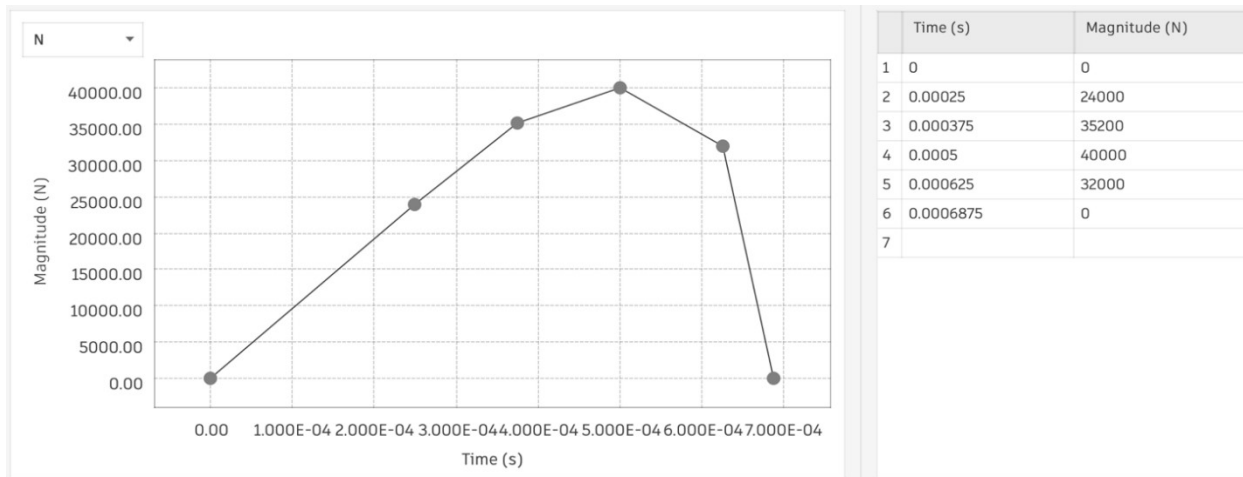
Properties of Each Material Within the Helmet

Material	Density (g/cm³)	Young's modulus (GPa)	Poisson's ratio	Yield strength (MPa)	Damping coefficient
EPP	0.05	0.02	0.25	0.515	0.15
E-TPU	0.015	0.01	0.35	1	0.18
PC	1.2	2.275	0.38	62.01	0
HS-PC	1.2	2.6	0.37	70	0

The headform was placed inside the helmet, and Fusion 360 global contact settings defined interactions among the shell, padding, and headform. The base of the headform was constrained to represent neck support while allowing the helmet to respond to the applied load.

Prescribed Loading and Mesh

A force-time history was applied to a selected frontal, side, or rear region of the helmet shell. Because the model prescribed force rather than an impactor velocity, the cases are described as low-, medium-, and high-magnitude loads rather than low-, medium-, and high-speed impacts. The low- and medium-magnitude curves were 25% and 50%, respectively, of the high-magnitude curve. The high-magnitude curve reached 40,000 N at 0.5000 ms and returned to zero at 0.6875 ms (Figure 1). The curve shape was based on prior impact-loading research (Bagherian et al., 2025; Chatham et al., 2025; Corrales et al., 2020).

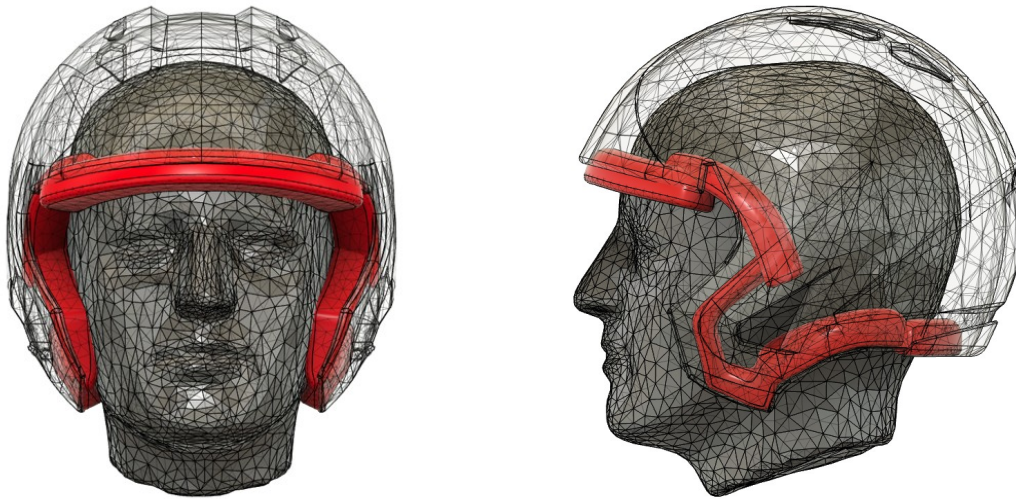
Figure 1*High-Magnitude Prescribed Load–Time History*

Note. The medium- and low-magnitude cases used 50% and 25% of this force magnitude, respectively.

The mesh was refined near the loaded region and was coarser in non-impacted regions to reduce computation time. Mesh size was scaled to part size using a 10% model-based setting. The reported mesh contained 4,475 faces and had a maximum element size of 24.708 mm. The generated mesh is shown in Figure 2.

Figure 2

Generated Mesh for the Impact Simulations in Front and Side Views



Outputs and Comparisons

For each completed simulation, the recorded outputs were peak force at the headform, peak linear headform acceleration, and total padding displacement. The same geometry, prescribed load, constraints, and contact setup were used when comparing materials, and only one material variable was changed at a time. Percentage reductions in force and acceleration were calculated relative to EPP, while percentage increases in displacement were calculated relative to EPP. Each condition produced one deterministic simulation result; therefore, no statistical significance tests were applied. Example simulation output visualizations are provided in the Appendix (Figures A1 and A2).

Results

Padding Performance

Across most comparable runs, expanded thermoplastic polyurethane (E-TPU) reduced peak headform contact force and peak headform acceleration compared to expanded polypropylene (EPP), but typically produced equal or larger padding displacement, meaning the

E-TPU padding compressed more. This suggests E-TPU reduced transmitted peak loads by increasing the cushioning stopping distance (the padding gives the head a longer distance and time to slow down due to higher compression).

Front Loading

For frontal impacts, E-TPU produced lower peak headform force than EPP at all three frontal load magnitudes (Figure 3).

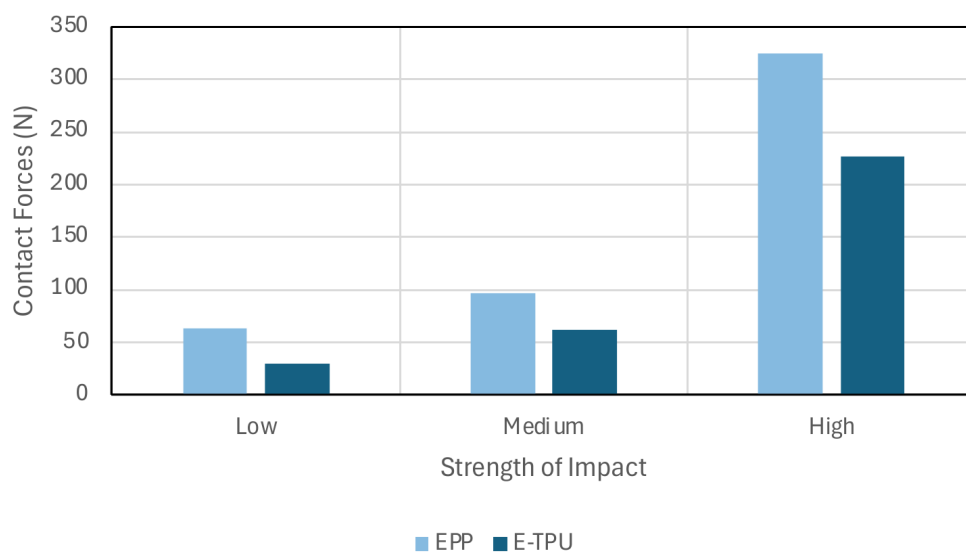
- Low: EPP = 63.0 N vs. E-TPU = 29.6 N (E-TPU 53% lower).
- Medium: EPP = 96.5 N vs. E-TPU = 62.0 N (E-TPU 36% lower).
- High: EPP = 323.9 N vs. E-TPU = 227.2 N (E-TPU 30% lower).

Peak linear acceleration was lower with E-TPU in the low- and high-magnitude cases but was nearly identical in the medium-magnitude case (Figure 4). The high-magnitude result acceleration decreased from 16.7 m/s² with EPP to 8.4 m/s² with E-TPU, a reduction of approximately 50%.

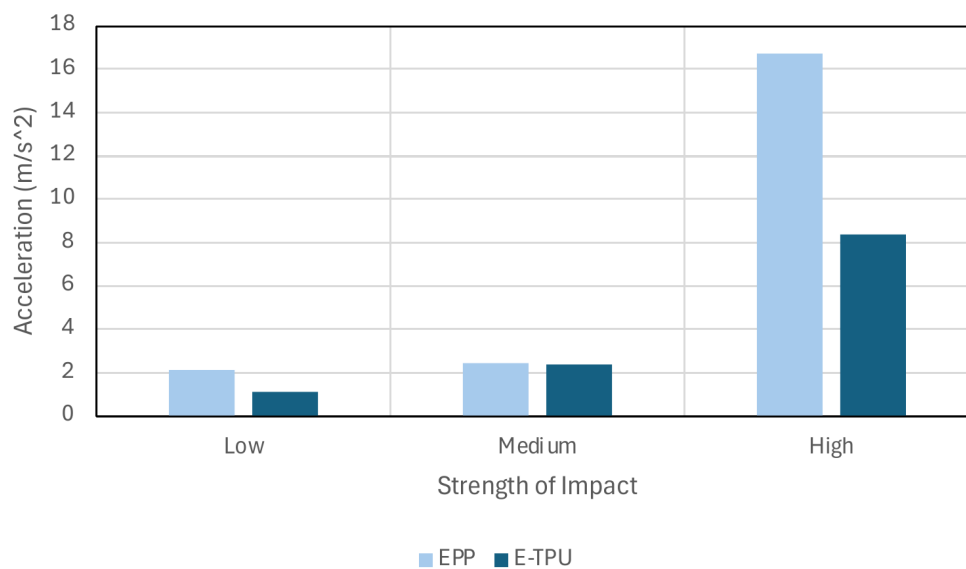
Padding displacement was 16% greater with E-TPU at the low magnitude and differed by less than 2% at the medium and high magnitudes.

Figure 3

Headform Contact Force Under Frontal Loading by Magnitude and Padding Material

**Figure 4**

Peak Linear Headform Acceleration Under Frontal Loading by Magnitude and Padding Material



Rear Impacts

For rear impacts, E-TPU reduced headform contact forces in the completed low- and medium-magnitude cases (Figure 5):

- Low: EPP = 37.6 N vs. E-TPU = 27.5 N (E-TPU 27% lower).
- Medium: EPP = 92.3 N vs. E-TPU = 34.5 N (E-TPU 63% lower).

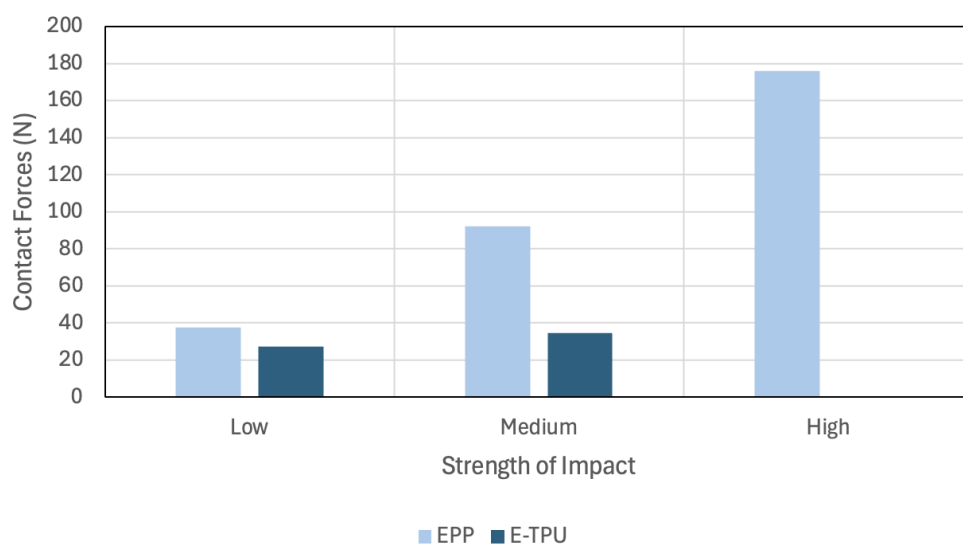
At the medium magnitude, total padding displacement increased from 2.91 mm with EPP to 5.30 mm with E-TPU, an increase of approximately 82%.

The high-magnitude rear E-TPU simulation did not converge due to excessive compression, so a direct high-speed back comparison was not available. This suggests that, in this configuration, the E-TPU padding model may have reached an extreme compression condition during the high-speed rear impact.

Rear acceleration was lower with E-TPU in the low-magnitude case (1.61 versus 0.96 m/s²; Figure 6) and nearly identical in the medium case (2.09 m/s² for both materials). A high-magnitude acceleration comparison was not available because the E-TPU run did not converge.

Figure 5

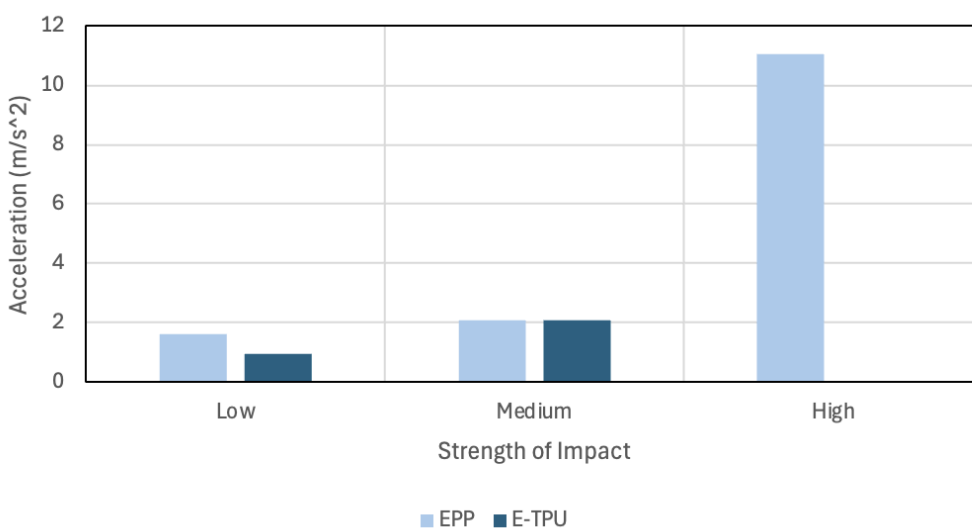
Headform Contact Force Under Rear Loading by Magnitude and Padding Material



Note. The high-magnitude E-TPU result is not shown because the simulation did not converge.

Figure 6

Peak Linear Headform Acceleration Under Rear Loading by Magnitude and Padding Material



Note. The high-magnitude E-TPU result is not shown because the simulation did not converge.

Side Impacts

For side impacts, E-TPU showed the largest improvements in acceleration and contact forces reduction across all magnitudes but also showed increased displacement at higher load magnitudes (Figures 7 and 8).

- Low: EPP contact = 137.4 N vs. E-TPU contact = 72.3 N (E-TPU 47% lower).
- Medium: EPP contact = 219.0 N vs. E-TPU contact = 114.0 N (E-TPU 48% lower).
- High speed: EPP contact = 314.6 N vs. E-TPU contact = 185.2 N (E-TPU 41% lower).

Peak linear acceleration was also lower with E-TPU at each side load magnitude, with reductions of approximately 53%, 54%, and 60% from low to high loading (Tables 2 and 3). The largest reduction occurred at high magnitude, where acceleration decreased from 34.9 m/s² to 13.9 m/s².

E-TPU also produced greater total padding displacement in the side cases. Relative to EPP, displacement increased by approximately 22% at low loading, 29% at medium loading, and 50% at high loading. The high-magnitude values were 12.7 mm for EPP and 19.0 mm for E-TPU (Tables 2 and 3).

Table 2*Simulation Results by Load Magnitude and Location for EPP*

Location	Load magnitude	Peak acceleration (m/s²)	Contact force (N)	Displacement (mm)
Frontal	Low	2.12	63.00	2.75
Frontal	Medium	2.42	96.46	5.30
Frontal	High	16.69	323.93	14.17
Side	Low	9.23	137.41	2.26
Side	Medium	21.95	219.05	4.57
Side	High	34.94	314.64	12.66
Rear	Low	1.61	37.56	1.87
Rear	Medium	2.09	92.26	2.91
Rear	High	11.06	176.14	6.32

Table 3*Simulation Results by Load Magnitude and Location for E-TPU*

Location	Load magnitude	Peak acceleration (m/s²)	Contact force (N)	Displacement (mm)
Frontal	Low	1.14	29.57	3.20
Frontal	Medium	2.37	62.04	5.29
Frontal	High	8.40	227.23	14.38
Side	Low	4.35	72.30	2.76
Side	Medium	9.99	113.97	5.91
Side	High	13.91	185.17	19.03
Rear	Low	0.96	27.49	2.07
Rear	Medium	2.09	34.65	5.30
Rear	High	NC	NC	NC

Note. NC = no convergence. The high-magnitude rear-loading E-TPU simulation did not converge.

This indicates E-TPU can reduce peak forces in side impacts by allowing greater compression, but it also increases the risk of excessive compression. If the padding compresses too much, it may stop behaving like a cushion and allow a more direct load transfer to the head.

Figure 7

Headform Contact Force Under Side Loading by Magnitude and Padding Material

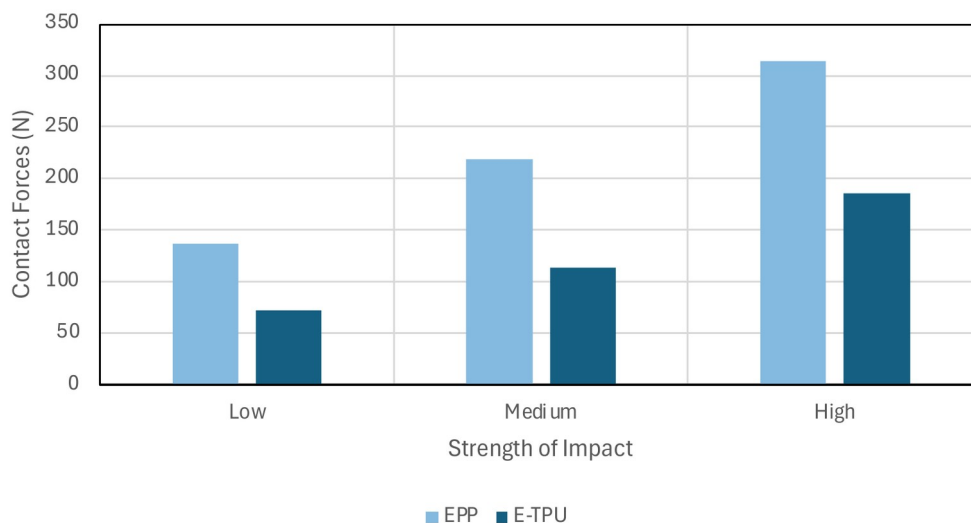
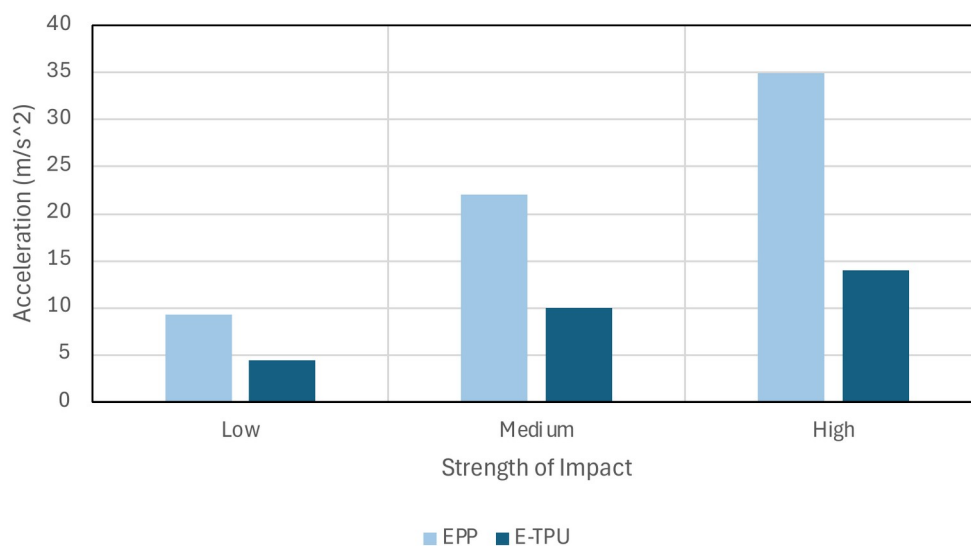


Figure 8

Peak Linear Headform Acceleration Under Side Loading by Magnitude and Padding Material



Summary of Padding Effects

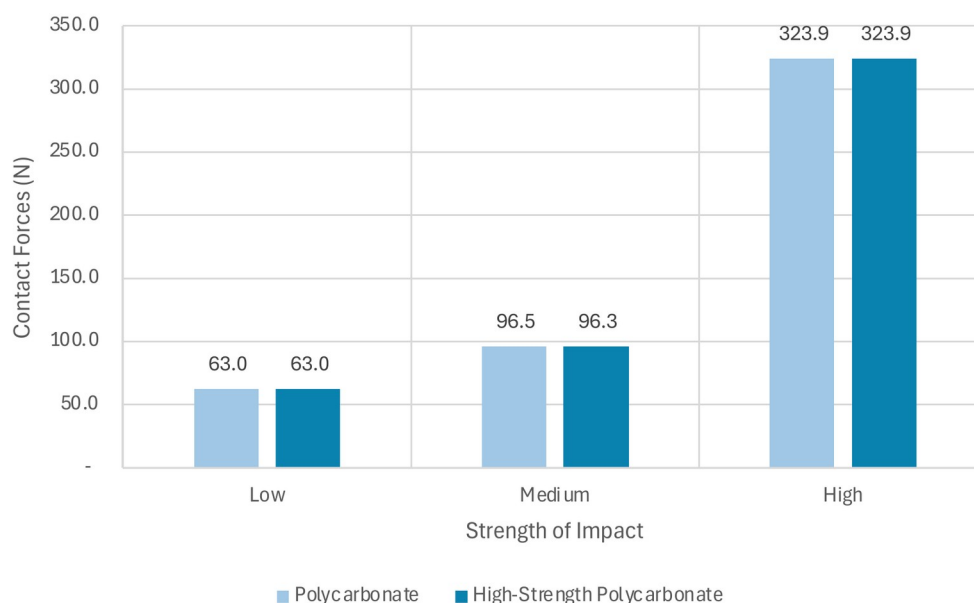
In summary, E-TPU generally reduced peak headform contact forces by about 30–53% (front) and 41–48% (side) across all speeds, with the most dramatic acceleration reductions occurring in the high-speed side impact case (60% lower than EPP). Additionally, back impacts showed strong force reductions at medium speed but also revealed excessive compression at high speeds.

Shell Material Comparison

The results for the frontal helmet impact were nearly identical when comparing standard polycarbonate (PC) to high-strength polycarbonate (HS-PC). Across the runs, the peak headform contact forces, peak headform accelerations, and peak padding displacements were essentially the same, with HS-PC only showing a very slight reduction in contact force (< 1 N) (Figure 9). This strongly suggests that, under the specific conditions of this simulation, changing the shell material from PC to HS-PC does not meaningfully change the force transmitted to the headform in a frontal hit.

Figure 9

Headform Contact Force Under Frontal Loading by Magnitude and Shell Material



Discussion

Padding Material Response

Across all converged frontal and side cases, E-TPU reduced peak headform force relative to EPP. E-TPU also reduced peak linear acceleration in most cases, with the clearest reductions occurring in side loading and in the high-magnitude frontal case. These results suggest that the modeled E-TPU configuration attenuated peak loading more effectively than the modeled EPP configuration under those conditions.

E-TPU generally showed equal or greater total displacement, especially during side loading. Greater displacement may indicate that the padding deformed over a longer stopping distance. However, the high-magnitude rear-impact E-TPU simulation did not converge because of excessive material compression, preventing a direct comparison under the high-speed rear-impact condition. This suggests that, in the modeled configuration, the E-TPU padding reached an extreme level of compression during the high-speed impact. At such high compression levels,

the padding may approach or reach densification, substantially reducing its ability to deform further and absorb impact energy. Consequently, beyond a certain impact-force magnitude, additional loading may be transmitted more directly through the compressed padding, limiting its effectiveness in attenuating peak forces.

Shell Material Response

The nearly identical PC and HS-PC results may indicate that the padding controlled much of the recorded headform response, meaning most of the impact energy was managed by the compression and behavior of the padding rather than shell flex or shell strength. In other words, if the foam is absorbing most of the energy and controlling the path of forces into the headform, then smaller increases in shell stiffness or yield strength (like the difference between HS polycarbonate and polycarbonate) may not noticeably change peak force or acceleration at the headform. However, in a real concussion scenario, shell material can still matter even if the numbers are similar in a simulation. A stiffer/stronger shell may spread contact over a slightly larger area, resist cracking better over repeated impacts, and potentially allow a thinner/lighter shell for the same durability. This would reduce the weight of the helmet and its inertia, which could lower rotational effects and neck strain in some plays. That means HS polycarbonate could still be beneficial for positions with frequent impacts (LB/TE) or high-speed open-field collisions (WR/DB), not necessarily because it dramatically reduces peak force in a single frontal collision, but because it may improve durability, reduce weight, and maintain performance over repeated high-speed hits.

Study Limitations

- The model used simplified downloaded helmet and headform geometries and only one head size.

- The headform base was constrained and did not include a validated neck model.
- Only linear acceleration was examined; rotational velocity, angular acceleration, and brain strain were not modeled.
- The load cases were prescribed force-time histories rather than impacts defined by a measured mass and velocity.

For these reasons, the performed simulations may not fully reflect real-world impact conditions. However, their primary value lies in comparing the relative performance of material configurations under the model conditions. The model should therefore be interpreted as an exploratory comparison tool, and its results should not be used to predict concussion probability or to claim that a material prevents concussion.

Design Implications and Position-Specific Hypotheses

The combination of the prior video-analysis project and the present simulation results motivates future testing of zoned or multilayer padding. A design could place a more deformable material in frontal and side regions while using a more compression-stable layer or material in the rear.

Based on last year's concussion-incident patterns (frequent wide receiver injuries and many back-to-ground hits) and this year's simulation results (E-TPU reduced peak loads in many cases but showed higher compression in rear impacts), a practical real-world approach that needs to be explored is zoned or position-specific helmet padding design.

Wide Receivers (WR): prioritize rear-impact and fall protection. Many WR concussion events involve falling while tracking and catching the ball, often leading to back-of-helmet ground contact. In this study, E-TPU showed signs of excessive compression and instability in high-speed back impacts, which suggests a WR-optimized configuration should emphasize rear

stability and reduce excessive compression risk. These results motivate future testing of WR helmets that use EPP padding to reduce the risk of excessive compression in severe rear impacts.

Cornerbacks (CB) and Safeties (S): prioritize side-impact mitigation. Defensive backs frequently experience side impacts in open-field tackling and collisions at angles. E-TPU produced some of the greatest improvements in side impacts, including a major reduction in headform acceleration at high speed. The results motivate future testing involving CB/S helmets, which could strongly consider E-TPU padding to reduce peak head loading during impacts.

Running Backs (RB): prioritize front and side impacts. RBs often experience impacts from multiple directions, including frontal and side hits while accelerating through gaps. E-TPU showed consistent reductions in peak force transfer in frontal and side impacts, making it a strong candidate for RB-focused designs. The results motivate future testing involving RB helmets, which could focus on E-TPU padding in regions prone to frontal and side impacts to reduce peak forces and accelerations transmitted to the headform.

Conclusions

Within the assumptions of this simplified computational model, padding material had a larger effect on the recorded headform-loading metrics than shell material. E-TPU produced lower peak headform force than EPP in every converged frontal and side case and reduced linear acceleration most strongly under side loading. E-TPU also produced greater displacement in several cases, especially at the side of the helmet. However, E-TPU padding reached an extreme level of compression during the high-speed rear impact. This might limit its effectiveness in attenuating peak forces. In addition, PC and HS-PC produced nearly identical frontal-force results.

The strongest design implication is that zoned or multilayer EPP/E-TPU systems are reasonable candidates for further validated testing. Such testing should determine whether a combined design can preserve the lower peak loading observed with E-TPU while limiting excessive deformation and improving rear-impact stability.

Further work, including the incorporation of rotational motion into the simulations and experimental validation, is needed before conclusions can be drawn regarding the effectiveness of the tested materials in reducing concussion risk.

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Appendix

Finite Element Headform Simulation Result Visualizations

Figure A1

Example Headform Contact Force Output

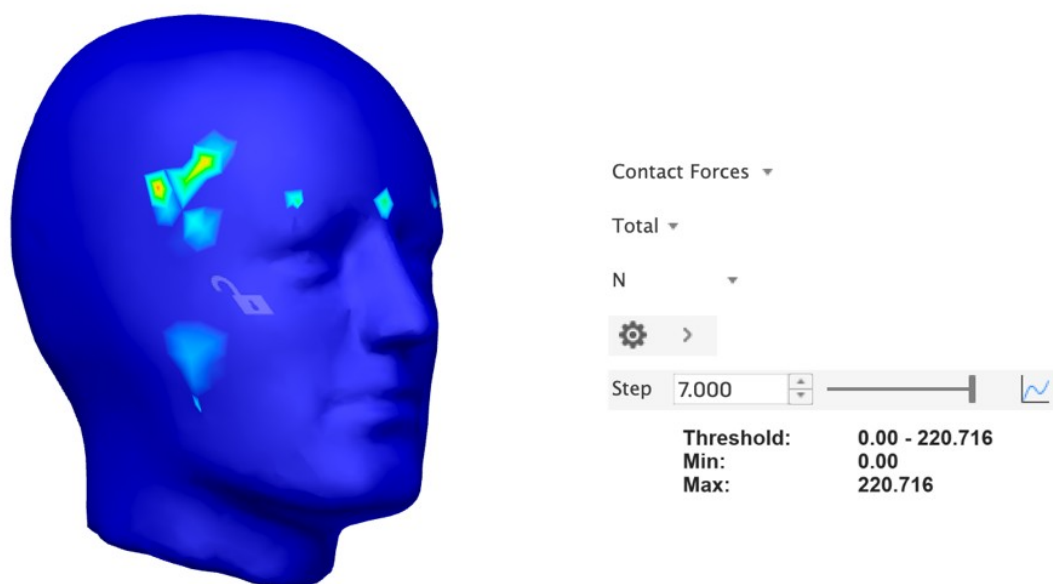


Figure A2*Example Headform Acceleration Output*