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# Cushioning Effect of Conventional Padded Helmets on Interaction between Cerebrospinal Fluid and Brain after a Low-Speed Head Impact

**Faiz Syed [1], Elisabeth Frankini [1], Kelsi Hurdle [2], Jodan Garcia [3], Rosalyn Chan-Akeley [4] and Milan Toma [1,*]**

1 Department of Osteopathic Manipulative Medicine, College of Osteopathic Medicine, New York Institute of Technology, Old Westbury, NY 11568, USA
2 Department of Anatomy, College of Osteopathic Medicine, New York Institute of Technology, Old Westbury, NY 11568, USA
3 Byrdine F. Lewis College of Nursing and Health Professions, Georgia State University, Urban Life Building, Suite 1280, Atlanta, GA 30303, USA
4 Lang Research Center, NewYork-Presbyterian Hospital Queens, New York, NY 11355, USA
* Correspondence: tomamil@tomamil.com

**Abstract:** Results of a recent experimental study challenge the widely-held belief that modern combat helmets are more effective at protecting soldiers against concussions. The research shows that helmets used during First World War without inner paddings may have an advantage in protecting soldiers' brains from concussions when relying solely on cerebrospinal fluid. The present study explains this counterintuitive finding by revealing that while cerebrospinal fluid can prevent direct brain-to-skull contact during a single event, its protective capabilities diminish with each subsequent event occurring in quick succession—something conventional padded helmets appear to aggravate. The cerebrospinal fluid requires a certain amount of time to reset after an acceleration/deceleration event, which allows it to effectively provide cushioning for any subsequent events and protect against potential brain damage. However, an immediate occurrence of a subsequent event, when the fluid has no time to settle down, may significantly diminish the effectiveness of the fluid's ability to provide adequate cushioning, thereby putting individuals at risk of serious injury. This new information may have implications for helmet design in the future and calls into question current assumptions regarding the best way to protect soldiers and athletes from concussions.

**Keywords:** fluid-structure interaction; cerebrospinal fluid; head; brain; Helmet; impact; concussion



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## 1. Introduction

Helmet use in sports has been controversial during the early years, but now it is universally accepted that helmets protect players from severe injuries and death. While there is no doubt about the safety offered by protective gear, concerns remain regarding how effective helmets are at preventing concussions/contusions [1]. While there have been personal anecdotal accounts suggesting that certain helmet designs may worsen concussions, these claims are not sufficient to determine the effectiveness of protective gear. It is important for individuals to make informed decisions when selecting helmets and other equipment based on scientific evidence and expert recommendations. Helmets are crucial for the safety of athletes in various sports. The specific design and features of a helmet depend on the athletic activity involved, as seen in football, cycling, or equestrian horse riding. While some designs may focus on preventing skull fractures and maximizing aerodynamics, others have different priorities based on their usage [2]. For example, while football helmets aim at preventing severe head injuries, equestrian helmets prioritize ventilation and temperature control for enhanced rider experience [3,4]. Regardless, it is essential to remember that after taking an impact even once while wearing a helmet meant for single use, that helmet must be replaced immediately with another one to ensure optimal protection during future activities [5,6]. In summary, the use of helmets is a crucial aspect of sports safety that should not be overlooked or dismissed lightly.

Chronic Traumatic Encephalopathy (CTE) poses a serious threat to those who suffer from repetitive head traumas such as concussions or sub-concussions [7]. This deadly degenerative brain disease damages important regions such as the entorhinal cortex hippocampus and amygdala, leading patients towards several severe symptoms including mood changes, depression, anxiety, short-term memory loss, behavioral issues, and speech difficulties, which eventually affect their day-to-day activities on a long-term basis [8]. Unfortunately, CTE is often only diagnosed posthumously making it difficult to determine the prevalence of the disease in living individuals. The lack of diagnosis during an individual's lifetime makes it harder for health experts and researchers alike furthering the need for extensive research toward preventative measures such as wearing a helmet during contact sports and other high-risk activities. Conclusively, the frequent collisions and physical contact involved in American Football make it a dangerous sport for players. The nature of the game makes it inevitable for athletes to sustain acceleration-deceleration forces that can lead to concussions or contusions in their brains. A study on 202 deceased football players found that 87% exhibited signs of CTE, with the majority showing severe symptoms such as dementia. However, the researchers noted a potential sample bias in their findings [9]. Despite the limitations of that study, it is clear that there is a significant correlation between football and CTE. This highlights the need for further research into preventative measures and better protection for athletes who participate in contact sports. Additionally, increased awareness among both players and coaches about potential risks can help minimize the long-term health effects associated with participation in these activities. Overall, more needs to be done to protect those who put their bodies on the line while playing sports at all levels.

Research has demonstrated that rotational acceleration is responsible for generating shear force in the brain, which is strongly associated with concussions [10]. Additionally, studies have shown that impacts to the front of the head produce the highest amounts of rotational acceleration and that hits to the top of the head result in a higher rate of concussions per impact during football matches [11]. The research on CTE in football players has highlighted concerns regarding the effectiveness of modern helmets. Studies conducted by bioengineering labs have revealed that current helmet designs do not provide sufficient protection against concussions and long-term neurological disorders such as CTE [12]. Therefore, it is essential to explore innovative technologies and analyses for designing new helmets that can offer better safety outcomes for athletes participating in contact sports such as football.

The ASTM (American Society for Testing and Materials) International meetings are important forums for the discussion of technical standards concerning a wide range of materials, products, systems, and services. In particular, these meetings provide an essential platform for the development and refinement of helmet standards, which play a critical role in ensuring safety across various industries. While it may not have been officially acknowledged in the past, helmet manufacturers and developers now recognize that traditional helmets are not adequate for protecting against concussions. Therefore, their latest designs concentrate on providing enhanced protection to prevent this type of injury. The grading system established by the American National Standards Institute (ANSI) provides consumers with a way to determine the level of protection provided by hard-capped sporting helmets [13]. This information is crucial in ensuring that individuals make informed decisions when selecting helmets for various activities and sports. By following ANSI guidelines, consumers can feel confident in their helmet choices and be better equipped to protect themselves from potential head injuries during athletic endeavors.

While there have been numerous studies on the effectiveness of contemporary military combat helmets in preventing traumatic brain injury [14–16], very few have attempted to compare them with historical helmets. However, a recent study by Op't Eynde et al. (2020)

compared various combat helmets from both eras and found that modern helmets did not provide significantly better protection than their historical counterparts when subjected to overhead blasts from cylindrical shock tubes [17]. In fact, some of the older designs actually performed even better in terms of pressure attenuation, see Figure 1. Military helmets undergo rigorous testing to ensure they meet standards for protection against a variety of injuries. The blunt impact is one such injury which is tested through the measurement of linear headform acceleration in drop tower tests designed specifically to evaluate their ability to protect against skull fracture [17]. Additionally, these helmets must also provide adequate ballistic and blast protection to keep our servicemen and women safe on the front lines.

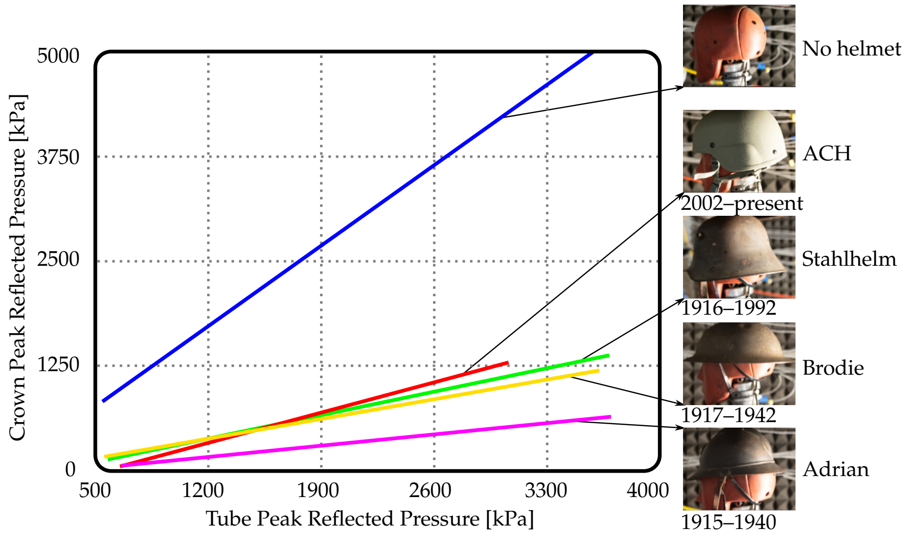



**Figure 1.** Experimental results (the linear regression fit for each helmet type) from a study by Op't Eynde et al. (2020) [17].

The widespread use of helmets in sports was not an immediate trend but instead emerged as a mandatory safety measure. Despite this mandate, many players were still resistant to wearing them and often signed waivers exempting themselves from doing so [18,19]. The most common reason for resistance among these players was overheating; however, there were no other major concerns mentioned regarding the lack of protection against concussions since such injuries did not occur frequently. Nevertheless, research in recent years has revealed that even minor head injuries can have long-term effects on an individual's cognitive abilities and mental health [20,21].

While helmets have been touted as a solution to prevent concussions, personal accounts from those who have experienced head injuries are crucial in assessing their efficacy. In the case of two jockeys who suffered concussions despite wearing helmets during an accident, it was noted that padded helmets may actually cause more harm than good by causing their heads to bounce more compared to the non-padded caps they had previously worn. The development of caps/helmets for jockeys is a relatively recent phenomenon and many riders have experienced wearing them both pre- and post-padding [22]. It cannot be assumed that the reported head bouncing inside the padded caps is inconsequential. In fact, some riders feel that they suffered more serious injuries in padded helmets than before their introduction. However, this alone does not necessarily mean the padding was to blame and further investigation is necessary to fully understand its impact on rider safety. These anecdotes highlight the need for further investigation and scrutiny into helmet design and its effectiveness in preventing concussion-related injuries. Overall, while helmets are an important safety measure, their effectiveness in preventing concussions is still being studied and debated.

It is possible that there may be some truth to the claims of individuals who have suffered more severe concussions while wearing padded helmets. Additionally, historical comparisons between combat helmet designs also provide support for this assertion. Therefore, further research is necessary to validate the hypothesis that head bouncing occurs in padded helmets and if it leads to potential injuries. The use of computational simulations can aid in confirming this theory. Additionally, understanding how such head bouncing impacts the brain is crucial for developing effective strategies to prevent concussion-related injuries among individuals who wear these types of helmets. In conclusion, more investigation into this topic is required before definitive conclusions can be drawn regarding its implications on helmet design and safety measures.

## 2. Materials and Methods

This section provides a thorough understanding of the materials and methods used in the study. The development process of the geometrical model is presented with detailed information on material properties. Computational methods are elaborated upon along with their validation process. Moreover, boundary conditions are discussed to provide an overall overview of the research methodology employed in this study.

### *2.1. Geometrical Model*

The head model used for this study is a comprehensive representation of the human brain and skull. The model consists of several parts, including the cerebrum, cerebellum, brainstem, and pituitary gland as well as fluid particles in the subarachnoid space to fill up gaps between different regions (Figure 2). Additionally, a two-layered helmet comprising thicker deformable padding and a thinner hard-shell cover is placed on top of the skull with no gaps to ensure snug fitment [23]. The realistic fit between the skull and deformable internal components of the helmet is achieved by assigning average reported dimensions (e.g., weight, thickness) and material properties to all its components [17,24]. The model is developed and validated through comparisons with cadaveric data and experiments, respectively, to ensure its accuracy and reliability [25]. The development of this patient-specific model is based on DICOM images from an online database. A 3D mesh is generated for an accurate representation of the individual's head anatomy for further analysis. Although some anatomical features are missing in this model, such as skin, spinal cord, meninges, and arachnoid granulation, it allows for precise evaluation of helmet design capabilities and improvements. Neglecting CSF flow (but not the CSF itself) is another simplification that does not impact overall accuracy or reliability when evaluating helmet designs. However, future models could benefit from including additional features to enhance accuracy and applicability toward more targeted helmet design optimization.

The simulation of the human brain and its interaction with the surrounding fluids/structures was achieved by modeling each component using various material properties based on the literature [26–30]. While the skull is assigned rigid material properties with a density of 1900 $kg{\cdot}m^{-3}$ [31], studies characterizing macroscopic physical characteristics have shown that the cerebrum, cerebellum, pituitary gland, and brainstem are viscoelastic materials [32]. To accurately model these components' behavior under different loading conditions, they are simulated using a non-linear elastic constitutive material model. Additionally, the smoothed-particle hydrodynamics (SPH) method, with a bulk modulus of 21.9 GPa [33] and density of 1000 $kg{\cdot}m^{-3}$ [34], is used to simulate CSF in the subarachnoid space between the skull and brain along with other cavities filled with fluid particles numbering 94,690. The different parts of the brain—cerebrum, cerebellum, brainstem, and pituitary gland—are made up of varying numbers of tetrahedral elements. Specifically, there are 96,385 tetrahedral elements in the cerebrum, 40,808 in the cerebellum, 18,634 in the brainstem, and 310 in the pituitary gland.

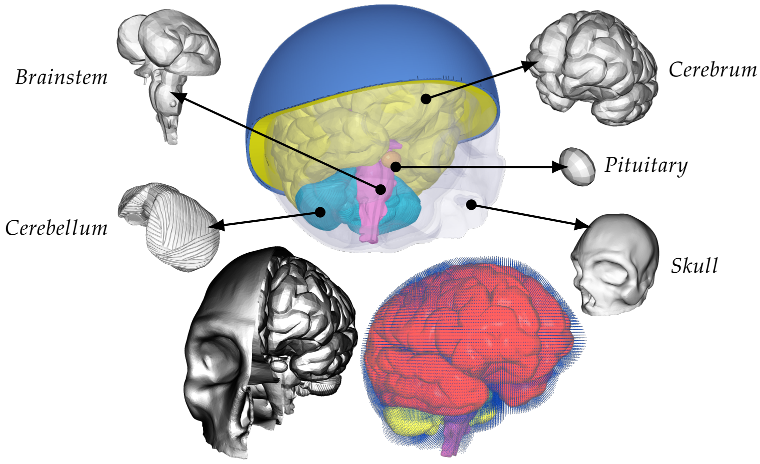



**Figure 2.** The model comprises different parts such as the skull, cerebrum, cerebellum, pituitary gland, and brain stem along with subarachnoid space and other cavities filled with fluid particles. Additionally, displayed is half of the skull to give better insight into its structure. The helmet included in the model has two layers; an outer hard-shell cover, colored blue, for protection, and inner padding, highlighted in yellow, for comfort purposes.

### *2.2. Computational Methods*

Smoothed-Particle Hydrodynamics (Figure 3) is a versatile computational method that was initially developed for astrophysical problems [35,36] but has found applications in many fields such as ballistics, volcanology, and oceanography [37]. With its ability to simulate the mechanics of continuum media including solid mechanics and fluid flows, it is becoming increasingly popular among researchers interested in biomedical engineering [38]. One of the promising applications of SPH in biomedical engineering is the study of the mechanism of traumatic brain injuries [39,40]. This study employed IMPETUS Afea Solver (IMPETUS Afea AS, Norway) to solve fluid motion and boundary interaction using SPH for the fluid domain and the high-order finite element method for the solid domain. The methodology has been described in detail in prior publications (e.g., [41]) which also validated the head model against cadaveric experimental data [25].

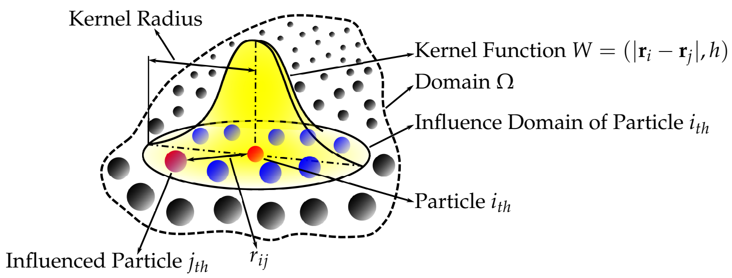



**Figure 3.** Smoothed-Particle Hydrodynamics Kernel approximation.

The IMPETUS Afea $\gamma$SPH Solver and IMPETUS Afea Solver were used to handle fluid motion and boundary interaction calculations as well as large deformations in solid parts, respectively. The advanced next-generation SPH method with increased accuracy was utilized by the $\gamma$SPH solver, while both solvers employed a commodity graphics processing unit (GPU) for parallel processing. Additionally, fully integrated solid elements were applied to eliminate hourglass modes and element inversion, which are common issues found in classic under-integrated elements. An explicit integration scheme was implemented to solve both fluid and solid domains along with their interactions. The $\gamma$SPH method is well-suited for complex applications due to its ability to account for movement in any direction and accurately model particle-to-structure contact. Unlike finite element fluid solvers that involve complicated contact and require remeshing of the fluid domain during simulation, IMPETUS provides a high resolution in terms of particle density. This feature makes it an invaluable tool for simulating helmet impacts on brain tissue, especially given the intricate structure of this organ.

The use of a Tesla K40 GPU with 12 GB of Graphic DDR memory and 2880 CUDA Cores has allowed for parallel acceleration in simulations. The resulting reduction in computation time is significant compared to traditional FSI techniques, taking only days instead of weeks. This advancement offers more efficient processing capabilities for complex engineering problems such as designing and analyzing safety equipment such as helmets for athletes, military and industrial workers.

### *2.3. Boundary Conditions*

This study aims to examine the interaction between the brain and skull under specific conditions resembling a low-speed head-on collision. The prescribed speed of 2 m·s$^{-1}$ is achieved through linearly increasing speed until it reaches this value, as shown by the solid blue line in Figure 4. After attaining stability at this constant speed, a sudden velocity drop to zero occurs before analyzing subsequent interactions. It is not uncommon for athletes to encounter these conditions in sports. Whether they collide with each other while running or suddenly stop after riding a bicycle leisurely into obstacles at similar speeds, it is important for athletes to be aware of the potential risks and take necessary precautions to avoid injury.

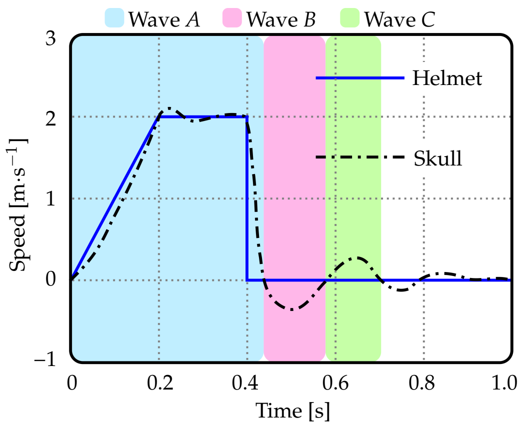



**Figure 4.** The non-solid padding in a helmet can cause oscillations of the skull when the helmet is subjected to prescribed speed (solid blue line). This is evident from the black dash-dotted line that represents the fluctuating speed of the skull inside the padded helmet.

## 3. Results

The results section presents a comprehensive analysis of various aspects related to skull and helmet motion. The first subsection highlights the relative motion between them by comparing their speeds (Figure 4). Subsequent sections delve into principal deviatoric stresses in different time instances and conditions, which are obtained through subtraction of mean stress from each principal stress. These stresses are derived from normal stress at an angle on a plane where shear stress is zero, with maximum and minimum values being considered for comparison purposes across various waves.

### *3.1. Relative Motion between the Helmet and Skull*

The deformable helmet padding results in relative movement between the head and helmet during changes in velocity. This can be observed in Figure 4, which shows the motion between the skull and helmet. The oscillations caused by this movement have a qualitative effect on the brain, as described in subsequent sections.

### *3.2. Demonstrating the Cushioning Effect of CSF*

The analysis of wave A alone highlights the significant cushioning effect of CSF for both coup and contrecoup responses. As evidenced in Figure 5, the accumulation of fluid particles during both the acceleration and deceleration phases provides a safeguard against direct contact between the brain and skull. Consequently, the brain remains positioned at the center of the skull unless this protective mechanism is disrupted [42]. The subsequent section will detail such disruptions in greater depth. A comprehensive evaluation that includes subsequent waves B and C is necessary to fully understand the dynamics of brain injury during head impact events.

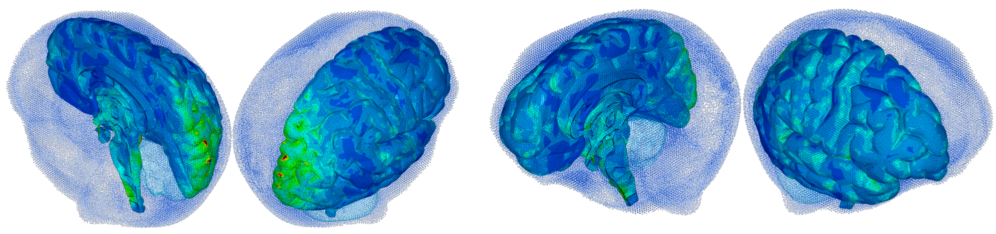
(a) Acceleration (b) Deceleration

**Figure 5.** Fluid particles positioning around the brain during the acceleration (coup) and deceleration (contrecoup) phases.

### 3.3. Cushioning Effect in Subsequent Waves

The research indicates that while CSF is highly effective in preventing direct contact between the brain and skull during a single event [43], its ability to cushion decreases with each subsequent wave of back-and-forth oscillations, such as those found in Figure 4. It requires sufficient time to settle down before being able to offer maximum protection once again.

The stress distributions on the brain during waves A and B are displayed in Figures 6 and 7, respectively, where fluid particles provide a protective cushioning effect against direct contact with the skull. While the stress values in wave B (Figure 7) are greater than those observed in wave A (Figure 6), there remains evidence of protection (i.e., fluid particles present) throughout all regions of the brain depicted in Figure 7. However, as illustrated by Figure 8 and particularly noticeable in its occipital view, some lobes do not exhibit any fluid particle presence between them and the skull. The absence of fluid particles in certain lobes of the brain poses a significant risk. The occipital view shown in Figure 8 serves as evidence that this lack of cushioning provided by the fluid particles could result in brain damage if subjected to a sudden stop such as the one simulated here.



Occipital view Frontal view

**Figure 6.** The stress distribution (Scaled; blue: 0, red: max in Wave C) on the brain at the peak of the wave *A*.

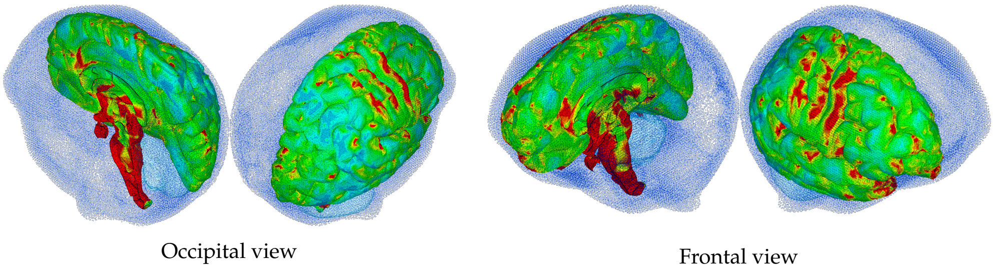



**Figure 7.** The stress distribution (Scaled; blue: 0, red: max in Wave C) on the brain at the peak of the wave *B*.

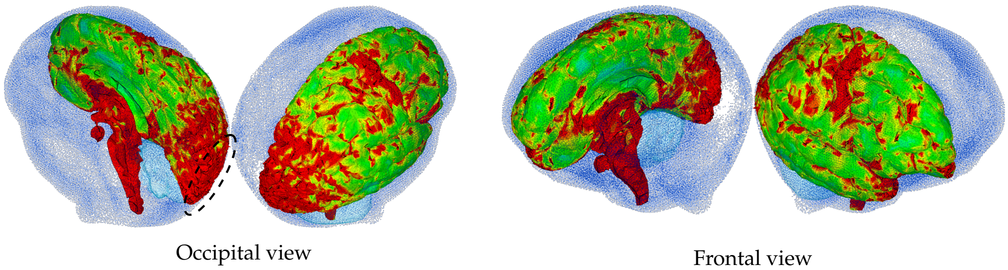



**Figure 8.** The stress distribution (Scaled; blue: 0, red: max in Wave C) on the brain at the peak of the wave *C*. Compared to waves *A* and *B*, no fluid particles are observed in the occipital lobe (dashed circle). Hence, direct brain-to-skull can be assumed in that area.

### *3.4. Comparative Analysis with and without the Helmet*

To demonstrate the effect of wearing a padded helmet on the brain, Figure 9 provides evidence of the positive impact that wearing a padded helmet has on the brain's stress distribution, as demonstrated by the reduced stress exerted on the occipital lobe. However, it is worth noting that there seems to be no change in stress levels experienced by the brainstem with or without a helmet. Additionally, while most studies focus on wave A as an indicator of brain trauma following direct impacts, this study highlights multiple waves present in padded helmets after such incidents.

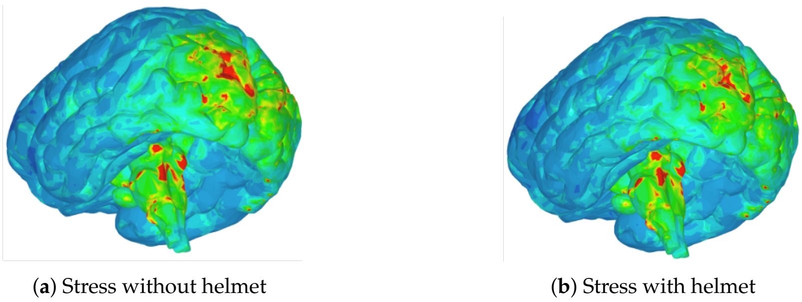



**Figure 9.** Stress distribution results (Scaled; blue: 0, red: max in Wave A) extracted at the peak of wave *A* without (**a**) and with (**b**) the helmet.

## 4. Discussion

While this study may suggest that helmets with hard-shell covers and soft(er) inner padding do not offer adequate protection against certain types of impacts, it is important to consider the fact that any type of helmet can only provide a limited amount of protection. The study conducted by Santos et al. demonstrated that incorporating extra suspension points or changes to the suspension tightening mechanism did not have a significant impact on the effectiveness of hard hats [44]. Therefore, their findings suggest that additional features in modern-day hard hat designs do not enhance their protective capabilities beyond what is already established. However, using a helmet—even one that may have some limitations—is still better than not wearing any head protection at all. It is also worth noting that different activities and sports require different types of helmets. For example, soft-shell helmet covers are a promising development in reducing the impact of head injuries. Though, further analysis is necessary to determine their effectiveness. Additionally, it is important to consider other factors such as the use of retention systems that securely strap helmets to athletes' heads when evaluating the overall efficacy of protective gear [45].

The role of CSF in protecting the brain from injuries cannot be overstated. The movement of CSF around the brain plays a crucial role in preventing injuries to the brain. However, studies have shown that quick changes in head speed can lead to more severe contrecoup injuries than coup injuries due to a diminished cushioning effect caused by a delayed return of CSF [25,39]. While CSF provides sufficient protection at the point of impact (coup injury), it may not return and settle down quickly enough to provide adequate cushioning on the opposite side (contrecoup injury).

The geometrical model used for this study is highly complex due to its various detailed parts and diverse material properties. Despite this complexity, there are plans to add more details such as cardiovasculature, skin, and hair, among others. Although the SPH method has been considered less precise numerically in the past decade it has undergone significant development and is now commonly used for studying biomedical applications that require patient-specificity through complex geometries. More traditional numerical FSI methods such as arbitrary Lagrangian-Eulerian formulations have also been utilized in these studies [46]. The conditions outlined in this paper are specifically designed to study sports that involve sudden stops due to player collisions such as rugby football, gridiron football, ice hockey, and martial arts. Nevertheless, these conditions can be readily adapted to analyze any sport depending on the research requirements.

While researchers in computational studies are often faced with the trade-off between accuracy and computational efficiency, it is important to consider the potential drawbacks of using simplified models. These models may compromise accuracy by omitting important details, resulting in unrealistic outcomes. Ultimately, finding a balance between these two factors can lead to more effective simulations and accurate results. Sacrificing numerical precision to lower computational costs may still yield useful, albeit slightly less accurate, results. However, the use of simplified geometrical models raises concerns about preserving patient-specificity and diminishing the usefulness of achieved outcomes [47]. It is important to note that accuracy does not necessarily equate with realism if attained by altering the geometry employed in modeling. Therefore, it is imperative to strike a balance between computational efficiency and maintaining fidelity to real-world anatomical structures for meaningful medical research applications [48]. Likewise, the use of an FSI technique is essential to accurately study CSF behavior in scenarios where the brain experiences multiple acceleration and deceleration events. Although FSI algorithms are more computationally expensive, they allow for fluid domains to move back and forth around the brain several times, which is necessary to demonstrate how CSF cushioning diminishes under such conditions. Using only solid elements would render it impossible to analyze this effect with any degree of accuracy or reliability.

## 5. Conclusions

While most studies on coup-contrecoup injuries concentrate solely on the two main phases of impact, our research highlights that additional movements are happening within a padded helmet after an initial blow—sudden stop (Figure 4). These smaller back-and-forth motions may seem insignificant compared to the first one; however, we showed that they can still cause serious damage. As these subsequent head movements occur, they compromise the ability of CSF inside the skull to prevent contact between the brain and skull bones. Therefore, even minor subsequent movement can lead to direct brain-to-skull contact with catastrophic consequences (Figure 8).

The authors conducted interviews with two individuals who experienced head injuries. While both individuals hit their heads in similar areas, one on a slow-moving bicycle and the other during a high-speed motorcycle accident, it was found that the cyclist suffered more serious concussion symptoms. It is hypothesized that this difference may be due to the hard-shell cover of the motorcycle helmet cracking upon impact and providing additional cushioning similar to soft-shell helmets. However, this remains speculative at this point. Further experimentation and studies are necessary to fully understand how different helmet designs can prevent concussions effectively. Therefore, more research is needed to determine the most effective helmet design and materials for preventing concussions. This highlights the importance of ongoing research and innovation in helmet design to ensure optimal protection for individuals engaging in high-risk activities. For more information, G. Tierney's (2021) review provides valuable insights into the complex relationship between concussion biomechanics, head acceleration exposure and brain injury criteria in sports [49].

While our study provides valuable insights into the impact of padded helmets on the cushioning effect of CSF protecting the brain, there is a need for further research to explore comprehensively various types of helmets and their effectiveness in mitigating concussion incidence among military personnel and others utilizing head protective equipment. The framework established by Op't Eynde et al. (2020) [17] highlights the importance of helmet design modifications that could enhance safety standards for individuals participating in high-risk activities. Therefore, future studies should focus on developing advanced helmet designs that can provide better protection against head injuries and reduce long-term health consequences.

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## Abbreviations

| | |
|---|---|
| CTE | Chronic Traumatic Encelopathy |
| ASTM | American Society for Testing and Materials |
| CSF | Cerebrospinal Fluid |
| ANSI | American National Standards Institute |
| FSI | Fluid-Structure Interaction |
| SPH | Smoothed-Particle Hydrodynamics |
| GPU | Graphics Processing Unit |
| DICOM | Digital Imaging and Communications in Medicine |

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