

Article

Computational Modelling and Biomechanical Analysis of Age-Related Craniocerebral Injuries: Insights into Bridging Veins

Monika Ratajczak ¹ , Mariusz Ptak ^{2,*} , Mateusz Dymek ² , Rafał Kubacki ³, Ricardo J. Alves de Sousa ⁴ , Claudia Sbriglio ² and Artur Kwiatkowski ^{5,6}

- ¹ Department of Biomedical Engineering, Institute of Material and Biomedical Engineering, Faculty of Mechanical Engineering, University of Zielona Gora, Prof. Szafrana 4, 65-516 Zielona Gora, Poland; m.ratajczak@iimb.uz.zgora.pl
 - ² Faculty of Mechanical Engineering, Wrocław University of Science and Technology, Lukasiewicz 7/9, 50-371 Wrocław, Poland; mateusz.dymek@pwr.edu.pl (M.D.)
 - ³ Faculty of Sport Sciences, University School of Physical Education in Wrocław, Ignacego Jana Paderewskiego 35, 51-612 Wrocław, Poland; rafal.kubacki@awf.wroc.pl
 - ⁴ TEMA—Centre for Mechanical Technology and Automation, Department of Mechanical Engineering, University of Aveiro, Campus de Santiago, 3810-193 Aveiro, Portugal; rsousa@ua.pt
 - ⁵ Department of Neurosurgery, Provincial Specialist Hospital in Legnica, Iwaszkiewicza 5, 59-220 Legnica, Poland
 - ⁶ Faculty of Medicine, Wrocław University of Science and Technology, Hoene-Wrońskiego 13c, 58-376 Wrocław, Poland
- * Correspondence: mariusz.ptak@pwr.edu.pl

Abstract: The aim of this study is to explain the higher incidence of subdural haematomas in elderly people compared to young adult. This research addresses the phenomenon by developing two distinct numerical models of the human head, simulating individuals people aged 77 and 28, respectively. These models are methodically constructed based on medical imaging data acquired through collaboration with hospitals and subsequently verified through empirical experimentation. Studies have shown that the main factor that influences the vulnerability to bridging vein rupture in older adults is the degenerative processes of nervous tissue. The most visible structural damage was observed in the outflow cuff segment. This phenomenon can be primarily attributed to specific geometric parameters associated with this anatomical region. The presented research emphasises the importance of computational models in understanding the pathomechanics of brain structures. As a result of the analyses, it was proven that the neurodegenerative processes of the brain that occur with age are crucial in understanding the higher incidence of subdural haematomas in elderly people.

Keywords: subdural haematomas; bridging veins; numerical models of human head; finite element analysis; traumatic brain injury; sport; elderly people; geriatric



Citation: Ratajczak, M.; Ptak, M.; Dymek, M.; Kubacki, R.; de Sousa, R.J.A.; Sbriglio, C.; Kwiatkowski, A. Computational Modelling and Biomechanical Analysis of Age-Related Craniocerebral Injuries: Insights into Bridging Veins. *Appl. Sci.* **2024**, *14*, 2681. <https://doi.org/10.3390/app14072681>

Academic Editor: Alexander Zhibanov

Received: 9 January 2024

Revised: 9 March 2024

Accepted: 20 March 2024

Published: 22 March 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Falls and head injuries are a major concern in sports and exercise science, directly impacting athletes' performance and well-being. Traumatic brain injuries (TBIs) resulting from head impacts represent a serious issue with significant implications for the sports community [1]. Although the consequences of falls are well documented, this paper focuses on the specific context of sport, particularly in terms of young adults and seniors. It is essential to recognise how age-related changes in brain pathophysiology, particularly in the context of sports, may influence the outcomes of head injuries. The understanding of head injuries in sports shall consider age-related differences, as they have an impact on injury mechanisms and outcomes. Interestingly, older athletes exhibit distinct physiological changes that can affect their response to head impacts. In the context of head impacts

related to sports, the elongation of the bridging veins in older athletes becomes a crucial factor. The bridging veins are essential to drain blood from the brain and are susceptible to injury upon head impact. With age, the elongation of these veins makes them more vulnerable to mechanical loading during sporting activities, increasing the risk of injury. In the specialised domain of sports and exercise sciences, the interaction between head impacts, bridging veins, and intracranial injuries deserves specific attention, particularly in the context of young adults and seniors involved in sports activities. Understanding how age-related physiological changes influence head injuries is vital for developing targeted preventive measures, effective treatment strategies, and customised rehabilitation protocols for athletes of different age groups.

Elderly people are the most prominent social group exposed to tissue dysfunctions resulting from falls. The highest percentage of victims can be observed in people over 65 years [2]. Falls are the leading cause of injury in this group—they happen for many reasons. The basic one is the change in the natural posture while walking, i.e., when we look at an elderly person, they have a slight tilt of the torso forward, and when moving, they do not raise their feet as high as younger people—they often shuffle on the ground. In addition, there is a natural decline in strength and a limited range of movements: after the age of 40, there is a permanent loss of muscle mass of approximately 6% per decade. Therefore, when seniors stumble, they have less chance of keeping their balance than a young person. In addition, there is another element—weakening eyesight [3]. As we age, our perception of contrast and depth deteriorates. Therefore, the reaction time of an elderly person to a potential obstacle is extended. Studies show that more than 60% of serious accidents occur in apartments [4,5].

The consequences of falls are multifaceted. Nevertheless, the most exposed area is the head. Head injuries are a serious socioeconomic problem associated with long-term treatment [6]. They are often associated with cognitive, physical, and emotional disabilities. Falls are the leading cause of head injuries [7]. Studies show that older people have significantly worse treatment outcomes than younger people with similar injuries [8]. In light of dementia processes that occur in the elderly, including Alzheimer's disease (AD), the issue of traumatic brain injury is neglected in public opinion [9].

Brain ageing is associated with physical changes in the brain [10]. There are also many changes in the physical properties of the brain, including tissue dehydration, as a result of which the cerebral vessels stiffen and the brain volume decreases. Reduced brain volume causes an increase in the distance between the dura mater and the surface of the brain. According to a study published by Peters [11], brain mass/volume is reduced by an average of 5% per decade from the age of 40. As a result of this phenomenon, the bridging veins can be elongated, making them more susceptible to damage under mechanical loading. Brain atrophy is considered to be the primary pathogenesis associated with an increased risk of acute subdural haematoma in the elderly. Epidemiological studies have shown a significantly higher damage rate to bridging veins in older people than in younger adults, with increased morbidity and mortality and worse treatment results [12]. Clinical studies suggest brain atrophy as the primary aetiology contributing to the increased risk of subdural haematoma in elderly patients [13]. The main reason for their formation is atrophy of brain tissue, which causes an increase in the subdural space. As a result of this phenomenon, the bridging veins may extend, making them more susceptible to damage during mechanical loads. The second important factor may be that veins in the elderly are more fragile, as confirmed by Horanin-Dusza's experimental studies [14]. Moreover, due to the elongation of the bridging veins, the lumen in the vessels narrows. This phenomenon causes a poorer blood supply to brain tissue, which may result in the degradation of nervous tissue. The atrophy of brain tissue is manifested by the enlargement of the sulci and ventricles, and the share of fluid spaces in the skull's capacity increases to the detriment of the brain tissue. The macroscopic anatomical changes associated with these are probably the result of the accumulation of changes at the microstructural level. The incidence of typical traumatic brain injuries depending on the age group is shown in Figure 1.

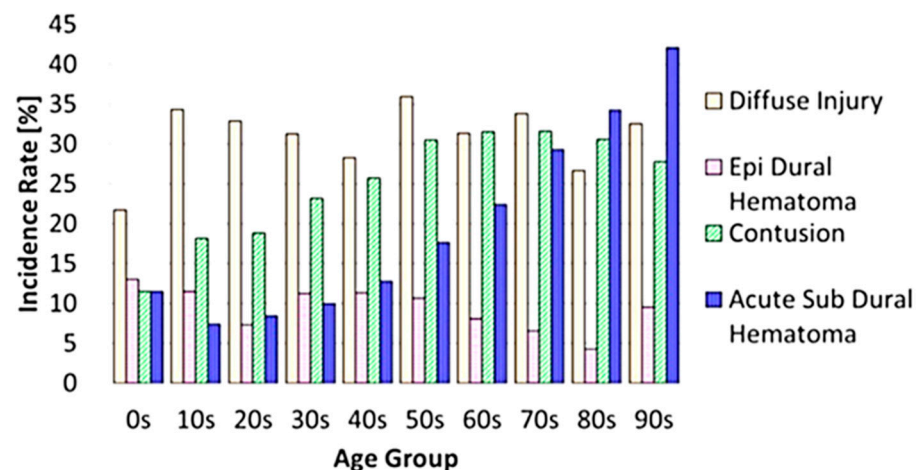


Figure 1. Brain injuries in different age groups [12].

It should be emphasised, however, that the pathomechanism of subdural haematoma formation is not fully understood. Currently, in the literature, the exact criteria for assessing the damage to the bridging veins are not fully defined [15]. Breaking the continuity of the structure of a bridging vein leads to the formation of a subdural haematoma. Presently, the recommended way to study the degradation of brain tissues, including vascular, is through medical imaging techniques such as angiography, magnetic resonance imaging, and computed tomography (Figure 2). However, these methods do not provide insight into the biomechanical behaviour of brain tissues. The problem of vascular tissue damage is extensive and requires further research. At the same time, in the literature, studies suggest that the main mechanisms of disturbances in the structure of the bridging vein continuity are directly related to exceeding their deformation limits. Currently, the mechanisms of cerebral vascular degradation are not precisely described and identified. It should be emphasised that experimental research is the optimum technique for studying biological preparations [16,17].

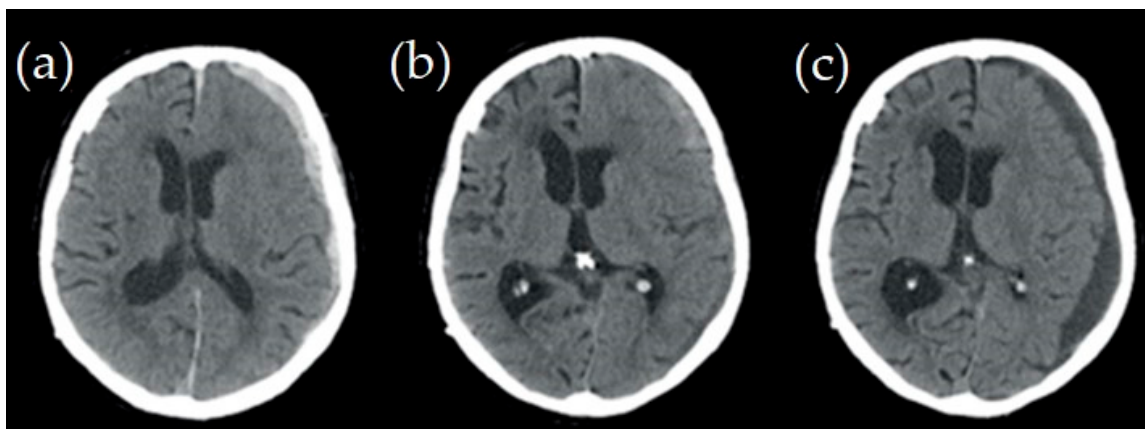


Figure 2. Evolution of a subdural haematoma (from acute to chronic) following a head injury in an elderly person. Head CT shows (a) left-sided hyperdense acute subdural haematoma (ASDH); (b) isodense subacute subdural haematoma; and (c) hypodense chronic subdural haematoma [18].

Nevertheless, undertaking research immediately after a person's death is significantly more difficult. It should also be emphasised that the research results presented by different authors are often divergent. The main reason for these discrepancies is the use of different research methods, e.g., the sampling place, the strain rate during measurement, and the freshness of the preparation. However, it should be emphasised that the bridging veins are deformed in the multiphase system of brain tissues, i.e., dura mater and nervous

tissue. Therefore, numerical modelling is currently one of the better alternative methods for identifying the response of brain structures to forces [19,20], in particular, the finite element method (FEM), which is the leading method in the analysis of dynamic phenomena [21–23]. Along with the development of computing power, there has also been an increased interest in using FEM in modelling the structures of the human head [24]. These models have been developed mainly for the needs of the communication and aviation industries [25–27]. So far, many numerical models of the head have been developed. However, little is still known about the pathomechanism of the formation of subdural haematomas in elderly people. Currently, there are several head models of elderly people in the literature, but most of these models are scaled and do not reproduce the actual anatomy of the human head. There is a lack of distinction in brain morphology, yet the biomechanics under load in these different cases are wholly different.

The research has significant potential impacts on understanding and mitigating the risks of subdural haematomas. By developing accurate numerical models of the human head, particularly focusing on 77- and 28-year-old individuals, the study provides insights into the biomechanics underlying vascular haemorrhage pathomechanisms.

An analysis of the state of the art has not shown a clear answer to whether there is a difference in the strain value of the bridging veins between the elderly and people who have not yet experienced brain atrophy. The volume of the brain may greatly influence the behaviour and mechanical parameters during impact. With the help of numerical models, which have significant proven biocompatibility, the examination of how brain volume influences the strain values in bridging veins and sinuses has been commenced in this study. The insights can inform preventive measures and interventions to reduce the occurrence and severity of subdural haematomas.

2. Materials and Methods

2.1. Case Studies

In cooperation with the Provincial Specialist Hospital in Legnica (Poland), the authors of the study analysed the medical cases of elderly people who suffered head injuries. Extensive analysis has shown that most of these victims suffered damage to the bridging veins as a result of a fall. The medical descriptions of the sample patients and their medical images are shown in Figures 3–5.

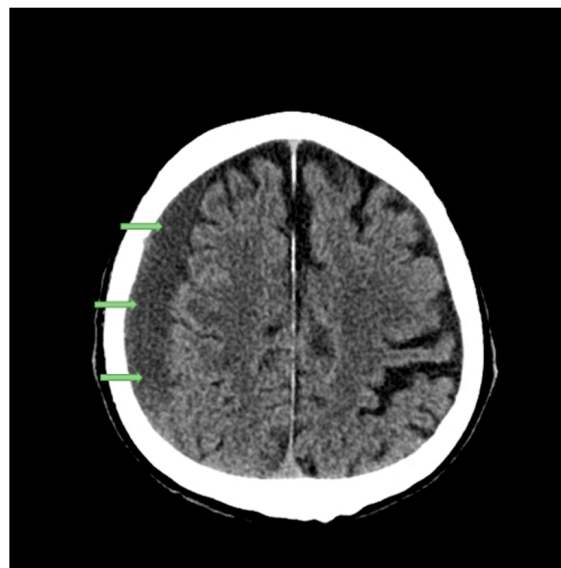


Figure 3. A 96-year-old man was admitted to the hospital because of a 1-month history of multiple falls at home. His medical history included hypertension and slight dementia. The main clinical symptom

was left hemiparesis, causing gait instability and difficulty walking. Computer tomography showed hypodense (dark) subdural haematoma over the right hemisphere (green arrows), compressing the cerebral hemisphere. The patient was operated on, and the haematoma was removed. After surgery, rapid improvement was observed, and he was discharged after one week of hospital stay with full recovery.

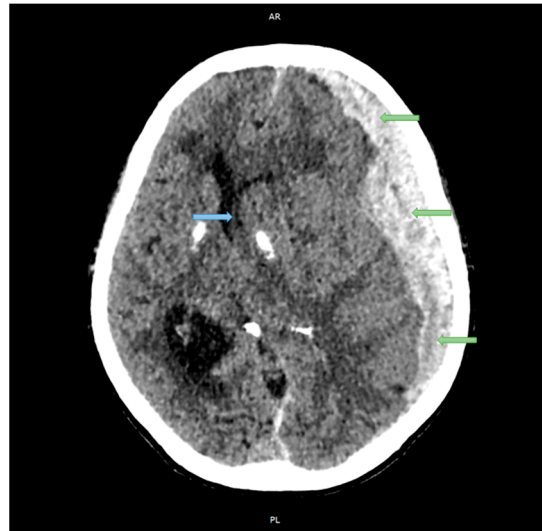


Figure 4. A 76-year-old woman with no significant medical history was admitted to the neurosurgery ward after falling off a ladder while hanging curtains. When presented to the emergency department (ED), she was deeply unconscious and rigid, with respiratory and circulatory failure. A computer tomography scan showed a massive, acute subdural haematoma over the left hemisphere (green arrows), causing a significant midline to shift to the right (blue arrow). The patient was immediately operated on, and the haematoma was removed. After surgery, she was moved to the intensive care unit, but no neurological improvement was observed. The patient died from irreversible loss of brain stem functions after 11 days of stay.

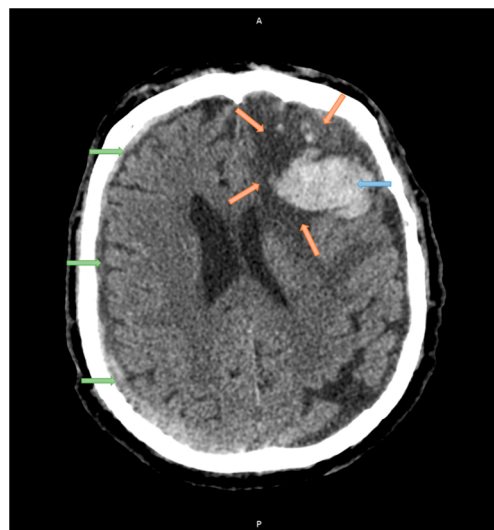


Figure 5. An 80-year-old man was admitted to the neurosurgery ward a day after falling in the bathroom. His medical history included dementia, parkinsonism, and atrial fibrillation, which required anticoagulant drugs. On-site evaluation by the emergency response team exposed poor lighting, a bathroom rug without a non-slip bottom surface, and the absence of a shower bar. The main clinical symptoms were somnolence and left paraparesis. Computer tomography revealed a

subdural haematoma over the right cerebral hemisphere (green arrows) and a cerebral contusion (blue arrow) surrounded by cerebral oedema (orange arrows). During a hospital stay, severe pneumonia and respiratory failure occurred. After the 81-day hospital stay, the patient was discharged to the social care home without complete recovery and required long-term personal care.

2.2. Development of the Human Head Numerical Model

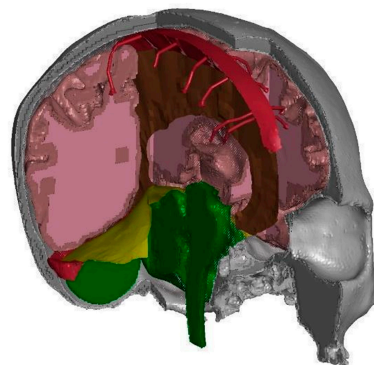
The development of numerical models representing the human heads of a 77-year-old and a 28-year-old involved several stages, including the acquisition of medical imaging data and the progression through geometric segmentation. This comprehensive process of obtaining, discretizing, and validating finite element method (FEM) models was presented in previous studies by the authors [28,29]. The building model method can be described in short: Medical Data Acquisition and Craniometry → Computer-Aided 3D Modelling and Structure Separation → Finite Element Modelling with Experimental and Submodel Tests → Detailed Modelling of CNS Structures → Verification Tests → Bridging Veins Strain Comparison.

It is worth underlining that the evaluation presented in this study is examined with strict cooperation between engineers and medical doctors. The medical data were collected, and specific regions of interest, crucial to understanding vascular haemorrhage pathomechanisms, were identified. Patients with average geometric parameters were investigated and chosen to ensure that the head models accommodated a broader demographic. Subsequently, head models of a 77-year-old and a 28-year-old individual were crafted using medical images derived from computed tomography and magnetic resonance imaging. To achieve this, pathology-free patient data were collected in the digital imaging and communications in medicine (DICOM) format from various medical institutions, including the Provincial Specialist Hospital in Legnica, the Lower Silesia Specialist Hospital of T. Marciniak, and the University Hospital of Wrocław, Poland.

The geometric models were detailed and constructed using open-source 3D Slicer software (<https://www.slicer.org/>). In particular, there have been no automated segmentation algorithms available for highly deformable tissues with irregular geometry, such as brain tissue. Consequently, the segmentation of brain structures required manual intervention. The process involved separating the left and right hemispheres of the brain, executed image by image. Much effort was expended to mimic the complicated external geometry of the brain, encompassing its detailed gyri and sulci.

Subsequently, the resulting 3D object was exported to the STL format and processed further digitally through computer-aided engineering (CAE) class software CATIA V5 R21. Finally, the geometry was translated into a discrete model (CAE) utilising the LS-DYNA R13 code (Figure 6). The material data for the individual head structures were determined based on the literature [30].

(a) 77-year-old numerical head model



(b) 28-year-old numerical head model

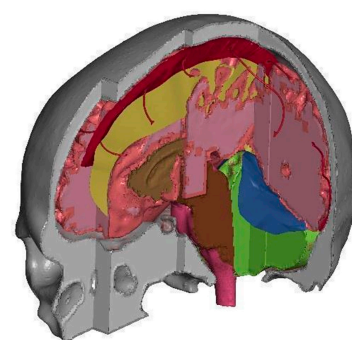


Figure 6. (a) 77-year-old numerical head model; (b) 28-year-old numerical head model.

A detailed description of the numerical modelling, as well as the material model comparison, is available in the authors' previous study regarding a 28-year-old head model [29].

2.3. Model Geometry

Particular attention was paid to mapping the correct geometry of the bridging veins (BV) and the superior sagittal sinus (SSS). The anatomical location of the bridging veins was discussed with neurosurgical doctors and compared with medical images obtained from hospitals. The bridging veins interconnect with the superior sagittal sinus through an outflow cuff segment. This part is narrower than the other bridging veins and drains at a unique angle into the superior sagittal sinus. These elements were included in our model (Figure 7). It should be noted that in most published numerical models, the authors use very simplified geometry of bridging veins (such as a beam or truss approach). An important difference that distinguishes the brain of a 28-year-old person from the brain of a 77-year-old person is degenerative change, such as brain atrophy. As stated in the introduction, these disappearances occur heterogeneously throughout the volume. However, most authors scale these models, which affects the calculation results.

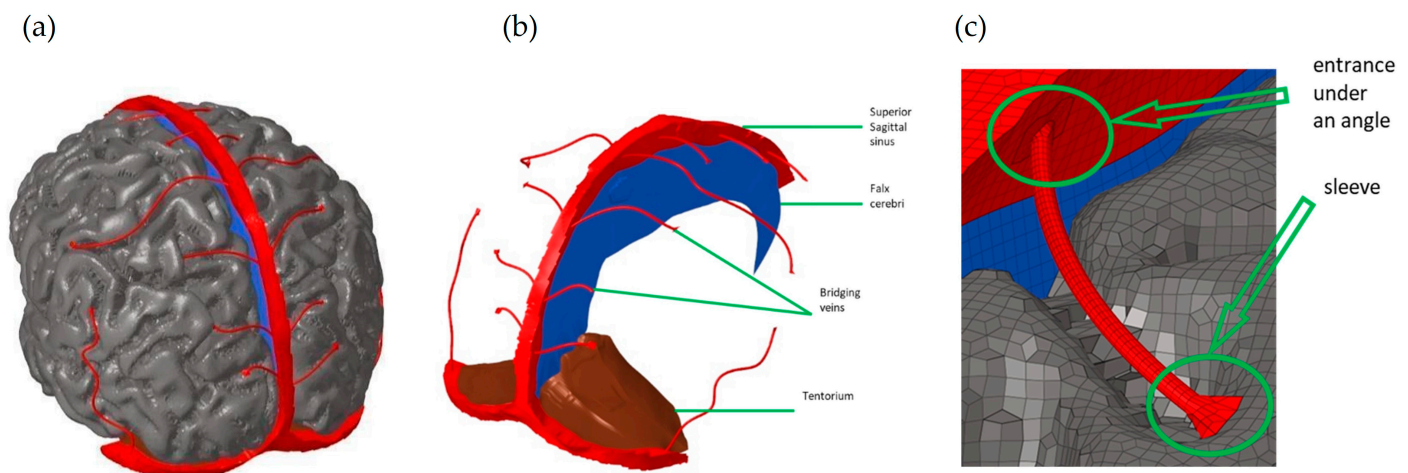


Figure 7. Bridging vein geometry: (a) overview; (b) central nervous system labelling; (c) BV-specific geometry.

2.4. Mechanical Properties of Brain Tissues

The mechanical parameters of the bridging veins were taken from Monea's research [31]. The mean age of the specimens prepared by Monea et al. was 82.25 ± 9.22 . It should be noted that most autopsy specimens come from older people, and there are currently no studies on the biological tissues of younger people. This fact is related to apparent ethical aspects. Nevertheless, in this study, the authors focused on the influence of brain volume on the degradation of the vascular structure of the bridging veins under the influence of load. The cerebrospinal fluid was modelled using smoothed-particle hydrodynamics (SPH). The density was set to $1 \times 10^{-6} \text{ kg/m}^3$ and the viscosity coefficient to $7 \times 10^{-10} \text{ kg/m}^3$, which matched the cerebrospinal fluid (CSF) properties. The number of SPH particles for both models is set to approximately 140,000. The particles move freely and interact with structural finite elements using a penalty-based contact definition. The material data for a 77-year-old person for individual head structures were determined based on the literature [30–34]. These data are presented in Table 1. The material data for a 28-year-old person were presented in our previous publication by Ptak et al. [29].

Table 1. Mechanical properties of brain tissues for a 77-year-old person; units: tonne/mm/s/MPa.

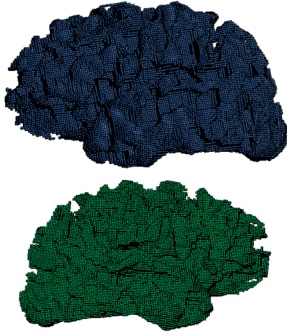
Structure	Reference	Density [t/m ³]	Young's Modulus or Bulk Modulus [MPa]	Other Material Parameters	Type No. of FEs	Image of Structure
White matter—left/right hemisphere	THUMS MAT_VISCOELASTIC 2 [35]	1.00×10^{-9}	<i>Bulk modulus</i> 2.16×10^{-3}	$G_0 = 12.5 \times 10^{-3}$ $G_1 = 6.125 \times 10^{-3}$	hexa 231,146/ 237,494	
Grey matter—left/right hemisphere	THUMS MAT_VISCOELASTIC 2 [35]	1.00×10^{-9}	<i>Bulk modulus</i> 2.16×10^{-3}	$G_0 = 10 \times 10^{-3}$ $G_1 = 5 \times 10^{-3}$	hexa 313,176/ 311,954	
Cerebellum brainstem	F.A.O. Fernandes et al., 2018 [30]	1.04×10^{-9}	–	$N = 0.49999$ $Mu1 = 0.0012$ $Alpha1 = 5.05007$	hexa 204,567	

Table 1. Cont.

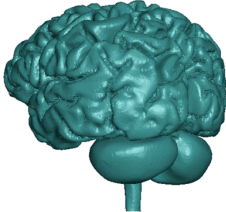
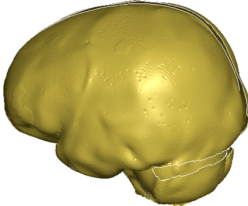
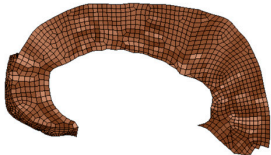
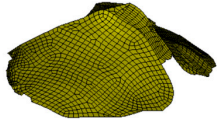
Structure	Reference	Density [t/m ³]	Young’s Modulus or Bulk Modulus [MPa]	Other Material Parameters	Type No. of FEs	Image of Structure
Pia mater	LLC Elemance—GHBMC Model 2014; M. Ratajczak et al., 2019 [32,34]	1.13×10^{-9}	31.5	$\nu = 0.45000$	shell 245,632	
Dura mater	LLC Elemance—GHBMC Model 2014; M. Ratajczak et al., 2019 [32,34]	1.13×10^{-9}	31.5	$\nu = 0.45000$	shell 92,152	
Falx cerebri	LLC Elemance—GHBMC Model 2014; M. Ratajczak et al., 2019 [32,34]	1.13×10^{-9}	31.5	$\nu = 0.45000$	shell 1197	
Tentorium cerebelli	LLC Elemance—GHBMC Model 2014; M. Ratajczak et al., 2019 [32,34]	1.13×10^{-9}	31.5	$\nu = 0.45000$	shell 1669	
Superior sagittal sinus and transversal sinus	LLC Elemance—GHBMC Model 2014; M. Ratajczak et al., 2019 [32,34]	1.04×10^{-9}	28.2	$\nu = 0.45000$	shell 10,627	

Table 1. Cont.

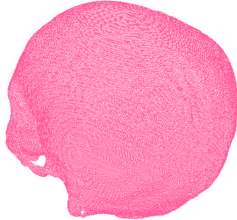
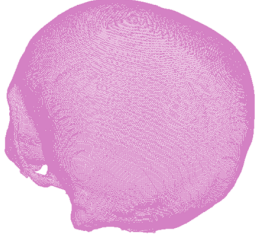
Structure	Reference	Density [t/m ³]	Young's Modulus or Bulk Modulus [MPa]	Other Material Parameters	Type No. of FEs	Image of Structure
Bridging veins	Monea et al., 2014 [31]	1.13×10^{-9}	30	0.48000	shell 10,627	
Lamina interna	Giordano and Kleiven 2016; M. Ratajczak et al., 2019 [33,34]	2.1×10^{-9}	$4 \times 10^{+3}$	0.25000	hexa 196,734	
Diploe	Giordano and Kleiven 2016; M. Ratajczak et al., 2019 [33,34]	1.0×10^{-9}	$1 \times 10^{+3}$	0.30000	hexa 326,812	
Lamina externa	Giordano and Kleiven 2016; M. Ratajczak et al., 2019 [33,34]	2.1×10^{-9}	$4 \times 10^{+3}$	0.25000	hexa 326,812	

Table 1. Cont.

Structure	Reference	Density [t/m ³]	Young's Modulus or Bulk Modulus [MPa]	Other Material Parameters	Type No. of FEs	Image of Structure
Cerebrospinal fluid (CSF)	DYNAmore GmbH 2018; Gomez-Gesteira et al., 2012 [32,36]	1×10^{-9}	–	viscosity coefficient 7×10^{-10}	SPH 191,406	
Corpus callosum	THUMS MAT_VISCOELASTIC 2 [35]	1.04×10^{-9}	same as for WM	same as for WM	hexa 3190	

2.5. Validation Boundary Conditions

The numerical simulation boundary conditions were established through experimental investigations conducted by Hardy in 2007 [37]. In his research, Hardy employed a 6-axis accelerometer capable of recording linear and angular acceleration to monitor the brain's displacement relative to the skull. The displacement of the brain was precisely controlled using natural density tracers (NDTs) applied to the brain tissue, and measurements were captured using a high-speed X-ray system. Precisely, six markers were strategically placed on the anterior frontal lobe column (denoted as “A”), and an additional six markers were positioned on the posterior parietal column (referred to as “P”).

In this study, the output from the accelerometer, comprising six distinct time acceleration profiles, was utilised as a function of the input load. This input load was applied to the centre of mass of the skull, as illustrated in the accompanying Figure 8. The experiment designated as C755-T2 was selected for the investigation since it is widely recognised in the literature as one of the most commonly used benchmarks for validating numerical finite element head models (FEHMs). Hardy's C755-T2 experiment involved subjecting the occipital region of the head to an impact at a velocity of 2 m per second [37].

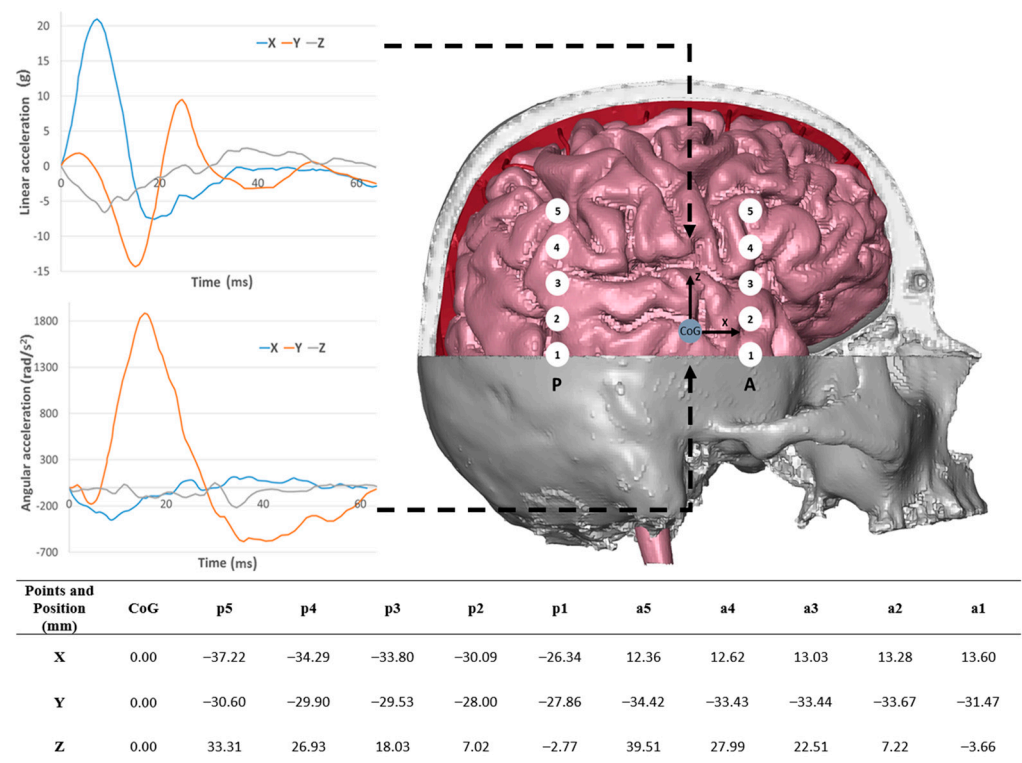


Figure 8. Boundary conditions—linear and angular acceleration load of the skull centre of gravity (CoG) according to Hardy et al. test C755-T2 [37]—marker numbers depicted for the frontal, A (anterior), and rear columns, P (posterior), with its coordinates.

Detailed descriptions and discussion of the validation results were presented in our previous authors' publications [28,29].

3. Results

As a result of the conducted research, the biomechanical response of the connection between the superior sagittal sinus (SSS) and the bridging vein (BV) was determined. The response of the venous systems of a 28-year-old person and a 77-year-old person was compared. The results show higher values of bridging vein strains in the case of a 77-year-old person (Figure 9 and Table 2). The bridging veins were slightly deformed under the same mechanical loading in young adult. The lowest strain values were obtained in the

occipital region of young adult. This explains why subdural haematomas are most often diagnosed in the frontoparietal region in younger people [38,39].

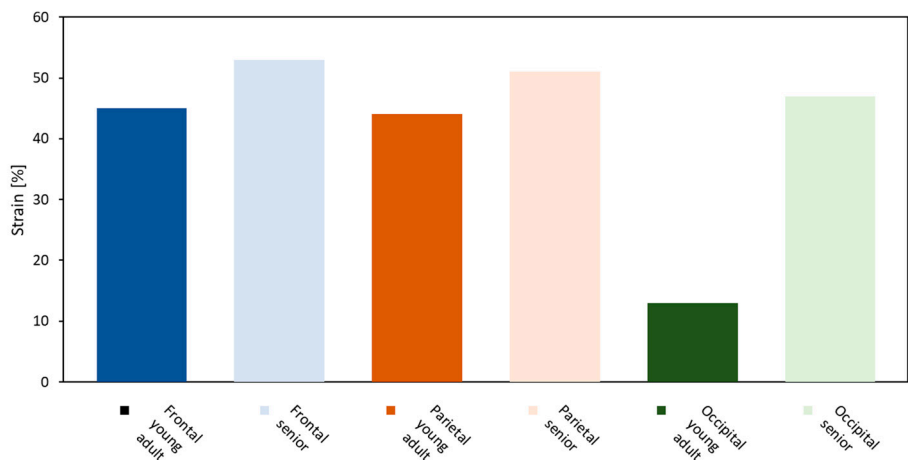


Figure 9. Maximum bridging vein strain for compared models.

Table 2. Bridging vein strain comparison for maximum values in each region for the 28-year-old and 77-year-old models.

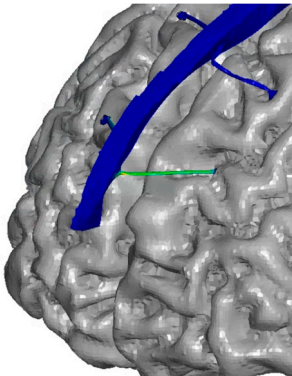
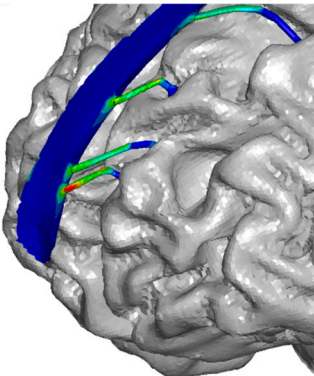
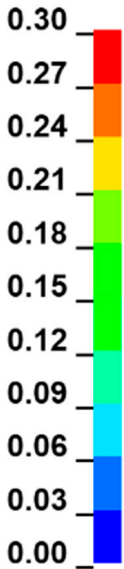
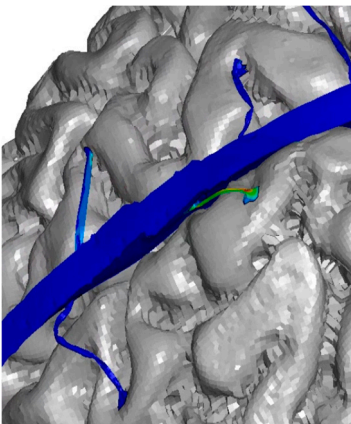
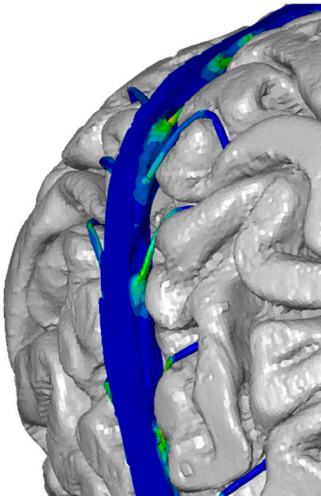
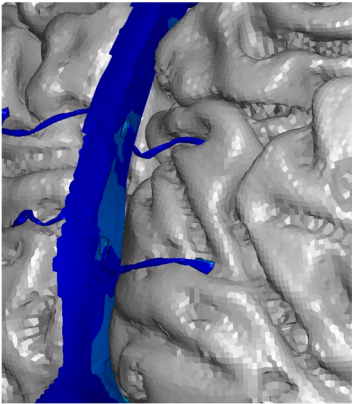
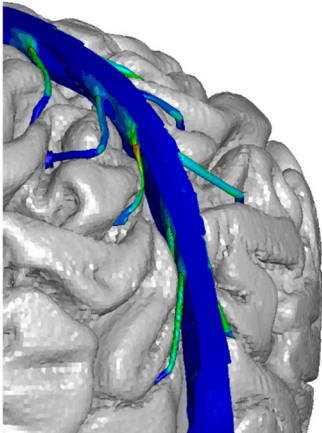
	28-Year-Old Model	77-Year-Old Model	Effective Strain Criterion [-]
Frontal veins			
Parietal veins			

Table 2. Cont.

	28-Year-Old Model	77-Year-Old Model	Effective Strain Criterion [-]
Occipital veins			

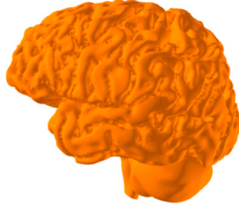
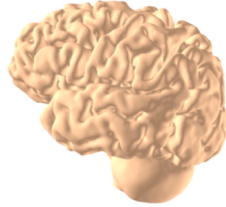
The brain tissue in the occipital region is the most densely packed, and there is the least space in the subdural space. Therefore, such large displacements of brain structures in this region in a 28-year-old person are not observed. This is the situation of so-called coup injury, i.e., the first contact of the brain with the inside of the skull. In a 28-year-old person, the greatest concentration of deformations was observed in the frontal–parietal region. For an older person, brain displacement is greater due to the shrinkage of the brain with age. Therefore, in the case of a 77-year-old person, damage to vascular structures in the occipital region may be observed. The study adopted mechanical parameters obtained from Monea’s research [31]. The strain criterion for the destruction of bridging veins given by this author is 29.82 ± 13.26 . Therefore, it can be concluded that with the same mechanical load, there was no damage to the bridging veins in a 28-year-old person. However, in an elderly person, the mentioned criterion was exceeded, which could cause a haemorrhage in the subdural space. Analysis of the results showed that the highest stress concentration occurs in the area of the junction of the superior sagittal sinus and the bridging veins (Table 2). Anatomically, this connection is called the outflow cuff segment. Clinical studies show that due to geometric conditions, this region is most frequently damaged [31]. It is worth highlighting that the anatomical structure strongly influences strain and stresses in BV.

Brain Physical Differences

The human brain is a complex organ that undergoes various changes throughout a person’s life. One of the most intriguing aspects of brain development and ageing is the difference in brain parameters between older adults and young adults. Based on our data obtained through computer-aided design (CAD) models, which indicate differences in brain volume, area, and mass, we could dive into these distinctions, which are presented in Table 3.

Figure 10 depicts axonometric views of the two different brain models: orange—young adult and yellow—senior brain models. The models were transformed to make their centres of geometry coincident, which were automatically set in CAD software (CATIA v5).

Table 3. An overview of the differences in brain parameters between matters (white and grey matter) between these two age groups, highlighting the variations in brain volume, area, and mass.

Brain Parameters (White and Grey Matter)	Young Adults (28 y)	Senior (77 y)	Difference (Young Adult vs. Senior)	Comments
				
Brain Volume	1.0406 [dm ³]	0.98088 [dm ³]	5.7%	Young Adults: On average, young adults tend to have larger brain volumes compared to older adults, with a ~6% difference. This is largely due to ongoing brain development and growth during childhood and adolescence [40]. Senior Adults: Brain volume typically decreases with age. This reduction can be attributed to factors such as loss of neurons and their connections, as well as changes in brain structural integrity. This decrease in volume can affect various cognitive functions.
Brain Area	165,893.3 [mm ³]	1,619,62.1 [mm ²]	2.4%	Young Adults: Younger individuals generally have a larger brain area compared to older adults, with a ~2% difference. The brain area encompasses the surface of the brain, which is important for processing information and facilitating communication between different brain regions. Senior Adults: Over time, there may be a slight reduction in the brain's surface area. This could be related to the gradual decline in cognitive functions, such as memory and processing speed, experienced by some older individuals.
Brain Mass	1.18 [kg]	1.02 [kg]	13.3%	Young Adults: Young adults typically have greater brain mass compared to older adults, with a ~13% difference. Brain mass is closely related to brain volume and is largely responsible for the organ's overall functionality. Senior Adults: As individuals age, there is often a decline in brain mass, primarily due to a decrease in the number of neurons and synaptic connections. This mass reduction can contribute to age-related cognitive decline.

Interestingly, the authors also carried out the geometrical deviation analysis of the young adult's brain model, which served as a reference for the senior's brain model (Figure 11). The largest and most significant deviations were located in the frontal lobes,

where the young adult's brain was bigger by approximately 18 mm. Research described in the literature suggests that the greatest changes related to ageing processes occur in the frontal cortex [41]. That is why most seniors have problems with cognitive functions [42]. We also noticed some deviation in the cerebellum. Yet, there may be anatomical differences between the brains as the deviation is positive (red) and negative (blue), which indicates the cerebellum's different position compared to the young adult's cerebellum.

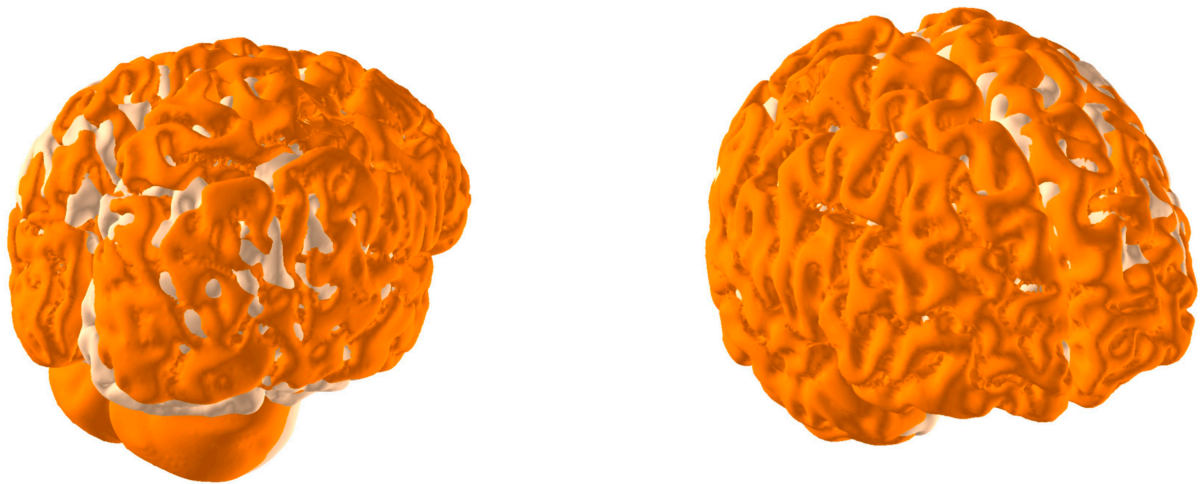


Figure 10. Axonometric views of the two different brain models: orange—young adult, and yellow—senior brain models.

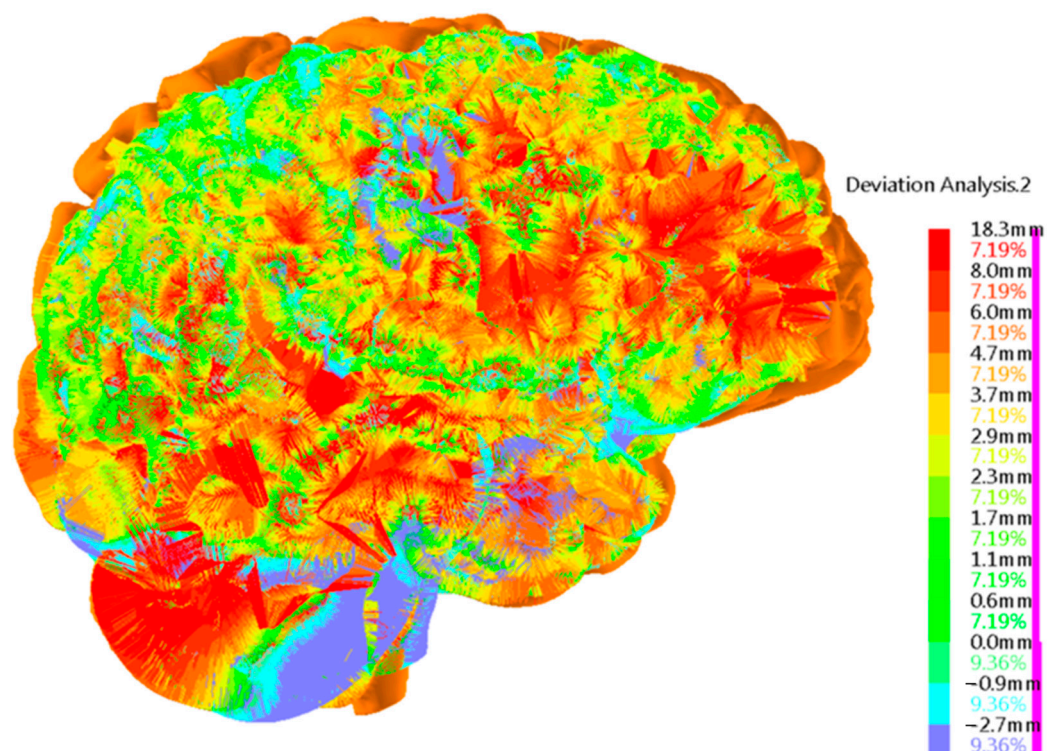


Figure 11. The deviation analysis of the young adult's (reference) and senior's brains: left—the quantitative comparison analysis in [mm]. The results distribution graph is also visible next to the scale.

4. Discussion and Limitations

The research results show that elder people have a greater predisposition to the formation of subdural haematomas. The main cause of this phenomenon is brain atrophy,

which leads to increased movement of the cerebral cortex. Therefore, it is crucial to recognise the limitations inherent in the selection of geometric models, the uniqueness of individual bridging vein layouts, and the relatively new nature of the smoothed-particle hydrodynamics (SPH) approach in finite element analysis. One of the primary limitations of this study is the reliance on geometrical models obtained from different individuals. While these models were carefully selected based on statistical analysis using craniometry data, it is essential to acknowledge that the inherent variability in anatomical structures among individuals may introduce biases or limitations to our findings. The diversity in cranial shapes and sizes among the selected models may not fully capture the anatomical diversity of the entire population. Another noteworthy limitation is the individual variability in bridging vein layout [16]. Due to their uniqueness, we compare these layouts to fingerprints, yet this individuality can pose challenges when attempting to establish universal patterns or guidelines. The study findings are based on a specific group of individuals. While they provide valuable insights, extrapolating these results to broader populations or clinical applications should be given attention.

Moreover, using SPH within the finite element framework represents a novel approach in this study. This study, based on the FE–SPH approach, endeavours to improve the biofidelity of the head better than the other numerical algorithms, such as the multi-body approach, by offering a more comprehensive and accurate representation of highly deformable tissues, particularly brain tissue. Through systematic manual segmentation and collaboration between engineers and medical doctors, the models developed in this study capture intricate anatomical details with greater fidelity. Additionally, including pathology-free patient data from diverse sources ensures broader demographic representation and enhances the validity of the models. The detailed description and validation of the developed numerical models further distinguish this study, providing a robust foundation for understanding vascular haemorrhage pathomechanisms. However, it is crucial to acknowledge that this technique is still relatively new in the context of biomedical modelling and simulation. As such, there may be inherent limitations associated with SPH, including the need for further investigation to fully understand its accuracy and applicability in modelling cranial biomechanics [43,44]. The results presented in this study should be considered as an original exploration of this approach, and further research should aim to validate and refine its use for more robust and accurate predictions. By recognising and addressing these limitations, we aim to facilitate future actions that can build upon our work and further advance the field of head biomechanics.

The insights from the paper can inform preventive measures and interventions to reduce the occurrence and severity of subdural haematomas. Some possible strategies based on the research findings may include improving head protection devices, enhancing diagnostic techniques for early detection, and implementing lifestyle modifications or preventive measures tailored to individuals at higher risk [45,46]. Overall, this research contributes to advancing knowledge in the field of head injury biomechanics and has the potential to improve patient outcomes and reduce the burden of subdural haematomas. The proven potential of virtual simulations may aid clinicians and forensic experts in determining the causes and consequences of head impacts in subdural haematoma, giving invaluable inputs impossible to obtain otherwise and providing a significant societal impact.

Nevertheless, it should be remembered that although other authors used different modelling approaches, similar research conclusions were obtained by Yanaoka, Abdi, and Zhou et al. [47–49]. In the case of the presented model, it is also worth noting that the brain was not scaled, but the original geometry was recreated.

5. Conclusions

As we age, our brains change slowly and structurally. Notably, the front part of the brain changes the most—as proven in the depicted deviation-based analysis. This is important to understanding why older people are more likely to have cognitive problems. Our study supports the idea that brain shrinkage makes older people more prone to

subdural haematomas, a type of brain injury. We found that in a 77-year-old, the veins in the brain are more strained under pressure compared to those in a 28-year-old. This observation validates the empirically established trend of a higher incidence of diagnosed subdural haematomas within the elderly demographic. This explains why older people are more often diagnosed with subdural haematomas, especially in the occipital region of the brain. This atrophic or shrinking process causes increased brain movement relative to the cranial enclosure during an impact. Additionally, due to the brain geometry, the highest strain values are notably reported in the proximity of the juncture between the bridging veins and the superior sagittal sinus. Overall, our research shows the complex relationship between ageing, brain changes, and the risk of brain injuries, helping researchers better understand the ageing brain.

Author Contributions: Conceptualization, M.R., M.P. and M.D.; methodology, M.R., M.P. and A.K.; software, M.P. and M.D.; validation, M.D. and C.S.; formal analysis, M.R., M.P., A.K. and R.J.A.d.S.; investigation, M.R., C.S. and R.K.; resources, M.R. and A.K.; writing—original draft preparation, M.R., M.P. and M.D.; writing—review and editing, M.R., M.P., C.S. and R.J.A.d.S.; visualization, M.R., M.P., M.D. and R.K.; supervision, M.R. and M.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Centre for Research and Development, Poland, grant number LIDER/8/0051/L-8/16/NCBR/2017. This research was also supported by PTDC/EME-EME/1239/2021 (BAFHTA).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Dymek, M.; Ptak, M.; Ratajczak, M.; Fernandes, F.A.O.; Kwiatkowski, A.; Wilhelm, J. Analysis of HIC and Hydrostatic Pressure in the Human Head during NOCSAE Tests of American Football Helmets. *Brain Sci.* **2021**, *11*, 287. [\[CrossRef\]](#)
2. Hawley, C.; Sakr, M.; Scapinello, S.; Bjorndalen, H. Head Injury among Older Adults and Their Clinical Management: One Year of Emergency Department Attendances at a UK Trauma Center. *Brain Inj.* **2022**, *36*, 868–875. [\[CrossRef\]](#)
3. Florczak, A.; Skierkowska, N.A.; Wąsicki, M. Assessing the Risk of Falls of Older People Using Specialized Diagnostic Tests. *Artic. J. Educ. Health Sport* **2019**, *9*, 397–405. [\[CrossRef\]](#)
4. Abhilash, K.; Tephilah, R.; Pradeeptha, S.; Gunasekaran, K.; Chandy, G. Injury Patterns and Outcomes of Trauma in the Geriatric Population Presenting to the Emergency Department in a Tertiary Care Hospital of South India. *J. Emerg. Trauma. Shock.* **2019**, *12*, 198–202. [\[CrossRef\]](#)
5. Alter, S.M.; Gonzalez, M.R.; Solano, J.J.; Clayton, L.M.; Hughes, P.G.; Shih, R.D. Comparing Rates of Skull Fractures in Female versus Male Geriatric Patients Who Sustain Head Injuries. *Am. J. Emerg. Med.* **2023**, *65*, 168–171. [\[CrossRef\]](#)
6. Ptak, M.; Ratajczak, M.; Kwiatkowski, A.; Sawicki, M.; Wilhelm, J.; Fernandes, F.A.O.; Druszczyk, A. Investigation of Biomechanics of Skull Structures Damages Caused by Dynamic Loads. *Acta Bioeng. Biomech.* **2018**, *20*, 143–150.
7. Holtzhausen, L.J.; Souissi, S.; Al Sayrafi, O.; May, A.; Farooq, A.; Grant, C.C.; Korakakis, V.; Rabia, S.; Segers, S.; Chamari, K. Arabic Translation and Cross-Cultural Adaptation of Sport Concussion Assessment Tool 5 (SCAT5). *Biol. Sport* **2021**, *38*, 129–144. [\[CrossRef\]](#)
8. Shi, J.; Wang, J.; Lang, J.; Zhang, Z.; Bi, Y.; Liu, R.; Jiang, S.; Hou, L. Effect of Different Motor Skills Training on Motor Control Network in the Frontal Lobe and Basal Ganglia. *Biol. Sport* **2020**, *37*, 405–413. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Waltzman, D.; Haarbauer-Krupa, J.; Womack, L.S. Traumatic Brain Injury in Older Adults—A Public Health Perspective. *JAMA Neurol.* **2022**, *79*, 437–438. [\[CrossRef\]](#) [\[PubMed\]](#)
10. Giorgio, A.; Santelli, L.; Tomassini, V.; Bosnell, R.; Smith, S.; De Stefano, N.; Johansen-Berg, H. Age-Related Changes in Grey and White Matter Structure throughout Adulthood. *Neuroimage* **2010**, *51*, 943–951. [\[CrossRef\]](#) [\[PubMed\]](#)
11. Peters, R. Ageing and the Brain. *Postgrad. Med. J.* **2006**, *82*, 84–88. [\[CrossRef\]](#)
12. Demsas, F.; Joiner, M.M.; Telma, K.; Flores, A.M.; Teklu, S.; Ross, E.G. Disparities in Peripheral Artery Disease Care: A Review and Call for Action. *Semin. Vasc. Surg.* **2022**, *35*, 141–154. [\[CrossRef\]](#)
13. Kleiven, S.; von Holst, H. Consequences of Head Size Following Trauma to the Human Head. *J. Biomech.* **2002**, *35*, 153–160. [\[CrossRef\]](#)

14. Horanin-Dusza, M. *The Analysis of the Biomechanical and Histological Properties of Cerebral Bridging Veins in Alcoholics and Nonalcoholics—the Importance in the Subdural Hematomas Etiology*; Medical University: Wrocław, Poland, 2009. (In Polish)
15. Famaey, N.; Ying Cui, Z.; Umuhire Musigazi, G.; Ivens, J.; Depreitere, B.; Verbeken, E.; Vander Sloten, J. Structural and Mechanical Characterisation of Bridging Veins: A Review. *J. Mech. Behav. Biomed. Mater.* **2015**, *41*, 222–240. [[CrossRef](#)]
16. Migueis, G.F.J.; Fernandes, F.A.O.; Ptak, M.; Ratajczak, M.; Alves de Sousa, R.J. Detection of Bridging Veins Rupture and Subdural Haematoma Onset Using a Finite Element Head Model. *Clin. Biomech.* **2019**, *63*, 104–111. [[CrossRef](#)] [[PubMed](#)]
17. Kurowiak, J.; Mackiewicz, A.; Klekiel, T.; Będziński, R. Evaluation of Selected Properties of Sodium Alginate-Based Hydrogel Material—Mechanical Strength, MDIC Analysis and Degradation. *Materials* **2022**, *15*, 1225. [[CrossRef](#)]
18. Kolias, A.G.; Chari, A.; Santarius, T.; Hutchinson, P.J. Chronic Subdural Haematoma: Modern Management and Emerging Therapies. *Nat. Rev. Neurol.* **2014**, *10*, 570–578. [[CrossRef](#)]
19. Dyniewicz, B.; Bajkowski, J.M.; Bajer, C.I. Effective Viscoplastic-Softening Model Suitable for Brain Impact Modelling. *Materials* **2022**, *15*, 2270. [[CrossRef](#)] [[PubMed](#)]
20. Glowinski, S.; Obst, M.; Majdanik, S.; Potocka-Banaś, B. Dynamic Model of a Humanoid Exoskeleton of a Lower Limb with Hydraulic Actuators. *Sensors* **2021**, *21*, 3432. [[CrossRef](#)]
21. Pietroń, K.; Mazurkiewicz, Ł.; Sybilski, K.; Małachowski, J. Correlation of Bone Material Model Using Voxel Mesh and Parametric Optimization. *Materials* **2022**, *15*, 5163. [[CrossRef](#)] [[PubMed](#)]
22. Klekiel, T.; Arkusz, K.; Sławiński, G.; Malesa, P.; Będziński, R. Numerical Analyses of Fracture Mechanism of the Pelvic Ring during Side-Impact Load. *Materials* **2022**, *15*, 5734. [[CrossRef](#)]
23. Sybilski, K.; Małachowski, J. Sensitivity Study on Seat Belt System Key Factors in Terms of Disabled Driver Behavior during Frontal Crash. *Acta Bioeng. Biomech.* **2019**, *21*, 169–180. [[CrossRef](#)] [[PubMed](#)]
24. Jozsko, K.; Wolański, W.; Burkacki, M.; Suchoń, S.; Zielonka, K.; Muszyński, A.; Gzik, M. Biomechanical Analysis of Injuries of Rally Driver with Head Supporting Device. *Acta Bioeng. Biomech.* **2016**, *18*, 159–169. [[CrossRef](#)] [[PubMed](#)]
25. Franklin, M.; Fildes, B.; Zhang, L.; Yang, K.; Sparke, L. Analysis of Finite Element Models for Head Injury Investigation: Reconstruction of Four Real-World Impacts. *Stapp Car Crash J.* **2005**, *49*, 1–32. [[PubMed](#)]
26. Horgan, T.J.; Gilchrist, M.D. The Creation of Three-Dimensional Finite Element Models for Simulating Head Impact Biomechanics. *Int. J. Crashworthiness* **2003**, *8*, 353–366. [[CrossRef](#)]
27. Kleiven, S. Predictors for Traumatic Brain Injuries Evaluated through Accident Reconstructions. *Stapp Car Crash J.* **2007**, *51*, 81–114. [[PubMed](#)]
28. Wilhelm, J.; Ptak, M.; Fernandes, F.A.O.; Kubicki, K.; Kwiatkowski, A.; Ratajczak, M.; Sawicki, M.; Szarek, D. Injury Biomechanics of a Child’s Head: Problems, Challenges and Possibilities with a New AHEAD Finite Element Model. *Appl. Sci.* **2020**, *10*, 4467. [[CrossRef](#)]
29. Ptak, M.; Dymek, M.; Sawicki, M.; Fernandes, F.A.O.; Wnuk, M.; Wilhelm, J.; Ratajczak, M.; Witkowska, D.; Kwiatkowski, A.; Poźniak, B.; et al. Experimental and Computational Approach to Human Brain Modelling—AHEAD. *Arch. Civil. Mech. Eng.* **2023**, *23*, 218. [[CrossRef](#)]
30. Fernandes, F.A.O.; Tchepel, D.; Alves de Sousa, R.J.; Ptak, M. Development and Validation of a New Finite Element Human Head Model. *Eng. Comput.* **2018**, *35*, 477–496. [[CrossRef](#)]
31. Monea, A.G.; Baeck, K.; Verbeken, E.; Verpoest, I.; Sloten, J.V.; Goffin, J.; Depreitere, B. The Biomechanical Behaviour of the Bridging Vein–Superior Sagittal Sinus Complex with Implications for the Mechanopathology of Acute Subdural Haematoma. *J. Mech. Behav. Biomed. Mater.* **2014**, *32*, 155–165. [[CrossRef](#)]
32. DYNAmore GmbH. *LS-DYNA Examples, Wave-Structure Interaction*; DYNAmore GmbH: Dresden, Germany, 2012.
33. Giordano, C.; Kleiven, S. Development of a 3-Year-Old Child FE Head Model, Continuously Scalable from 1.5-to 6-Year-Old. In Proceedings of the IRCOBI Conference, Malaga, Spain, 14–16 September 2016; pp. 288–302.
34. Ratajczak, M.; Ptak, M.; Chybowski, L.; Gawdzińska, K.; Będziński, R. Material and Structural Modeling Aspects of Brain Tissue Deformation under Dynamic Loads. *Materials* **2019**, *12*, 271. [[CrossRef](#)]
35. DynaMore Human Model—Total HUMAN Model for Safety THUMS v 4.0. Available online: <https://www.dynamore.se/en/products/models/human> (accessed on 16 December 2023).
36. Gomez-Gesteira, M.; Rogers, B.D.; Crespo, A.J.C.; Dalrymple, R.A.; Narayanaswamy, M.; Dominguez, J.M. SPHysics—Development of a Free-Surface Fluid Solver—Part 1: Theory and Formulations. *Comput. Geosci.* **2012**, *48*, 289–299. [[CrossRef](#)]
37. Hardy, W.N.; Mason, M.J.; Foster, C.D.; Shah, C.S.; Kopacz, J.M.; Yang, K.H.; King, A.I.; Bishop, J.; Bey, M.; Anderst, W.; et al. A Study of the Response of the Human Cadaver Head to Impact. *Stapp Car Crash J.* **2007**, *51*, 17–80. [[CrossRef](#)] [[PubMed](#)]
38. Tsui, E.Y.K.; Fai Ma, K.; Cheung, Y.K.; Chan, J.H.M.; Yuen, M.K. Rapid Spontaneous Resolution and Redistribution of Acute Subdural Hematoma in a Patient with Chronic Alcoholism: A Case Report. *Eur. J. Radiol.* **2000**, *36*, 53–57. [[CrossRef](#)] [[PubMed](#)]
39. Kim, H.I.; Oh, Y.J.; Cho, Y.N.; Choi, Y.-C. Subdural Hemorrhage Mimicking Peripheral Neuropathy. *J. Korean Neurosurg. Soc.* **2014**, *56*, 166–167. [[CrossRef](#)] [[PubMed](#)]
40. Wolański, W.; Kawlewska, E.; Larysz, D.; Gzik, M.; Gorwa, J.; Michnik, R. Prediction of the Child’s Head Growth in the First Year of Life. In *Lecture Notes in Computational Vision and Biomechanics*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 267–275.
41. DeCarli, C.; Massaro, J.; Harvey, D.; Hald, J.; Tullberg, M.; Au, R.; Beiser, A.; D’Agostino, R.; Wolf, P.A. Measures of Brain Morphology and Infarction in the Framingham Heart Study: Establishing What Is Normal. *Neurobiol. Aging* **2005**, *26*, 491–510. [[CrossRef](#)] [[PubMed](#)]

42. Zanto, T.P.; Gazzaley, A. Aging of the Frontal Lobe. In *Handbook of Clinical Neurology*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 369–389.
43. Toma, M.; Nguyen, P.D.H. Fluid–Structure Interaction Analysis of Cerebrospinal Fluid with a Comprehensive Head Model Subject to a Rapid Acceleration and Deceleration. *Brain Inj.* **2018**, *32*, 1576–1584. [[CrossRef](#)] [[PubMed](#)]
44. Madhukar, A.; Chen, Y.; Ostojja-Starzewski, M. Effect of Cerebrospinal Fluid Modeling on Spherically Convergent Shear Waves during Blunt Head Trauma. *Int. J. Numer. Method. Biomed. Eng.* **2017**, *33*, e2881. [[CrossRef](#)] [[PubMed](#)]
45. Ptak, M.; Wilhelm, J.; Sawicki, M.; Dymek, M.; Fernandes, F.A.O.; Kristen, H.; Garatea, E. Assessment of Child Safety on Bicycles in Baby Carriers—The Importance of Evaluating Both Head and Neck Injuries. *J. Safety Res.* **2023**, *85*, 254–265. [[CrossRef](#)]
46. Li, S.; Xiao, Z.; Zhang, Y.; Li, Q.M. Impact Analysis of a Honeycomb-Filled Motorcycle Helmet Based on Coupled Head-Helmet Modelling. *Int. J. Mech. Sci.* **2021**, *199*, 106406. [[CrossRef](#)]
47. Yanaoka, T.; Dokko, Y. A Parametric Study of Age-Related Factors Affecting Intracranial Responses under Impact Loading Using a Human Head/Brain FE Model. In Proceedings of the IRCOBI Conference, Gothenburg, Sweden, 11–13 September 2013.
48. Abdi, H.; Sanchez-Molina, D.; Garcia-Vilana, S.; Rahimi-Movaghar, V. Quantifying the Effect of Cerebral Atrophy on Head Injury Risk in Elderly Individuals: Insights from Computational Biomechanics and Experimental Analysis of Bridging Veins. *Injury* **2023**, *54*, 111125. [[CrossRef](#)] [[PubMed](#)]
49. Zhou, Z.; Li, X.; Kleiven, S. Biomechanics of Acute Subdural Hematoma in the Elderly: A Fluid-Structure Interaction Study. *J. Neurotrauma* **2019**, *36*, 2099–2108. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.