Heliyon 10 (2024) e31123

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Quantitative assessment of traumatic brain injury risk in diverse age groups of females: Insights from computational biomechanics

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A R T I C L E I N F O

Keywords:
Traumatic brain injury (TBI)
Head impact
Finite element model (FEM)
Female
Injury prevention
Computational biomechanics

A B S T R A C T

Traumatic Brain Injury (TBI) stands as a multifaceted health concern, exhibiting varying influences across human population. This study delves into the biomechanical complexities of TBI within gender-specific contexts, focusing on females. Our primary objective is to investigate distinctive injury mechanisms and risks associated with females, emphasizing the imperative for tailored investigations within this cohort.

By employing Fluid-Structure Interaction (FSI) Analysis, we conducted simulations to quantify biomechanical responses to traumatic forces across diverse age groups of females. The study utilized a scaling technique to create finite element models (FEMs). The young female FEM, based on anthropometric data, showcased a 15 % smaller head geometry compared to the young male FEM. Moreover, while the elderly female FEM closely mirrored the young female FEM in most structural aspects, it showed distinctive features such as brain atrophy and increased cerebrospinal fluid (CSF) layer thickness. Notably, the child female FEM (ages 7–11 years) replicated around 95 % of the young female FEM's geometry. These structural distinctions meticulously captured age-specific variations across our modeled female age groups. It's noteworthy that identical conditions, encompassing impact intensity, loading type, and boundary conditions, were maintained across all FEMs in this biomechanical finite element analysis, ensuring comparative results.

The findings unveiled significant variations in frontal and occipital pressures among diverse age groups, highlighting potential age-related discrepancies in TBI susceptibility among females. These variations were primarily linked to differences in anatomical features, including brain volume, CSF thickness, and brain condition, as the same material properties were used in the FEMs. These results were approximately 4.70, 6.33 and 6.43 % in frontal area of brain in diverse age groups of females (young, elderly, and child) respectively compared to young male FEM. Comparing the FEM results between the young female and the elderly female, we observed a decrease in occipital brain pressure at the same point, reducing from 171,993 to 167,793 Pa, marking an approximate 2.5 % decrease. While typically the elderly exhibit greater brain vulnerability compared to the young, our findings showcase a reduction in brain pressure. Notably, upon assessing the relative movement between the brain and the skull at the point

Abbreviations: FEM, Finite Element Model; TBI, Traumatic Brain Injury; MS, Multiple Sclerosis; CSF, Cerebrospinal Fluid; CT, Computed Tomography; MRI, Magnetic Resonance Imaging; FSI, Fluid-Structure Interaction.

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https://doi.org/10.1016/j.heliyon.2024.e31123
Received 9 December 2023; Received in revised form 9 May 2024; Accepted 10 May 2024
Available online 11 May 2024
2405-8440/

located in occipital area, we observed greater relative movement in the elderly (1.8 mm) compared to the young female (1.04 mm). Therefore, brain atrophy increases the range of motion of the brain within the cranial space. The study underscores the critical necessity for nuanced TBI risk assessment tailored to age and gender, emphasizing the importance of age-specific protective strategies in managing TBIs across diverse demographics. Future research employing individual modeling techniques and exploring a wider age spectrum holds promise in refining our understanding of TBI mechanisms and adopting targeted approaches to mitigate TBI in diverse groups.

1. Introduction

Traumatic Brain Injury (TBI) remains a critical global health concern with profound socio-economic and public health implications [1,2]. TBI affects individuals across a wide spectrum of demographics, but the specific risk factors, outcomes, and mechanisms of injury can vary significantly among different groups [3,4]. While TBI research has traditionally centered on general populations, there's a growing recognition of the necessity for tailored investigations, particularly in the context of unique subpopulations such as females [5–7]. It is now clear that TBI doesn't uniformly impact all individuals. Emerging evidence underscores the pivotal role of gender in shaping the manifestations of TBI. These distinctions encompass variations in cranial and brain anatomy, as well as disparities in the material properties of these tissues, ultimately resulting in unique biomechanical responses to injury [8,9]. Amidst these considerations, several critical research questions emerge:

- How do gender- and age-specific differences in cranial and brain anatomy lead to changes in TBI risk and outcomes among different population groups?
- What are the distinct biomechanical responses to TBI in females compared to males, and different age groups, and how do these responses influence injury severity?
- How can computational biomechanics approaches be leveraged to quantify and predict TBI risk specifically in female populations, different age groups, considering their unique anatomical and biomechanical characteristics?

Despite this growing awareness, the vulnerabilities of subpopulations, particularly females, remain a relatively underexplored domain within the TBI research landscape. Therefore, comprehending the distinct biomechanical aspects of TBI in females represents a critical step forward in mitigating the impact of this devastating injury.

Anatomical disparities between males and females have been recognized as pivotal factors influencing the differing responses to TBI [10]. These disparities encompass variations in cranial anatomy and head-neck biomechanics. Notably, males generally possess larger total brain volumes, higher Intracranial Volume (8–15 %), and greater tissue/region-specific volumes when compared to females [11]. Caviness Jr (1996) conducted a study utilizing Volumetric MRI-based morphometry to analyze the brains of 30 typically developing children aged between 7 and 11 years. The findings revealed that within this age range, the brain reaches 95 % of the volume observed in the adult brain. Additionally, the study noted that the female child's brain volume is approximately 93 % of the male child's brain volume [12]. These differences in brain size significantly influence the biomechanics of TBI, determining how forces are transmitted and absorbed during an impact event.

Biomechanical studies, especially those employing computational techniques, have been instrumental in shedding light on how anatomical changes can impact the trauma response in individuals. Through the simulation of the mechanical behavior of the brain and skull under various conditions, researchers can explore the influence of anatomical variations on TBI risk [13–15]. Of particular relevance to this study, two pivotal investigations by Abdi et al., in 2023 have provided invaluable insights into the intricate relationship between brain anatomy, biomechanics, and head injury risk. The first study, examined the effect of brain atrophy on brain injury in individuals with multiple sclerosis (MS). Employing a FSI model and MRI data, the research investigated the impact of brain atrophy at different stages of MS progression. This study revealed that brain atrophy in MS patients can accelerate and exacerbate the effects of traumatic impacts. The degree of atrophy was found to lead to varying injury outcomes [16]. In a subsequent study, the same research team focused on the elderly population and quantitatively explored the relationship between cerebral atrophy and the risk of head injury. Utilizing advanced computational biomechanics techniques, they developed head models representing both healthy brains and those with varying degrees of atrophy. These models were then subjected to impact loading conditions. The outcomes demonstrated a positive correlation between increased brain atrophy and elevated head injury risk. Furthermore, the mechanical properties of cerebral bridging veins were identified as a critical factor in injury susceptibility, particularly among older individuals. These studies collectively contribute to our understanding of the complex interplay between anatomical changes, biomechanics, and head injury risk across diverse medical conditions and age groups [9].

In a study conducted in 2023 by Gustavo P. Carmo et al. the authors addressed the pressing issue of traumatic brain injuries by introducing a novel finite element head model for females. Their comprehensive methodology encompassed medical image acquisition, age-specific brain material modeling, and validation through experimental data on human cadavers. The results revealed a high degree of correlation between numerical displacement curves and experimental data, with a notable similarity in pressure fields when compared to another model [8].

The primary aim of this study is to delve into the intricate biomechanical aspects of TBI, with a specific focus on females. By studying the mechanics of TBI within gender-specific contexts, we can uncover vital insights into the distinct injury mechanisms and risks associated with females. To achieve this, we employ a cutting-edge approach, FSI Analysis, to model and simulate the complex interactions between cerebral tissues, cerebrospinal fluid, and the surrounding structures. By utilizing FSI, we aim to accurately quantify and visualize the biomechanical responses to traumatic forces, providing invaluable insights into TBI specific to females.

2. Materials and methods

2.1. Methodology

Our study aimed to comprehensively represent the female population by encompassing three distinct age groups: children (7–11 years), young adults, and elderly individuals. This selection allowed us to capture developmental differences in cranial and brain structures, acknowledging the distinct biomechanical characteristics associated with different life stages. There are two primary methods to investigate brain damage in females:

1) **Finite Element Modeling with Scaling Technique:** In the present study, this method was used. We constructed a finite element model (FEM) of a healthy young male head. Subsequently, we utilized a scaling technique to modify the size of the skull and brain based on anthropometric data specific to the age groups of females (young, elderly and child). This approach enabled us to simulate and analyze the influence of head trauma across different developmental stages.
2) **Individualized Finite Element Modeling using Imaging Data:** In the second method, individual FEMs can be created for each of the three age groups of females. It involves using CT scans and MRI images obtained from participants in each age group to create personalized FEMs. By incorporating individual imaging data, we can account for anatomical variations and structural differences unique to each age group.

By employing these methodologies, we sought to gain insights into the biomechanical responses to brain injury across different stages of female development, laying the foundation for a more nuanced understanding of traumatic brain damage in females.

2.2. Finite element modeling

The creation of our finite element head models involved a meticulous process to accurately represent the complexities of the head-

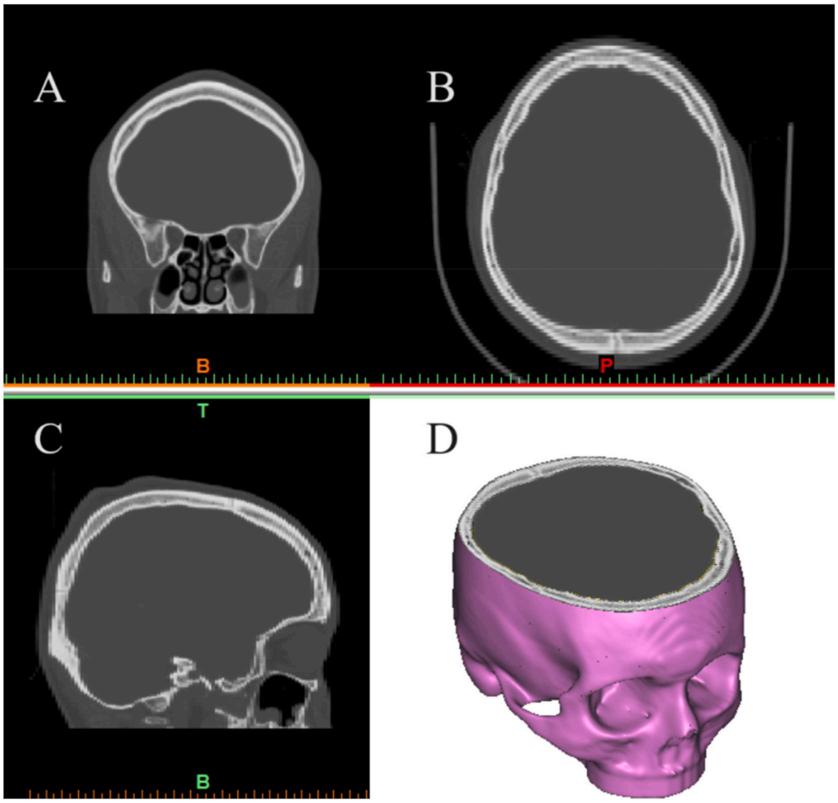

Fig. 1. Illustrating the process of constructing a finite element head model utilizing CT scan images: A: Coronal view, B: Axial view, C: Sagittal view, and D: Finalized Three-dimensional FEM representation.

brain system. The coordinates of key anatomical points were extracted from the medical images in a point cloud format. Subsequently, using SolidWorks version 2017, we transformed this data into a final volumetric and analyzable geometry, as illustrated in Fig. 1 (A: Coronal view, B: Axial view, C: Sagittal view, and D: Finalized Three-dimensional FEM representation).

The intricacies of the FEMs included comprehensive representations of the scalp, skull, cerebrospinal fluid (CSF), and brain. In Fig. 2, a visual representation is presented, elucidating the skeletal components comprising the skull and face (A: Frontal view of skull bone geometry and B: Cross-sectional view with transverse cut, highlighting the distinct layers and structures of the geometry). Additionally, the details of brain tissue are prominently depicted, affording a comprehensive insight into the anatomical structures under consideration.

In this study, we employed finite element modeling with a scaling technique to investigate head injury biomechanics across various age groups. Initially, a FEM representing the head of a healthy young male was constructed. Subsequently, employing anthropometric data specific to female age cohorts (young, elderly, and child), we applied a scaling technique to adjust the skull and brain sizes accordingly [11,12]. This innovative approach allowed for the creation of diverse models simulating different developmental stages. Table 1 encapsulates crucial details of these FEMs, including brain volume, CSF thickness, and the corresponding brain conditions simulated, ranging from a healthy state in young and child females to severe atrophy in elderly females. Additionally, the total mass of the head model varied across different demographic groups: it was 5.101 kg in the young male, 4.436 kg in the young female, 4.433 kg in the elderly female, and 4.214 kg in the Child Female group (ages 7–11 years). This methodology facilitated a comprehensive exploration of head trauma effects across distinct developmental phases, providing valuable insights into the biomechanical nuances of head injuries in varying age demographics.

To simulate the dynamics of head impact, we employed COMSOL Multiphysics and executed a FSI model. FSI Analysis was selected over other possible methods due to its unique ability to accurately model the complex interactions between fluid and solid components in biomechanical systems. Unlike traditional approaches that model fluid and solid domains separately, FSI enables the simultaneous consideration of fluid dynamics and solid mechanics within a unified framework. This integrated approach is particularly advantageous for our study on TBI, where understanding the dynamic interactions between cerebrospinal fluid and brain tissue is essential. By capturing the dynamic coupling between fluid and solid structures, FSI provides a more realistic representation of physiological phenomena, thereby enhancing the fidelity of our biomechanical simulations.

In this model, the CSF was conceptualized as a fluid domain, while the neighboring structures, such as the skull bones, facial bones, and brain tissue, were conceptualized as solid domains. This formulation allowed for the precise transmission of forces and motion between the fluid and solid constituents, enabling a realistic representation of the biomechanical responses to traumatic forces.

2.3. Material properties

Table 2 provides the material properties applied across all groups. Through COMSOL Multiphysics, our study implemented a FSI model to emulate head impact dynamics. Within this model, CSF was represented as a fluid domain with a density of 1000 kg/m^3 and a dynamic viscosity of 0.001 Pa s [9]. In contrast, the skull bones, facial bones, and brain tissue were delineated as solid domains, facilitating precise force and motion transmission between constituents. The skull bone was modeled as elastic structure, characterized by a density of 2100 kg/m^3, a Young's modulus of 7 GPa [17–20]. For the brain tissue, a viscoelastic formulation was adopted, incorporating a shear modulus (G_0) of 12.5 kPa, a shear modulus at infinite time (G_∞) of 2.5 kPa, a decay constant of 80 s^{-1}, and a bulk modulus of 2.19 GPa. The brain's viscoelastic behavior was defined using a Prony series function in COMSOL Multiphysics [21]:

$$G(t) = G_\infty + (G_0 - G_\infty)e^{-\beta t}$$

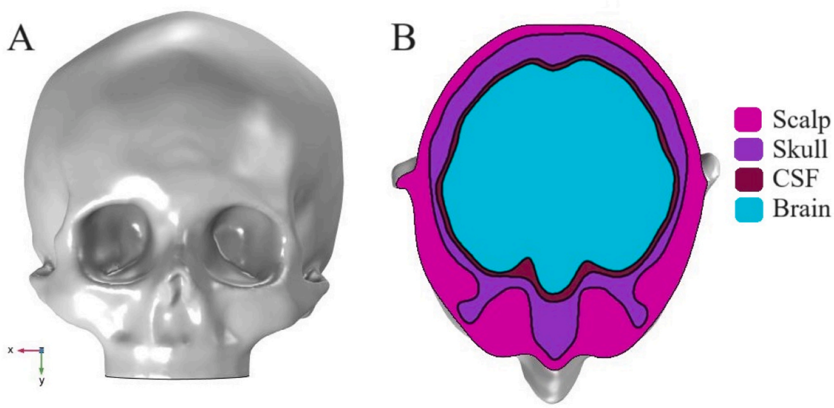

Fig. 2. Detailed view of head model. A: Frontal view of skull bone geometry. B: Cross-sectional view with transverse cut, highlighting the distinct layers and structures of the geometry.

Table 1
Characteristics of FEMs representing head structures in different age groups.

FEMs	Brain Volume (cm^3)	CSF Thickness (mm)	Brain Condition
Young Male	1419	2	Healthy
Young Female	1234	2	Healthy
Elderly Female	1172	3.8	Severe Atrophy
Child Female (7–11 years)	1172	2	Healthy

Table 2
Mechanical properties of head components used in FEMs.

Components	Behavior	Density	Young's modules	Poisson's ratio	Bulk Modulus	Ref.
Scalp	Elastic	1130 kg/m3	16.7 MPa	0.42	—	[17,18]
Skull bone	Elastic	2100 kg/m3	7000 MPa	0.22	–	[19,20]
Brain	Viscoelastic	1060 kg/m3	–	0.49	2.19 GPa	[21]
CSF	Fluid	1000 kg/m3	–	–		[9]

2.4. Model validation

To validate the head FEMs used in this study, we relied on experimental data obtained from Nahum et al. In their research, two series of human head cadavers were utilized. Series I consisted of eight separate impact experiments conducted on individual heads, during which intracranial pressure measurements were recorded. Series II involved successive impacts on a single sample [22]. In Nahum's experiment, the human head underwent a 45-degree rotation in the Frankfurt plane to the horizontal position before an impact was applied using an impactor. The mass and velocity of the impactor were recorded as 5.59 kg and 9.94 m/s, respectively (experiment 37). The force-time diagram necessary for our study was extracted from the impact force data reported by Nahum et al. and then applied to the young male FEM. Specifically, Fig. 3 illustrates the force-time diagram used in experiment number 37. We calculated the intracranial pressure and head acceleration in young male head model simulation and compared them to Nahum's experiment for validation purposes.

Sensitivity analyses were conducted to assess the influence of key parameters on the model's predictions, providing insights into the robustness of our computational approach. With the number of 177128 tetrahedral elements for FEM, the results show independence from the element size. Table 3 shows the results of mesh sensitivity in young male model at Time = 0.0017 s.

2.5. Final impact loading conditions

In our final investigation, particular emphasis was placed on scrutinizing rotational loading within the sagittal plane, aligning with the observation of anterior-posterior head motion in frontal crashes. To address this critical aspect, we incorporated experimental kinematics, introducing peak translational acceleration of 450 g and peak rotational acceleration of 26.2 krad/s^2 [23]. The impact loading conditions adopted for our study are elucidated in Fig. 4, involving clockwise rotational motion around the x-axis combined with translational motion along the z-axis. The left panel of Fig. 4 shows rotational acceleration, while the right panel shows translational acceleration. These loading conditions were chosen to simulate the dynamics observed in frontal crashes, allowing for a comprehensive examination of the biomechanical responses of the head-brain system.

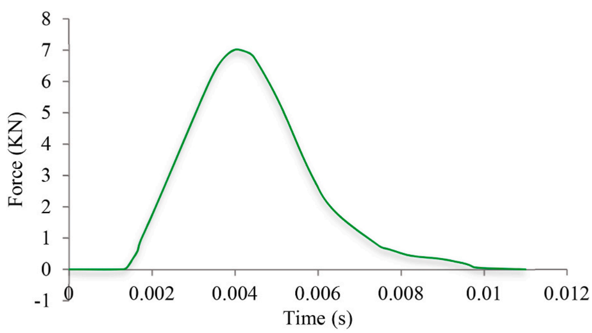

Fig. 3. Force-time diagram derived from experiment 37 by Nahum applied to the young male FEM.

Table 3
Mesh sensitivity results in young male model at Time = 0.0017 s.

Run No.	1	2	3	4	5	6
Number of elements	31901	39625	57790	95680	124805	177128
Frontal Pressure (Pa)	−202330	−204055	−205141	−205314	−206146	−206408

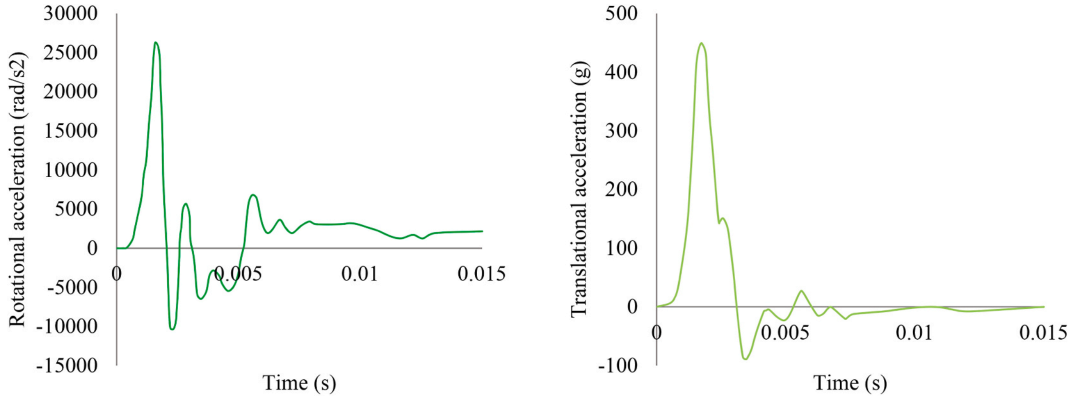

Fig. 4. Head loading conditions employed in the impact study: Left Panel: rotational acceleration and Right Panel: translational acceleration.

3. Results

3.1. Results of validation

Our computational FEMs underwent rigorous validation against Nahum's experiments. By applying loading conditions on the young male FEM, we calculated intracranial pressures in key regions, namely the frontal and occipital regions. Comparative analysis between experimental and numerical data, as presented in Table 4, revealed remarkable alignment. Specifically, the frontal region exhibited a maximum relative error of approximately 6 %, while the occipital region demonstrated the lowest relative error of about 3 %. For visual representation, refer to Fig. 5, illustrating pressure contours during head impact at time = 0.004 s (A: brain pressure and B: CSF pressure).

It is notable that, in our simulation of head impacts, the positive and negative pressure values derived from both the frontal and occipital regions of the brain are referenced against the baseline pressure within the brain tissue. Positive pressure signifies compressive forces, whereas negative pressure indicates tensile forces in relation to this baseline pressure within the brain tissue.

3.2. Results of final impact

Assessment of impact dynamics provided quantifiable insights into pressure variations across different models. Frontal pressures, detailed in Fig. 6, indicated distinct values among the studied groups: −206408 Pa for the young male FEM, −196712 Pa for young female FEM, −193331 Pa for elderly female FEM, and −193137 Pa for child female FEM.

Similarly, occipital pressures (Fig. 7) showcased variations: 180339 Pa for the young male, 171993 Pa for young female, 167793 Pa for elderly females, and 168094 Pa for child female.

Furthermore, Fig. 8 visually encapsulated maximum pressure contours in a lateral view across the diverse FEMs, occurring at 17 ms, elucidating differential pressure distributions based on age and gender (A: Young male, B: Young female, C: Elderly female and D: Child female).

Fig. 9 intricately depicted contours of maximum first principal logarithmic strains in the frontal view and the cutting side of the side view across the FEMs, manifesting varying strain distributions within 0.015 s post-impact, highlighting age and gender-related distinctions (A: Young male, B: Young female, C: Elderly female and D: Child female).

Table 4
Comparison of intracranial pressure between simulation and experiment, extracted from Nahum et al.'s experiment No. 37. Error rates indicate agreement between simulated and experimental results.

Region	Frontal	Left Occipital #1	Right Occipital #1
Nahum Experiment	141188 Pa	−45463 Pa	−48396 Pa
Simulation	149700 Pa	−46820 Pa	−49830 Pa
Error	6 %	3 %	3 %

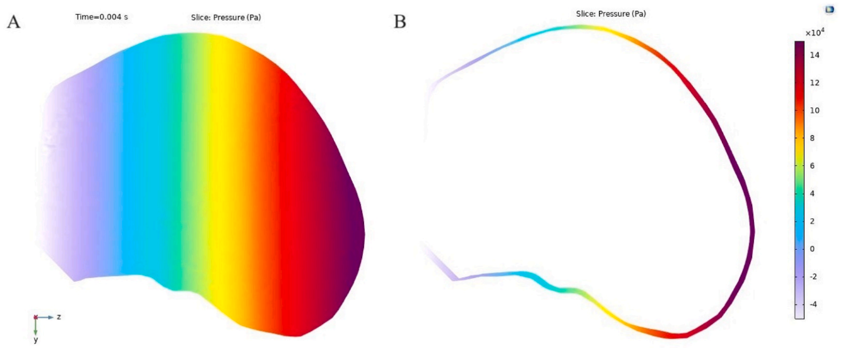

Fig. 5. Pressure contours during head impact at peak time (0.004 s): A: brain pressure and B: CSF pressure.

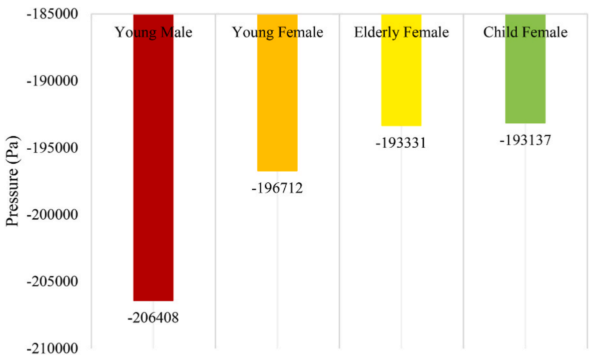

Fig. 6. Analyzing maximum frontal pressure variations among FEM groups in head injury simulation at 17 ms.

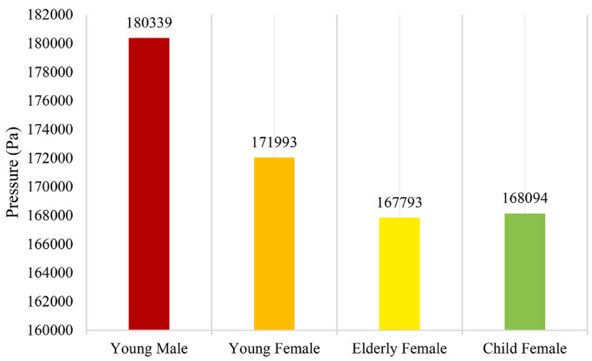

Fig. 7. Investigating comparative maximum occipital pressure at 17 ms in various FEM groups.

4. Discussion

In the present study, we used FEMs for head simulation that represent structural variations among diverse female age groups. The young female FEM, based on anthropometric data, exhibits a 15 % smaller head geometry compared to the young male FEM. Additionally, the elderly female FEM closely resembles the young female FEM in most structural aspects, yet displays distinct brain atrophy and an increased CSF layer thickness. Notably, child female FEM (ages 7–11 years) was approximately 95 % of the geometry of young female FEM. These structural differences meticulously reflect age-specific variations across our modeled females age groups.

4.1. Biomechanical responses and age-related variations

The findings from our computational biomechanics study elucidate differential responses to traumatic forces among diverse age groups of females, offering crucial insights into TBI dynamics within gender-specific contexts. It is important to note that the same conditions among the FEMs (including: impact intensity, type of loading and boundary conditions for all FEMs) were performed in this

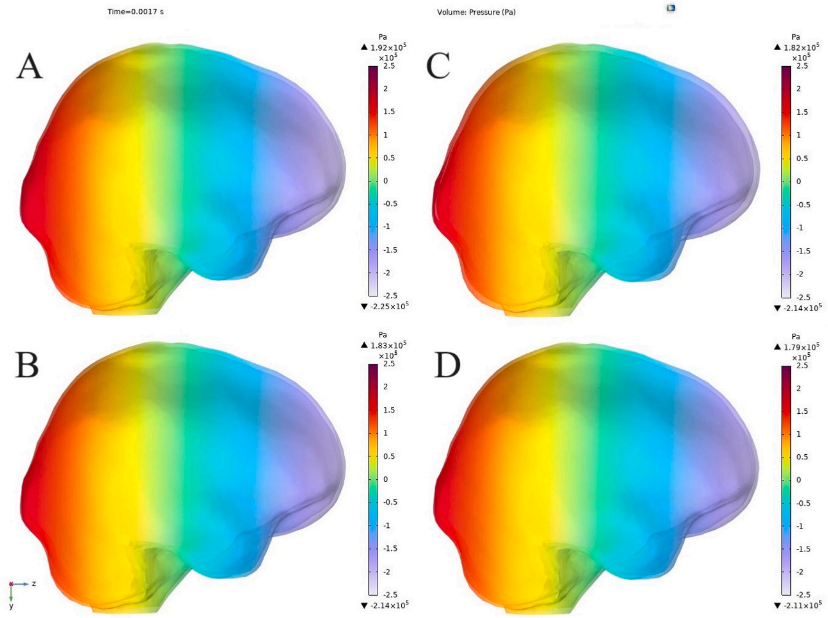

Fig. 8. Lateral view of maximum pressure contours in diverse FEMs at 17 ms: A: Young male B: Young female C: Elderly female D: Child female.

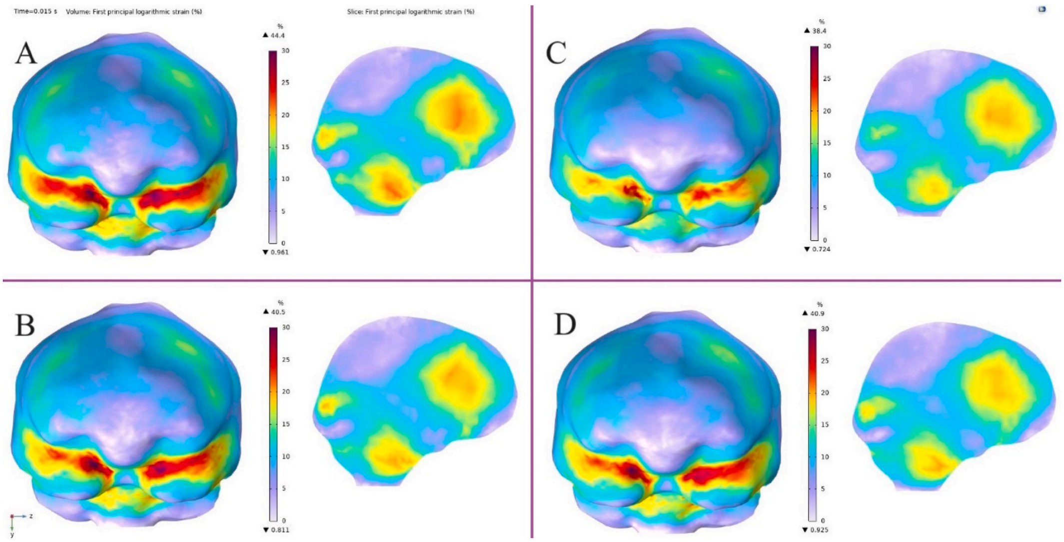

Fig. 9. Maximum first principal logarithmic strains in frontal and side views in FEMs at 0.015 s: A: Young male B: Young female C: Elderly female D: Child female.

biomechanical finite element analysis and the results were comparative. In this scenario, where the material properties also are identical, any variations observed in pressure responses, such as the frontal and occipital pressures, can be attributed predominantly to the differences in anatomical features like brain volume, CSF thickness, and brain condition among the FEMs.

The results of the pressure in the frontal area of the brain show significant changes in diverse age groups of females (young, elderly, and child) compared to the young male FEM, showcasing respective changes of approximately 4.70 %, 6.33 % and 6.43 %, respectively. Findings related to changes in occipital pressure also show a significant percentage of changes. The young female FEM, the elderly female FEM and the child female FEM displayed significant reductions in occipital pressures, with percentage reductions of approximately 4.63 %, 6.96 % and 6.79 %, respectively. These outcomes demonstrate distinct biomechanical responses to traumatic forces across age and gender groups, emphasizing potential age-related differences in susceptibility to TBI. The observed percentage changes in occipital pressures emphasize the importance of considering age-specific biomechanical responses when assessing injury risks. Appropriate preventive measures and interventions to address specific age groups of females may be critical in reducing the influence of traumatic forces on the brain, highlighting the necessity of age-tailored protective strategies in the management of TBI.

Comparing the FEM results between the young female and the elderly female, we observed a decrease in occipital brain pressure at the same point, reducing from 171,993 to 167,793 Pa, marking an approximate 2.5 % decrease. While typically the elderly exhibit greater brain vulnerability compared to the young, our findings showcase a reduction in brain pressure. Notably, upon assessing the relative movement between the brain and the skull at the point located in occipital area, we observed greater relative movement in the elderly (1.8 mm) compared to the young female (1.04 mm). This finding is consistent with our prior research on the impact of atrophy in MS patients on the severity of head injuries, as well as findings from Zhou et al.'s (2019) study, which delved into the effects of atrophy and aging on injury [10,24]. Therefore, brain atrophy increases the range of motion of the brain within the cranial space. Extending our analysis to the frontal area, a comparison between young and elderly females revealed an increase in relative movement in the elderly (10.94 mm) compared to young female (10.50 mm). This heightened relative movement, coupled with the observed alterations in frontal brain pressure, emphasizes the intricate relationship between anatomical changes and biomechanical responses in traumatic brain injury scenarios.

The findings of this study offer valuable insights into a crucial question: which factor holds greater significance, brain volume or CSF thickness? To address this inquiry, we begin by comparing the results of a Young Male with those of a Young Female, maintaining a constant CSF thickness of 2 mm but observing a significant decrease in brain volume from 1419 to 1234 cm^3 (nearly a 13 % reduction). Correspondingly, the pressure in the frontal region declined from −206408 Pa to −196712 Pa, representing an approximate 4.70 % decrease. Next, we contrast the outcomes of an Elderly Female with those of a Child Female (aged 7–11 years), wherein the latter maintains a consistent brain volume of 1172 cm^3 but experiences a decrease in CSF thickness from 3.8 to 2 mm. Consequently, the pressure in the frontal region decreased marginally from −193331 Pa to −193137 Pa, indicating a minimal decrease of about 0.1 %. While a superficial comparison solely on brain surface pressure suggests that larger brain volume entails more pronounced effects in traumatic incidents, it is crucial to acknowledge that alterations in CSF thickness not only impact brain pressure and stress but also significantly augment the relative displacement between the brain and the skull. This increased mobility within the cranial cavity heightens the vulnerability of the human head to trauma, underscoring the multifaceted nature of factors influencing traumatic outcomes. The multifaceted nature of some of these factors and the results of the study have also been considered in several other studies [9,16,21].

In a prior investigation conducted in 2022 by García-Vilana and Sánchez-Molina [25], researchers delved into the influence of age on the mechanical properties of bridging veins. The outcomes of the mechanical tests revealed a notable inverse relationship between age and the ultimate force, stress, and strain of these veins. However, no significant correlation was discerned between age and yield properties or Young's modulus. These findings strongly suggest a decline in the mechanical resilience of bridging veins with advancing age. Therefore, it's important to acknowledge that considering the mechanical properties at different ages, such as the diverse mechanical characteristics of cerebral bridging veins, skull bone, and brain tissue, could potentially yield significant alterations in the results. However, it's essential to note that in our interpretation, we held mechanical properties constant to focus on examining the effects of geometry more closely.

4.2. *Implications for traumatic brain injury risk assessment*

The findings from this study bear significant implications for the assessment and understanding of TBI risks across diverse age groups of females. The observed variations in frontal and occipital pressures, attributed primarily to anatomical differences among the FEMs, emphasize the necessity of nuanced TBI risk assessment protocols. The distinctive biomechanical responses across age and gender groups underscore the need for tailored approaches in assessing injury susceptibility. Notably, while the elderly often carry the presumption of heightened vulnerability to TBI, the observed reductions in brain pressure in this age group challenge these presumptions. Furthermore, these findings advocate for the development of age- and gender-specific risk assessment models that consider anatomical variations and their impact on biomechanical responses to traumatic forces. Such models could aid in predicting individualized injury risks and contribute to the formulation of targeted preventive strategies. Understanding the intricacies of age and gender related structural changes and their influence on injury susceptibility is paramount in refining TBI risk assessment frameworks and enhancing injury prevention measures.

4.3. *Limitations, considerations, and future directions*

In reflecting on our study's findings, it is important to acknowledge certain limitations and to outline potential avenues for future research that could refine and extend our understanding of TBI biomechanics.

- **Simulation Realism and Model Precision:** While our study's simulation settings and models were carefully designed to capture key biomechanical aspects, it is essential to recognize that these computational representations may not fully replicate the complexity of real-world conditions. As such, caution is advised in directly applying our findings to clinical or real-life scenarios, as the simplifications inherent in computational modeling may not fully capture the intricacies of human physiology and behavior.
- **Age-Specific Analysis and Modeling Techniques:** Our study focused on specific age groups, aiming to investigate age-related variations in TBI biomechanics. However, it is imperative to acknowledge that our study's scope was limited to certain age demographics, namely young, elderly, and child females. Expanding our analysis to encompass a broader age spectrum would provide a more comprehensive understanding of age-related biomechanical responses to TBI. Furthermore, while our study utilized Finite Element Modeling with Scaling Technique, which enables an approximation of age-related anatomical differences, future research

employing Individualized Finite Element Modeling based on individual imaging data could offer more precise representations of anatomical diversity within each age group.

- **Assumptions Regarding Brain Properties:** Another limitation of our study is the assumption of constant mechanical properties of the brain, such as density and modulus of elasticity, throughout the lifespan. While our focus on isolating geometrical changes allowed for a more precise investigation of their impact on head injury severity, we acknowledge that variations in these properties with aging may influence injury outcomes. Although ongoing research, including our recent investigation into density variations and their impact on head injury severity, aims to address this limitation, further studies exploring material properties across different ages are warranted to enhance our understanding in this area [26].
- **Comprehensive Biomechanical Analysis:** Another limitation of our study is the focus solely on biomechanical properties of the skull, CSF, and brain, without considering other factors that may influence susceptibility to TBI, such as differences in neck musculature, relative risk of fall, and participation in high-risk activities. While our research provides valuable insights into the biomechanical aspects of TBI, future studies should aim to incorporate these additional factors to offer a more comprehensive understanding of TBI susceptibility and risk factors.

Acknowledging and addressing these limitations pave the way for future research endeavors in computational biomechanics. By refining modeling techniques, incorporating individualized data, and considering a broader range of factors, we can advance our understanding of TBI biomechanics and develop more effective strategies for prevention, diagnosis, and treatment.

5. Conclusion

In conclusion, this study provides valuable insights into gender- and age-related biomechanical responses to TBI. The findings showed significant variations in frontal and occipital pressures across age groups, emphasizing potential age-related differences in susceptibility to TBI. These pressure differences predominantly due to anatomical variations, including brain volume, CSF thickness, and brain condition among the FEMs. Future research, leveraging individualized modeling techniques and exploring a wider age range, holds promise for refining our understanding of TBI dynamics and formulating more targeted approaches in mitigating TBIs across diverse groups.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Hamed Abdi: Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Abolfazl Mirani:** Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization. **Ramezan Jafari:** Writing – review & editing, Writing – original draft, Validation, Software, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Thanks to guidance and advice from "Clinical Research Development Unit of Baqiyatallah Hospital".

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