

Analysis of Optic Nerve Stress, Strain, and Pressure in Human Eyes with Different Axial Lengths under Different G-force Levels at a Normal Intraocular Pressure of 20 mmHg

Chia-Wen Lee,¹ Peng-San Cheng,² Chia-Jui Chang,³
Linda Yi-Chieh Poon,^{4,5} Chao-Ming Hsu,^{2*} and Cheng-Fu Yang^{3,6**}

¹School of Information Engineering, Xiamen Ocean Vocational College, Xiamen 361102, China

²Department of Mechanical Engineering, National Kaohsiung University of Science and Technology,
Kaohsiung 807, Taiwan

³Department of Chemical and Materials Engineering, National University of Kaohsiung,
Kaohsiung 811, Taiwan

⁴Department of Ophthalmology, Kaohsiung Chang Gung Memorial Hospital,
Kaohsiung 833, Taiwan

⁵School of Medicine, Chang Gung University, Taoyuan 333, Taiwan

⁶Department of Aeronautical Engineering, Chaoyang University of Technology, Taichung 413, Taiwan

(Received February 3, 2026; accepted October 15, 2026)

Keywords: nerve stress, strain, pressure, human eyes, different axial lengths, different G-force levels

In this study, we present a finite-element-based investigation of the biomechanical responses of the human eye under combined G-force loading and physiological intraocular pressure (IOP), with an emphasis on implications for ophthalmic sensing and measurement reliability. Three-dimensional eye models with different axial lengths were constructed and imported into ANSYS to perform modal and transient dynamic analyses. Modal analysis revealed that an increase in axial length consistently reduced the natural frequencies across all vibration modes, while the corresponding mode shapes remained largely unchanged, indicating preserved structural deformation patterns despite geometric variation. Dynamic simulations were conducted by constraining the eyeball to displace only along the primary loading axis, with external acceleration gradually increased from 1 to 6G. Within a normal human IOP of 20 mmHg, the resulting stress, strain, and pressure distributions in the optic nerve were systematically analyzed for eyes with different axial lengths. The results demonstrate that axial length significantly affects the magnitude and spatial distribution of optic nerve mechanical responses under different G-force levels, suggesting a nonnegligible coupling effect between ocular geometry and external dynamic loading. From a sensing perspective, these findings provide quantitative mechanical indicators that are critical for the calibration, interpretation, and validation of ophthalmic pressure and strain-related sensors. The primary objective is to clarify how ocular axial length affects optic nerve mechanical responses under different G-force levels at a normal IOP. However, the analysis is limited to numerical simulations with simplified material properties and boundary conditions, without direct experimental validation. Future investigations will be focused on improving the biomechanical representation of ocular tissues

*Corresponding author: e-mail: jammy@nkust.edu.tw

**Corresponding author: e-mail: cfyang@nuk.edu.tw

<https://doi.org/10.18494/SAM6274>

and evaluating the predicted responses under controlled experimental loading conditions. The proposed numerical framework offers a reliable platform for evaluating ocular biomechanical behavior under dynamic environments, thereby supporting the development of sensor-assisted diagnostic tools and enhancing the accuracy of eye-related biomechanical measurements in both clinical and aerospace contexts.

1. Introduction

The mechanical response of the human eye to external loading is a critical factor affecting both visual safety and the reliability of ophthalmic sensing technologies. Under physiological conditions, intraocular pressure (IOP) maintains ocular shape and ensures stable biomechanical equilibrium. For healthy adults, an IOP of approximately 20 mmHg is generally regarded as within the normal range.⁽¹⁾ However, even under normal IOP, additional external forces, such as acceleration-induced G-forces, can significantly modify stress transmission pathways within ocular tissues, particularly in the optic nerve. These effects are of increasing concern in dynamic environments involving rapid acceleration, vibration, or impact, where ocular biomechanics may deviate substantially from static clinical assumptions. G-force is particularly important in aviation because acceleration and changes in flight direction can generate additional inertial loading on ocular tissues. During normal commercial flights, passengers generally experience acceleration close to 1G, with relatively small deviations during takeoff, landing, and turbulence. In contrast, aerobatic maneuvers and high-performance aircraft operations may expose occupants to several G, potentially increasing mechanical load on the eyeball and optic nerve. Therefore, evaluating ocular responses under different G-force conditions is important for understanding acceleration-induced biomechanical changes and their implications for ophthalmic sensing.

From a materials and structural mechanics perspective, the eye is a heterogeneous biomechanical system composed of soft tissues with distinct elastic properties. Variations in ocular geometry, especially axial length, further complicate its mechanical behavior.⁽²⁾ Axial elongation, commonly associated with myopia, alters load distribution and structural stiffness, potentially amplifying localized stress and strain under external excitation. Such geometric dependence introduces uncertainty when interpreting measurements obtained from ocular sensors, as identical pressure readings may correspond to different internal mechanical states across individuals.^(3–5) Therefore, understanding how axial length affects optic nerve stress, strain, and pressure responses under combined IOP and G-force loading is essential for sensor-informed ophthalmic assessment. Recent decades have witnessed rapid development in ophthalmic sensing technologies, including contact and noncontact tonometry, implantable pressure sensors, and wireless microelectromechanical systems.^(6,7) These sensors have substantially improved the ability to monitor IOP in clinical and experimental settings.

Nevertheless, most existing sensing approaches focus on scalar pressure measurement and are limited in their capacity to capture distributed mechanical quantities such as strain and internal stress. Furthermore, sensor readings are typically interpreted without explicitly accounting for dynamic external loading or individual anatomical variation. This limitation

becomes particularly evident under nonstatic conditions, where transient forces may induce complex mechanical interactions that cannot be directly resolved through point-based sensing alone. To complement physical sensor measurements, computational modeling has emerged as an effective tool for biomechanical analysis and virtual sensing. In this context, numerical models function as distributed sensors, providing spatially resolved information on stress, strain, and pressure fields that are otherwise inaccessible *in vivo*. Finite element-based approaches are especially well suited for this purpose, as they enable the integration of material properties, geometric variation, and dynamic loading conditions within a unified framework. By coupling normal IOP conditions with externally applied G-force, such models allow the systematic evaluation of how mechanical signals propagate through ocular tissues and concentrate in vulnerable regions such as the optic nerve.^(8,9)

Liu *et al.* have recently demonstrated that ocular geometry, tissue properties, and loading conditions significantly affect optic nerve biomechanics.⁽¹⁰⁾ They reported that gaze-induced optic nerve head deformation increases with axial elongation, whereas Li *et al.* emphasized the importance of anatomical variations in finite element predictions.⁽¹¹⁾ However, the relationship among axial length, optic nerve surface pressure, and high G-force loading under a fixed physiological IOP remains insufficiently characterized. Further analysis of these coupled mechanical responses may provide useful information for interpreting ophthalmic sensing measurements. In this study, a finite element modeling framework is developed to investigate the biomechanical responses of human eyes with different axial lengths under a physiological IOP of 20 mmHg and external G-force loading. The analysis focuses on the resulting stress, strain, and pressure distributions in the optic nerve, treating these mechanical quantities as sensor-relevant indicators of ocular response. Modal and dynamic analyses are employed to examine how variation in axial length affects vibration characteristics and transient mechanical behavior under increasing G-force level.

By constraining motion along the primary loading direction, the simulations isolate the effects of acceleration-induced forces on optic nerve mechanics. The significance of this work lies in its relevance to sensor calibration, interpretation, and design. In our recently published paper in *Sensors and Materials*, we reported our investigation of optic nerve stress and strain under different G-force and IOP conditions.⁽¹²⁾ Building on that framework, the present work is focused more specifically on human eyes with different axial lengths at a fixed physiological IOP of 20 mmHg, with particular attention given to optic nerve surface pressure and its relationship to stress and strain responses. By examining pressure variations under three acceleration orientations and using a defined pressure extraction surface, the analysis enables a more focused assessment of geometry-dependent optic nerve loading and its implications for ophthalmic sensing. The obtained results provide quantitative insight into how geometric variability affects internal mechanical states under dynamic conditions, even when IOP remains within the normal range. Such information is valuable for improving the accuracy of ophthalmic pressure and strain sensors, as well as for developing model-assisted sensing strategies that integrate measured signals with biomechanical predictions. An important unresolved issue is the limited understanding of how individual ocular geometry and acceleration direction jointly affect internal optic nerve loading. Although the present numerical framework addresses this

issue through comparative simulations, experimental validation and more realistic tissue modeling remain necessary to improve its applicability to physiological conditions. Ultimately, the proposed approach contributes to a deeper understanding of ocular biomechanics under combined internal and external loading, supporting the advancement of sensor-based diagnostics and safety evaluation in ophthalmology and related fields.

2. Methodology

The numerical analysis of fluid and solid mechanics problems is commonly performed by the finite volume method (FVM) or the finite element method (FEM). In FVM, the computational domain is subdivided into numerous control volumes, within which governing equations are integrated and discretized in accordance with prescribed boundary conditions to obtain numerical solutions. FEM is particularly suitable for ocular biomechanical analysis because the human eye consists of multiple interconnected tissues with complex geometries and different mechanical properties. By discretizing these tissues into finite elements, FEM enables the evaluation of localized stress, strain, and deformation under prescribed loading and boundary conditions. Furthermore, it allows systematic comparisons of mechanical responses among eyes with different axial lengths, providing information that is difficult to obtain through direct experimental measurements. In this study, biomechanical simulations were conducted using the finite-element-based commercial software ANSYS Workbench 2020 R2, which consists of preprocessing, solution, and post-processing stages. During preprocessing, the appropriate analysis modules are selected, and material properties are defined by inputting relevant parameters into the material library. Fundamental simulation settings are then established, including material assignment, mesh generation, applied loads, and boundary conditions.

A mesh convergence analysis was conducted to ensure the numerical reliability of the finite element model. The mesh density was progressively increased, and the resulting stress values at the scleral apex and the central region of the optic nerve were compared. The results indicated that the numerical differences remained within 1% when the mesh contained approximately 375000 elements. Therefore, this mesh density was adopted for the subsequent simulations to achieve an appropriate balance between numerical accuracy and computational efficiency. After the numerical solution was obtained, post-processing tools were employed to extract nodal and elemental results, as well as global response parameters such as stress, strain, displacement, natural frequencies, and resonance characteristics. These numerical outputs were further visualized as contour maps and graphical distributions, enabling the intuitive interpretation of complex biomechanical responses and facilitating the analysis of the eye under dynamic loading conditions. The mechanical properties of the ocular tissues were defined using representative values obtained in previous biomechanical studies. Young's moduli of the sclera, cornea, and optic nerve were approximately 3.0, 1.5, and 0.030 MPa, while those of the ciliary body, aqueous humor, and vitreous humor were 11.0, 0.037, and 0.042 MPa, respectively. Poisson's ratio was generally set to 0.49 for nearly incompressible soft tissues, except for the ciliary body, for which a value of 0.40 was adopted. The material densities ranged approximately from 999 to 1600 kg/m³, depending on the ocular component. In addition, the eyeball was surrounded by

orbital adipose tissue rather than air, with a representative Young's modulus of 0.047 MPa, to account for the mechanical support provided by the surrounding soft tissue.

Owing to individual physiological variability, human eyeballs exhibit differences in geometric dimensions. In this study, the dimensions of all ocular components were defined referring to ophthalmological data and previously published literature.^(8,9) The three-dimensional geometric modeling of the human eye was performed using SolidWorks, and the resulting models were subsequently imported into ANSYS for numerical analysis. The modeled left human eyeball consists of the sclera, cornea, ciliary body, zonular fibers, optic nerve, aqueous humor, and vitreous humor, with the entire eyeball externally surrounded by a concentric annular layer representing orbital adipose tissue. The left eyeball was selected as a representative model for consistency in the numerical simulations. No specific biomechanical distinction between the left and right eyes was assumed. Under equivalent anatomical and mirrored loading conditions, both eyes are expected to exhibit similar overall mechanical responses. Therefore, only the left eye was modeled to facilitate systematic comparisons under different axial lengths and G-force levels. The detailed configuration and dimensions of each ocular component are illustrated in Fig. 1(a). For the normal eye model, the average axial length was set to 24 mm, with a maximum eyeball width of 22.5 mm. The cornea was defined with a radius of 7.6 mm and a thickness of 0.55 mm, while the sclera had a radius of 11.25 mm and a thickness of 0.75 mm. The

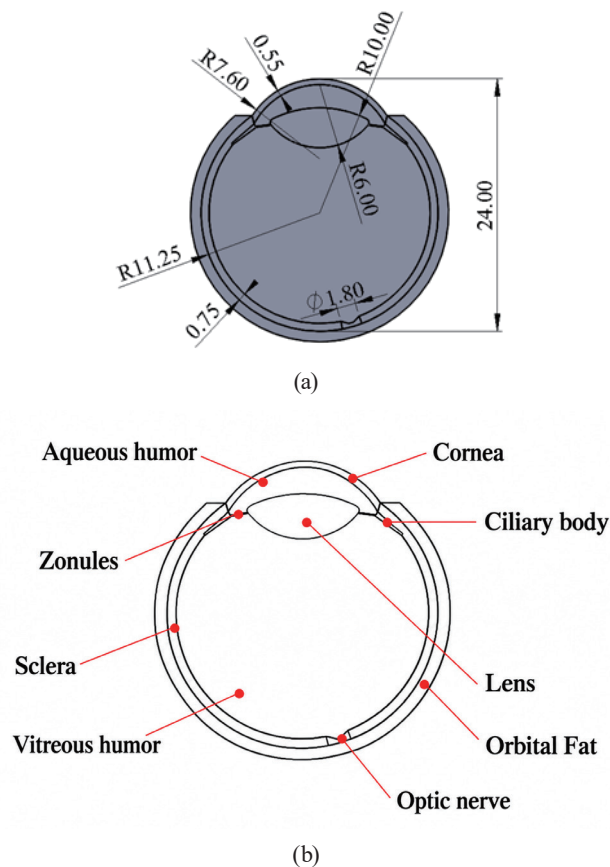


Fig. 1. (Color online) Ocular structure of the eyeball with an axial length of 24 mm: (a) geometric dimensions and (b) structural configuration of the eyeball model.

crystalline lens was modeled with anterior and posterior curvature radii of 10 and 6 mm, respectively. The optic nerve was positioned slightly inferonasal to the ocular axis, with a maximum diameter of 1.8 mm, as shown in Fig. 1(b).

The overall appearance of the assembled eyeball model is presented in Figs. 2(a) and 2(b), where all components are smoothly connected without gaps or discontinuities to ensure numerical stability and biomechanical continuity. Three representative flight orientations were considered to investigate the effects of acceleration on ocular biomechanics: vertical climb, level flight, and vertical descent. Vertical climb represents upward aircraft motion, level flight corresponds to horizontal motion, and vertical descent represents downward aircraft motion. These orientations were introduced to examine the effects of flight direction on the mechanical responses of the optic nerve under different G-force levels. The corresponding flight orientations and applied G-force directions are illustrated schematically to clarify the loading conditions used in the numerical simulations. In the transient structural simulations, the eyeball was constrained to allow displacement only along the Y-axis, while movements along the other axes were restricted. A time step of 0.1 s was adopted, and the applied acceleration increased progressively at a rate of 1G per second, reaching 6G after 6 s. The gravitational loading direction was adjusted using the Standard Earth Gravity function in ANSYS to represent the

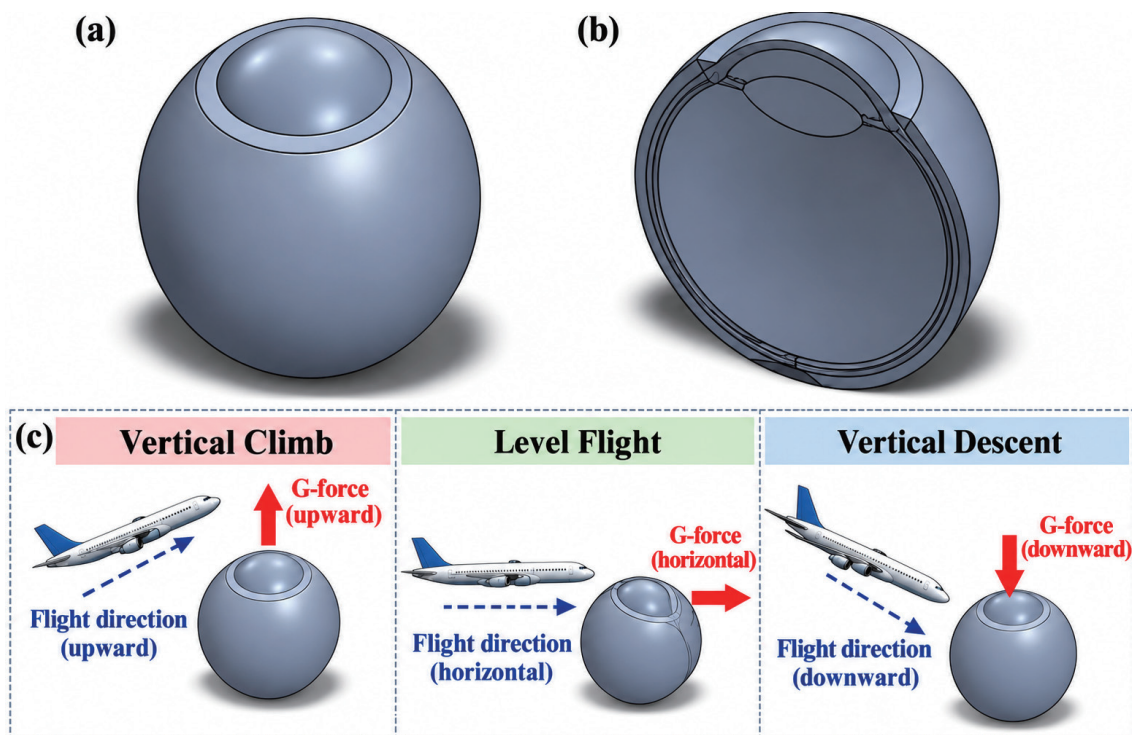


Fig. 2. (Color online) Eyeball model and schematic representation of flight orientations: (a) isometric view of the eyeball model, (b) isometric cross-sectional view, and (c) schematic illustration of vertical climb, level flight, and vertical descent, including the corresponding applied G-force directions.

three flight orientations. An IOP of 20 mmHg was applied to the inner surface of the eyeball throughout the simulations.

As illustrated in Fig. 2(c), the blue dashed arrows indicate the aircraft flight directions, whereas the red solid arrows represent the assumed G-force loading directions applied to the eyeball models. The three configurations correspond to upward, horizontal, and downward loading orientations, respectively. These simplified loading conditions were used to investigate how different acceleration directions affect the mechanical responses of ocular tissues. By comparing the resulting optic nerve stress, strain, and pressure distributions, the effects of flight orientation on ocular biomechanics can be systematically evaluated. In this section, we discuss the effects of G-force on the optic nerve in human eyes with a normal axial length under different IOP conditions. The applied G-force range of 1–6G was selected to investigate the progressive effects of acceleration on optic nerve biomechanics. While normal commercial flight generally involves acceleration close to 1G, higher G-force levels may occur during aerobatic maneuvers or a high-performance flight. Accordingly, the upper loading conditions were included to evaluate ocular mechanical sensitivity under elevated acceleration rather than to represent typical commercial passenger exposure. The analysis focuses on three key biomechanical indicators of optic nerve response: stress, strain, and surface pressure. Stress and strain represent the internal mechanical state of the optic nerve, while surface pressure is evaluated to quantify the external mechanical load acting on the optic nerve boundary.

The optic nerve surface pressure was calculated using the classical pressure definition $P = F/A$, where F denotes the resultant force acting on the optic nerve surface and A represents the effective contact area. This formulation enables the direct comparison of pressure variations under different loading conditions and provides a sensor-relevant mechanical metric that complements the analysis of stress and strain. To ensure consistency and reproducibility, all biomechanical data were extracted from predefined locations, as illustrated in Fig. 3. Figure 3(a) shows the data extraction region for optic nerve stress and strain, located at the characteristic position where mechanical load is most pronounced. Figure 3(b) illustrates the force application surface used for pressure calculation, with an effective area of 0.17 mm². By fixing the data acquisition locations and surface area, variations in stress, strain, and pressure can be attributed directly to changes in IOP and external G-force, rather than to numerical or geometric inconsistencies. This systematic data extraction strategy enables reliable comparison across different IOP levels and acceleration conditions, thereby enhancing the accuracy of biomechanical interpretation and supporting the sensor-oriented assessment of optic nerve loading under dynamic environments.

3. Simulation Results and Discussion

Figure 4 presents the optic nerve pressure responses of eyes under five different IOP levels, subjected to varying G-forces across three flight orientations. As shown in the figure, for each posture, the optic nerve exhibits no abrupt or discontinuous changes in mechanical response when IOP varies within the investigated range. This indicates that flight orientation alone does not substantially alter the overall pattern of optic nerve pressure responses under the investigated

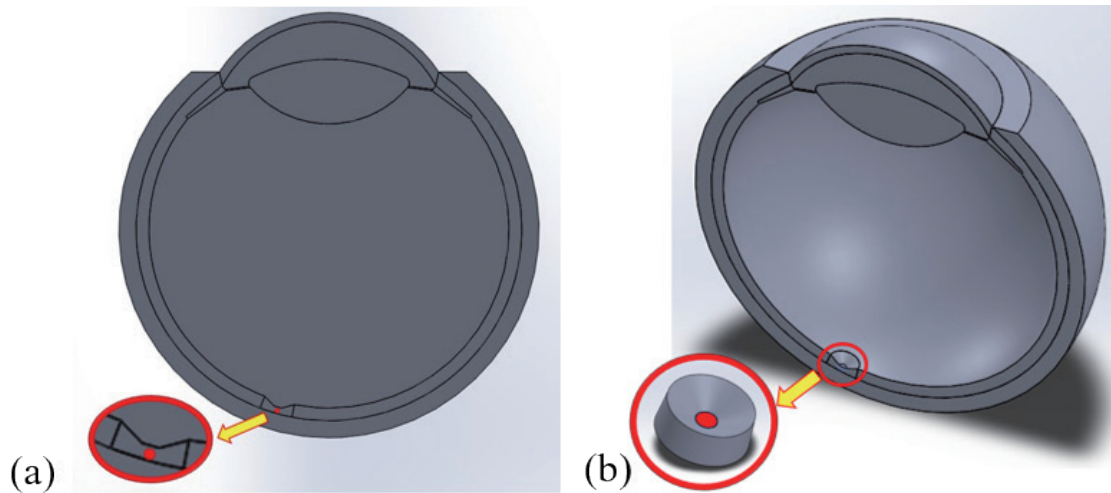


Fig. 3. (Color online) (a) Stress and strain extraction point and (b) pressure extraction surface.

IOP conditions. However, when the eyes are subjected to increasing G-force, the effect of IOP on optic nerve loading becomes more pronounced. Across all three flight orientations, optic nerve pressure increases with IOP, consistently following the order of $50 > 40 > 30 > 20 > 10$ mmHg. In this analysis, pressure sensitivity to G-force refers to the change in optic nerve pressure with increasing acceleration under a given IOP condition. The results indicate that higher IOP produces greater optic nerve pressure under the investigated loading conditions. These findings demonstrate that IOP is an important factor affecting the mechanical load on the optic nerve.

From a biomechanical perspective, elevated IOP increases the prestress state of ocular tissues, reducing their capacity to accommodate additional external load. Consequently, under G-force loading, eyes with higher IOP exhibit a greater optic nerve pressure than those with lower IOP. In contrast, lower IOP is associated with reduced optic nerve pressure under comparable acceleration conditions. These findings highlight an important interaction between internal pressure and external dynamic forces: although changes in IOP alone do not significantly alter optic nerve behavior across different postures, higher IOP markedly enhances the mechanical effects of G-force. From a sensing and measurement standpoint, this suggests that ophthalmic pressure and strain sensors should account not only for absolute IOP values but also for their coupling with external acceleration. Ignoring this interaction may lead to the underestimation of optic nerve mechanical risk under high-IOP conditions, particularly in dynamic environments involving motion, vibration, or rapid acceleration.

In this section, we analyze the biomechanical responses of the optic nerve in human eyes with different axial lengths subjected to G-force loading under a physiological IOP of 20 mmHg. Five eye models with distinct axial lengths were evaluated under the three representative flight postures (level flight, vertical climb, and vertical descent) to examine how ocular geometry affects optic nerve stress, strain, and pressure under dynamic acceleration. Figures 5(a)–5(c) illustrate the optic nerve stress trends for the five axial lengths under the three flight postures. Von Mises stress is an equivalent stress measure that combines the effects of normal and shear

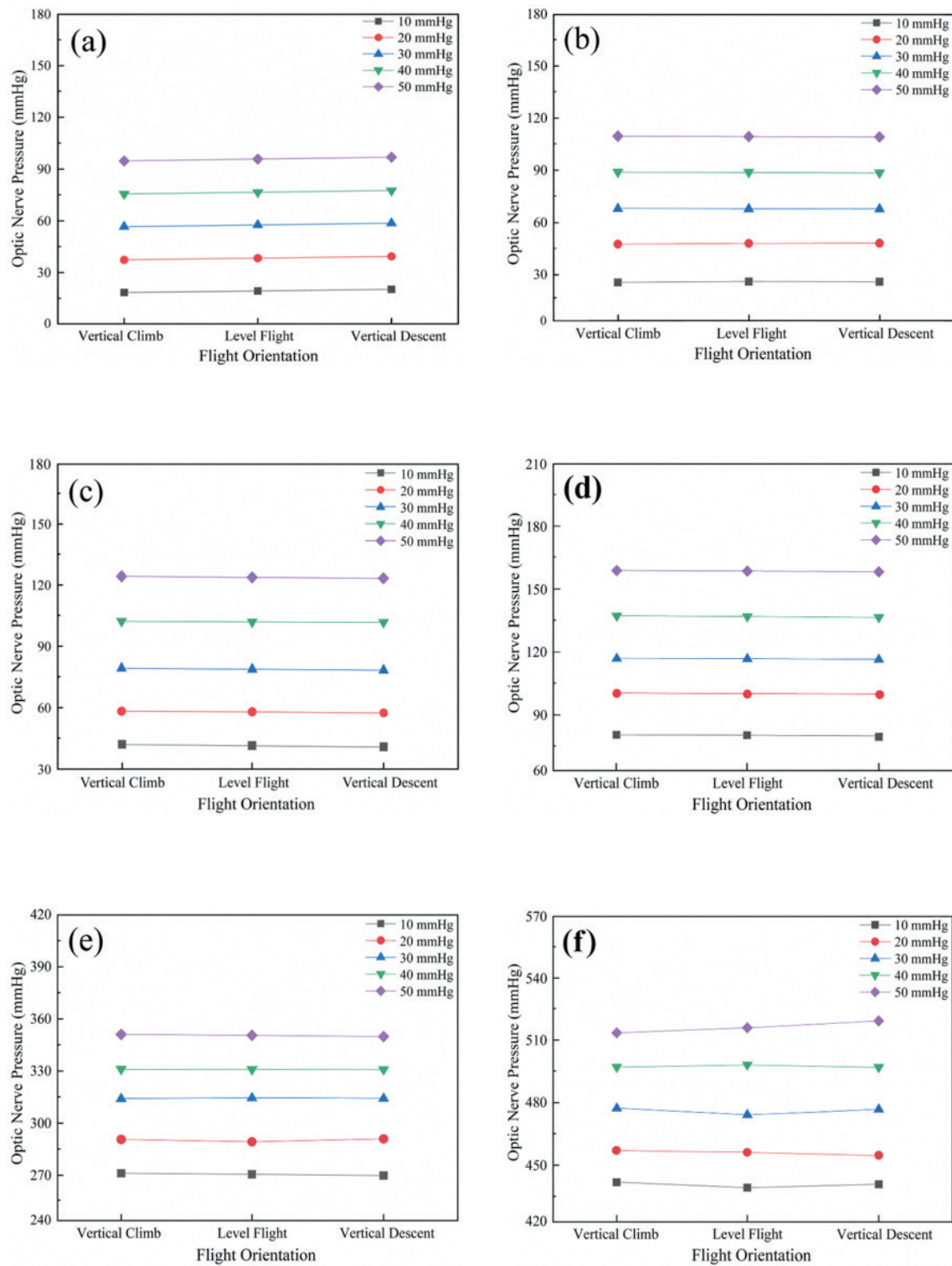


Fig. 4. (Color online) Optic nerve pressure responses under different IOP and G-force conditions for three flight orientations: (a) resting condition, (b) 1G, (c) 2G, (d) 4G, (e) 5G, and (f) 6G.

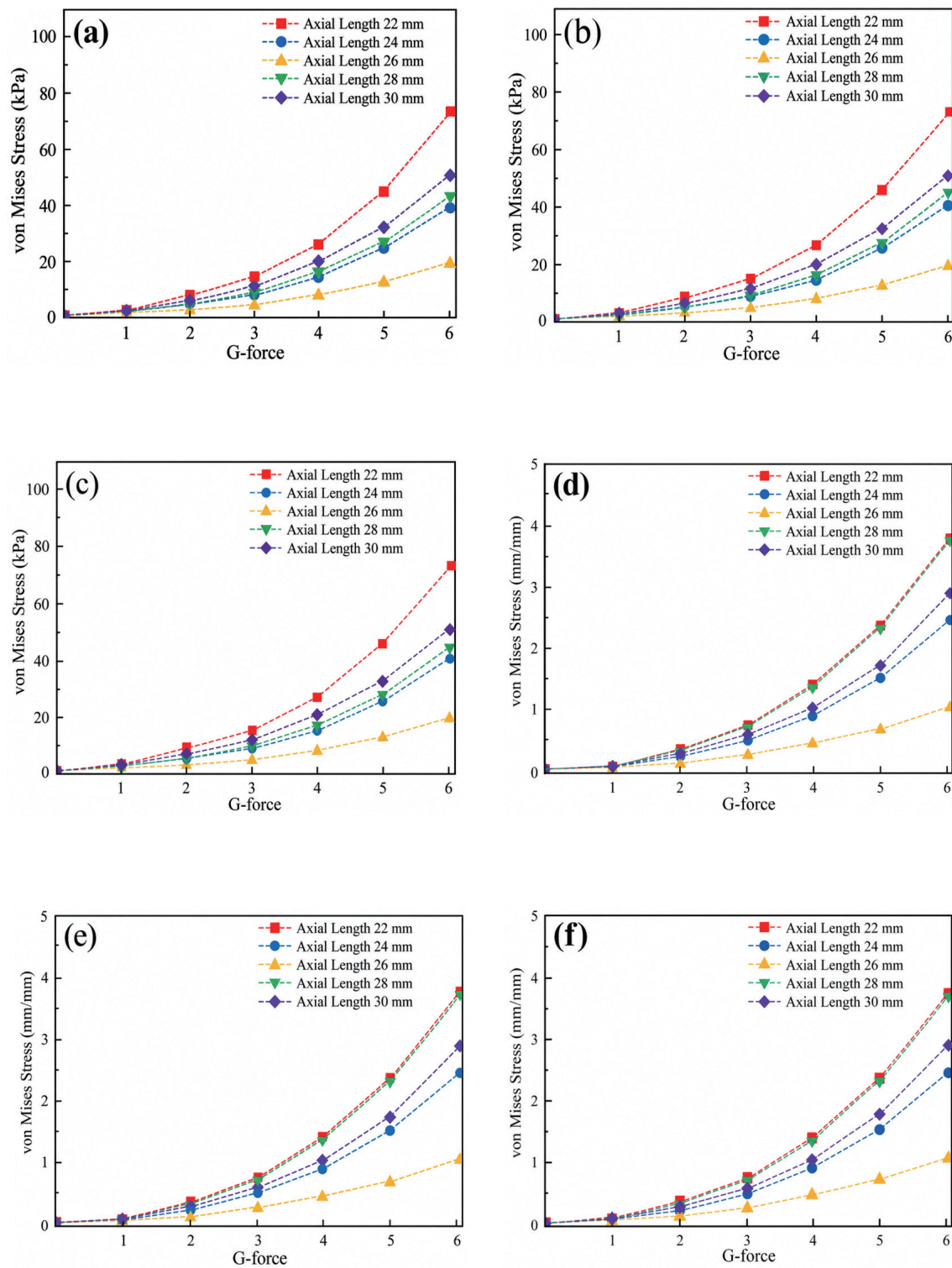


Fig. 5. (Color online) Trends in optic nerve stress and strain in eyes with five different axial lengths under different G-force levels loading for different flight postures: optic nerve stress during (a) level flight, (b) vertical climb, and (c) vertical descent; and optic nerve strain during (d) level flight, (e) vertical climb, and (f) vertical descent.

stresses into a single scalar value. It represents the intensity of distortional stress under multiaxial loading conditions. In the present simulations, von Mises stress was used to compare the mechanical load on the optic nerve among different axial lengths and G-force levels. Higher values indicate greater equivalent stress concentrations within the optic nerve, rather than directly representing tissue damage. Regardless of flight orientation, the stress responses exhibit similar monotonic increasing trends with increasing G-force, indicating that the direction of acceleration does not significantly alter the qualitative pattern of stress evolution. However, pronounced differences are observed in the rate of stress increase among eyes with different axial lengths. When acceleration reaches approximately 3G, a clear divergence among stress slopes emerges, demonstrating a strong dependence of stress sensitivity on ocular geometry.

These results indicate that eyes with smaller (22 mm) and larger (30 mm) axial lengths exhibit a higher optic nerve stress under elevated G-force loading than do eyes of intermediate axial lengths. This behavior may be associated with differences in structural stiffness and acceleration-induced load transmission arising from variations in ocular geometry. From a biomechanical standpoint, the reduced axial length increases structural stiffness and limits deformation accommodation, while excessive elongation alters load transmission pathways and reduces mechanical stability. Both geometric deviations therefore amplify stress concentrations in the optic nerve under dynamic loading. The corresponding optic nerve strain trends are shown in Figs. 5(d)–5(f). For all axial lengths and flight postures, strain increases monotonically with G-force, closely following the stress evolution patterns. As acceleration approaches 6G, the strain responses of eyes with axial lengths of 22 and 28 mm become increasingly similar. This convergence is attributed to the pronounced stress increase observed in the 28 mm axial length model at higher G levels, which leads to a corresponding increase in strain. Overall, from approximately 3G onward, stress and strain trends across different axial lengths become more comparable, suggesting a transition to a geometry-dominated mechanical response regime in which acceleration effects outweigh moderate geometric differences.

Figure 6 presents the optic nerve pressure trends for the five axial lengths under the three flight postures. The results indicate that eyes with the smallest axial length (22 mm) and the largest axial length (30 mm) experience the highest optic nerve pressure when acceleration reaches 6G. Notably, in the 22-mm-axial-length eye, a substantial pressure drop occurs at approximately 2G, followed by a rapid pressure increase beginning at 3G. With further increase in G-force, the pressure increase in the 22 mm eye becomes significantly steeper than that of the other models. In contrast, eyes with intermediate axial lengths exhibit similar pressure evolution behaviors, characterized by a gradual and monotonic increase in pressure with G-force. This distinct response suggests that shorter eyes are more susceptible to abrupt pressure redistribution under moderate acceleration, while longer and intermediate eyes respond in a more uniform manner. From a sensing and measurement perspective, these findings demonstrate that optic nerve mechanical responses under loading at different G-force levels are strongly affected by axial length, even when IOP remains within the normal physiological range. The observed variations in stress, strain, and pressure highlight the limitations of relying solely on scalar IOP measurements to assess ocular risk under dynamic conditions. Instead, model-assisted biomechanical analysis provides critical complementary information that can enhance the interpretation, calibration, and validation of ophthalmic pressure and strain sensors.

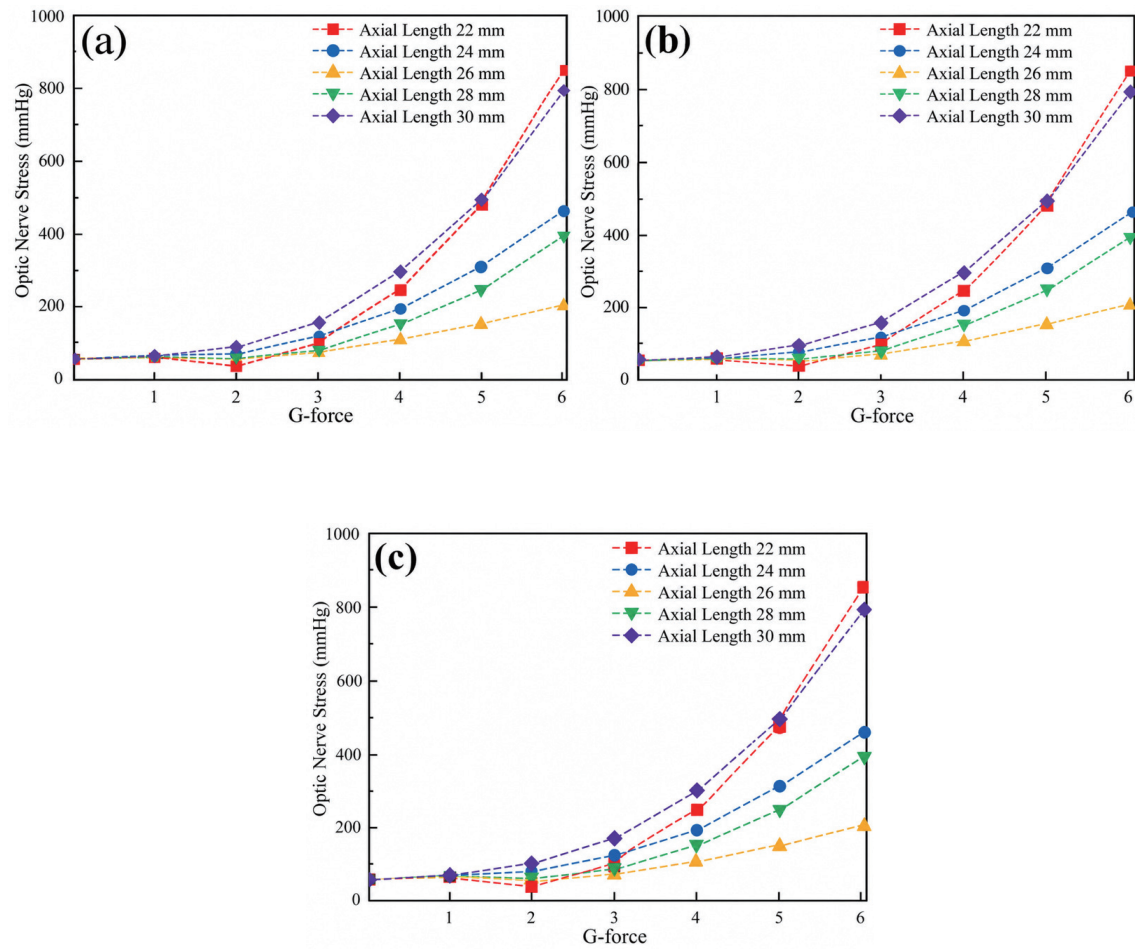


Fig. 6. (Color online) Trends of optic nerve pressure in eyes of five different axial lengths under loading at different G-force levels for different flight postures during (a) level flight, (b) vertical climb, and (c) vertical descent.

Such insights are particularly valuable for sensor-based diagnostics and safety evaluation in environments involving acceleration, vibration, or rapid motion, where conventional static measurements may underestimate internal mechanical loading. Beyond the observed trends in stress, strain, and pressure, the present results provide further insight into the underlying biomechanical mechanisms governing optic nerve responses under combined IOP and external acceleration. The distinct axial-length-dependent behaviors observed in this study indicate that the eye does not respond to G-force as a uniformly scaled structure. Instead, the redistribution of mechanical loads within ocular tissues is strongly modulated by geometric configuration, particularly under moderate to high acceleration levels. From a structural mechanics perspective, eyes with smaller axial lengths exhibit increased overall stiffness as a result of reduced internal volume and a more compact load-bearing framework. This stiffness limits deformation accommodation under acceleration, resulting in elevated stress concentrations within the optic

nerve. Conversely, elongated eyes exhibit increased compliance but altered load transmission paths, which can lead to stress amplification through geometric instability and uneven force redistribution. These competing mechanisms explain why both shortened (22 mm) and elongated (30 mm) eyes experience high optic nerve stress and pressure under high G-force conditions compared with eyes of intermediate axial lengths.

4. Conclusions

In this study, we investigated the biomechanical responses of the human optic nerve under combined IOP and G-force loading, with emphasis on the effects of ocular geometry and dynamic acceleration. Finite element simulations were performed to evaluate optic nerve stress, strain, and pressure in eyes of different axial lengths and IOP levels under representative flight postures. The results show that optic nerve mechanical responses increase monotonically with G-force while posture has a limited effect on the qualitative trends of stress and strain. Elevated IOP is associated with greater optic nerve pressure under G-force loading, indicating an interaction between internal pressure and external acceleration. These findings highlight the importance of considering IOP when evaluating optic nerve mechanical responses under dynamic conditions. In contrast, eyes with lower IOP demonstrate more compliant mechanical behavior and reduced sensitivity to G-force loading. Ocular geometry was found to be another critical factor governing optic nerve biomechanics. Both shortened and elongated eyes experience higher optic nerve stress and pressure under high G-force conditions than do eyes of intermediate axial length. Shorter eyes exhibit increased structural stiffness, whereas elongated eyes show altered load transmission and reduced mechanical stability, leading to stress amplification in both cases. These geometric effects become particularly pronounced beyond approximately 3G. From a sensing and measurement perspective, the findings highlight the limitations of relying solely on scalar IOP measurements to assess optic nerve risk under dynamic conditions. Model-assisted biomechanical analysis provides complementary, spatially resolved information that can enhance the interpretation and calibration of ophthalmic pressure and strain sensors, supporting more reliable ocular risk assessment in dynamic environments involving acceleration and vibration. Nevertheless, the present findings are limited by the simplified ocular material models and the absence of direct experimental validation. In future research, we will incorporate more realistic tissue properties and controlled mechanical experiments to further assess the reliability and physiological relevance of the predicted optic nerve responses.

Acknowledgments

This research was supported by projects under Natural Science Foundation of Xiamen No. 3502Z202573327, NSTC 113-2622-E-390-001, and NSTC 113-2221-E-390-011.

References

- 1 K. Y. Wu, M. Mina, M. Carbonneau, M. Marchand, and S. D. Tran: *Micromachines* **14** (2023) 1915.
- 2 S. Chinnaswamy, V. Natarajan, S. Samiappan, and R. Gurumurthy: *Eng. Proc.* **59** (2023) 179.
- 3 Y. Shi, N. Jiang, P. Bikkannavar, M. Francesca Cordeiro, and A. K. Yetisen: *Analyst* **146** (2021) 6416.
- 4 A. Rajan, J. Vishnu, and B. Shankar: *Biosensors* **14** (2024) 483.
- 5 T. Liu, Y. L. Cai, M. Y. Hu, Z. Wang, X. Liu, M. Chen, and K. Wang: *Adv. Ophthalmol. Pract. Res.* **5** (2025) 142.
- 6 K. Y. Wu, M. Mina, M. Carbonneau, M. Marchand, and S. D. Tran: *Micromachines* **14** (2023) 1915.
- 7 P. Zolfaghari, A. D. Yalcinkaya, and O. Ferhanoglu: *IEEE Photon. Technol. Lett.* **35** (2023) 887.
- 8 J. C. Barry, M. Dunne, and T. Kirschkamp: *Ophthalmic Physiol. Opt.* **21** (2001) 450.
- 9 I. A. Sigal, J. Grimm, J. S. Schuman, L. Kagemann, H. Ishikawa, and G. Wollstein: *IEEE Trans. Med. Imaging* **33** (2014) 1381.
- 10 T. Liu, Y. X. Wang, J. B. Jonas, Q. V. Hoang, M. J. A. Girard, and X. Wang: *Invest. Ophthalmol. Vis. Sci.* **66** (2025) 21.
- 11 Q. Li, B. Zhan, T. Liu, Y. Han, S. Xin, Z. Chen, T. A. Tun, and X. Wang: *Eye* **40** (2026) 238.
- 12 C. W. Lee, P. S. Cheng, C. M. Hsu, J. Zheng, L. Y. C. Poon, and C. F. Yang: *Sens. Mater.* **38** (2026) 4069.