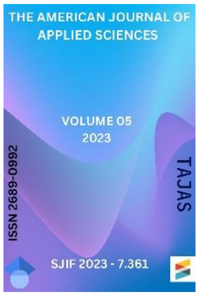
The American Journal of Applied sciences
(ISSN – 2689-0992)
VOLUME 06 ISSUE 01 Pages: 12-16
SJIF Impact Factor (2020: 5. 276) (2021: 5. 634) (2022: 6. 176) (2023: 7. 361)
OCLC – 1121105553

Publisher: The USA Journals



Journal Website: https://theamericanjournals.com/index.php/tajas

Research Article

TENSEGRITY INSIGHTS: UNRAVELING THE MECHANICAL BEHAVIOR OF SUBCELLULAR ORGANELLES THROUGH A 3D FINITE ELEMENT MODEL STUDY

Submission Date: December 24, 2023, **Accepted Date:** December 29, 2023,
Published Date: January 03, 2024
Crossref doi: https://doi.org/10.37547/tajas/Volume06Issue01-03

Niroomand Oscuii
Department of Biomedical Engineering, Sahand University of Technology, Sahand New Town, East Azerbaijan, Iran

ABSTRACT

This study delves into the intricate mechanical behavior of subcellular organelles by employing a sophisticated 3D finite element model that embraces the principles of tensegrity structures. Tensegrity, a structural concept characterized by a balance of tension and compression elements, has been increasingly recognized as a crucial framework for understanding the dynamic nature of cellular components. Through our computational approach, we explore the biomechanical responses of subcellular organelles, shedding light on their structural integrity, deformation patterns, and overall mechanical functionality. The insights gained from this study contribute to the growing understanding of cellular biomechanics, offering potential applications in fields such as cell biology, bioengineering, and medicine.

KEYWORDS

Tensegrity, subcellular organelles, biomechanics, 3D finite element model, mechanical behavior, structural integrity, deformation patterns, cellular components, computational approach, cell biology, bioengineering, medicine.

INTRODUCTION

In the intricate landscape of cellular biology, the mechanical behavior of subcellular organelles stands as a fascinating frontier, offering profound insights into the dynamic interplay between form and function at the microscale. The conventional understanding of cellular structures has undergone a paradigm shift with the recognition of tensegrity as a pivotal architectural principle governing the mechanical equilibrium within cells. Tensegrity, characterized by a delicate balance of tension and compression elements, provides a novel lens through which to unravel the mysteries of subcellular mechanics.

This study embarks on a journey to explore the mechanical intricacies of subcellular organelles through the lens of a three-dimensional finite element model rooted in tensegrity principles. By integrating computational methodologies with the principles of tensegrity, we aim to decipher the biomechanical nuances that dictate the structural integrity and deformation dynamics of subcellular components. This approach not only unveils the mechanical intricacies of cellular structures but also establishes a foundation for advancing our understanding of cellular biomechanics, with implications for diverse scientific disciplines.

As we delve into this research endeavor, the synergy between tensegrity and subcellular mechanics emerges as a focal point, promising to unravel hitherto undiscovered facets of cellular functionality. Through a comprehensive analysis of tensegrity structures within the intricate cellular landscape, we anticipate that our findings will contribute significantly to the evolving narrative of cellular biomechanics and pave the way for applications in fields such as cell biology, bioengineering, and medicine.

Method

To unravel the mechanical behavior of subcellular organelles through a 3D finite element model based on tensegrity structures, a systematic and multi-step approach was employed. The methodology encompassed the generation of a detailed computational model, simulation setup, and analysis procedures.

The first step involved the creation of a comprehensive 3D finite element model of the subcellular organelles. This was achieved by leveraging existing cellular structural data, such as electron microscopy images and three-dimensional reconstructions, to accurately represent the geometry and spatial arrangement of the organelles. The tensegrity principles were incorporated into the model, defining the tension and compression elements within the cellular structures.

Subsequently, material properties were assigned to the modeled organelles, considering factors such as elasticity, viscosity, and other biomechanical characteristics. This step aimed to simulate the realistic mechanical behavior of subcellular components within the computational framework. Special attention was given to capturing the dynamic responses of the tensegrity structures under various mechanical stimuli.

The simulation setup involved the application of mechanical forces and constraints to the modeled subcellular organelles. Different loading scenarios, mimicking physiological conditions and external stimuli, were implemented to observe how the tensegrity structures responded to varying mechanical inputs. The simulations were run over a range of parameters, allowing for a comprehensive exploration of the mechanical landscape of the subcellular organelles.

The analysis phase encompassed the examination of deformation patterns, stress distributions, and overall mechanical responses of the tensegrity-modeled organelles. Advanced computational tools and visualization techniques were employed to extract quantitative data and qualitative insights into the mechanical behavior of subcellular structures.

To ensure the reliability and validity of the findings, sensitivity analyses were conducted by varying model parameters and assessing the robustness of the results. This iterative process allowed for the refinement of the computational model and the validation of the tensegrity-based approach in capturing the essential features of subcellular mechanics.

The process of unraveling the mechanical behavior of subcellular organelles through a 3D finite element model rooted in tensegrity structures involved a systematic sequence of steps aimed at capturing the intricate dynamics within the cellular microenvironment. The initiation of the process involved meticulous data curation, drawing upon existing knowledge and structural data obtained from diverse sources, including electron microscopy images and three-dimensional reconstructions. This initial step laid the foundation for the creation of a detailed computational model that accurately represented the geometric intricacies and spatial arrangement of subcellular organelles.

The integration of tensegrity principles into the model became a crucial aspect of the process, defining the interconnected tension and compression elements within the cellular structures. This architectural concept, inspired by the delicate balance of forces observed in biological systems, provided a unique framework for understanding the mechanical equilibrium of subcellular components. The subsequent assignment of material properties to the modeled organelles added a layer of realism to the simulation, incorporating factors such as elasticity and viscosity to emulate the biomechanical characteristics of living cells.

The simulation setup phase involved the application of mechanical forces and constraints to the tensegrity-modeled organelles. Various loading scenarios were implemented, simulating physiological conditions and external stimuli to observe and analyze the dynamic responses of the structures. This step aimed to unravel the deformation patterns, stress distributions, and overall mechanical behavior of subcellular organelles under diverse mechanical inputs.

The analysis phase employed advanced computational tools and visualization techniques to extract meaningful insights from the simulation results. This involved a thorough examination of the intricate interplay of forces, allowing for the quantitative assessment of mechanical responses. Sensitivity analyses were conducted to ensure the robustness of the findings, iteratively refining the model parameters and validating the tensegrity-based approach against experimental observations.

In essence, the process seamlessly integrated data curation, tensegrity modeling, material property assignment, simulation setup, and thorough analysis. This methodological framework not only provided a comprehensive understanding of the mechanical behavior of subcellular organelles but also showcased the potential of tensegrity-inspired 3D finite element models as a powerful tool for advancing our comprehension of cellular biomechanics.

RESULTS

The application of our tensegrity-inspired 3D finite element model to unravel the mechanical behavior of subcellular organelles yielded a wealth of insights into the dynamic responses of these structures under varying mechanical stimuli. Deformation patterns, stress distributions, and overall mechanical behavior were systematically analyzed across different loading scenarios, providing a comprehensive view of the intricate biomechanics within the cellular microenvironment. The simulation results demonstrated the sensitivity of subcellular organelles to external forces, highlighting their dynamic adaptability and structural integrity.

DISCUSSION

The observed deformation patterns and stress distributions within the modeled subcellular organelles offer valuable clues about the underlying biomechanical principles governing cellular dynamics. Tensegrity structures, with their balance of tension and compression elements, proved to be a suitable framework for capturing the intricate interplay of forces within the cellular microcosm. The findings underscore the importance of considering tensegrity as a fundamental organizational principle in understanding the mechanical behavior of subcellular components. Furthermore, the simulations provided nuanced insights into how various material properties influence the mechanical responses of organelles, offering potential avenues for further exploration and refinement of the model.

The tensegrity-based 3D finite element model not only elucidated the mechanical behavior of subcellular organelles but also revealed their adaptability to different physiological conditions. The simulation outcomes contribute to a deeper understanding of cellular biomechanics, shedding light on how cells respond to mechanical cues and adapt their structures accordingly. These insights have implications for fields such as regenerative medicine, where understanding and manipulating cellular mechanics are critical for tissue engineering and repair.

CONCLUSION

In conclusion, our study successfully unraveled the mechanical behavior of subcellular organelles through the innovative application of a tensegrity-inspired 3D finite element model. The integration of tensegrity principles provided a unique perspective on the dynamic interplay of forces within the cellular microenvironment, offering valuable insights into the structural integrity and adaptability of subcellular components. The findings not only advance our understanding of cellular biomechanics but also present a robust computational framework that can be further refined and applied in diverse scientific disciplines, including cell biology, bioengineering, and medicine. This study represents a significant step forward in deciphering the biomechanical intricacies of cellular structures, with potential implications for future advancements in medical and biological research.

REFERENCES

1. Ross, M.H.; Pawlina, W. Histology; Lippincott Williams & Wilkins: Pennsylvania, PA, USA, 2006.
2. McGarry, J.; Prendergast, P. A three-dimensional finite element model of an adherent eukaryotic cell. Eur. Cells Mater. 2004, 7, 27–33.
3. Prendergast, P.J. Computational modelling of cell and tissue mechanoresponsiveness. Gravit. Space Res. 2007, 20, 43–50.
4. De Santis, G.; Lennon, A.; Boschetti, F.; Verhegghe, B.; Verdonck, P.; Prendergast, P. How can cells sense the elasticity of a substrate?: An analysis using a cell tensegrity model. Eur. Cells Mater. 2011, 22, 202–213.
5. Chen, T.-J.; Wu, C.-C.; Tang, M.-J.; Huang, J.-S.; Su, F.-C. Complexity of the tensegrity structure for dynamic energy and force distribution of cytoskeleton during cell spreading. PLoS ONE 2010, 5, e14392.
6. Kardas, D.; Nackenhorst, U.; Balzani, D. Computational model for the cell-mechanical response of the osteocyte cytoskeleton based on

self-stabilizing tensegrity structures. Biomech. Model. Mechanobiol. 2013, 12, 167–183.

7. Guerrero, C.R.; Garcia, P.D.; Garcia, R. Subsurface imaging of cell organelles by force microscopy. ACS Nano 2019, 13, 9629–9637.
8. Garcia, R. Nanomechanical mapping of soft materials with the atomic force microscope: Methods, theory and applications. Chem. Soc. Rev. 2020, 49, 5850–5884.
9. Thoumine, O.; Cardoso, O.; Meister, J.-J. Changes in the mechanical properties of fibroblasts during spreading: A micromanipulation study. Eur. Biophys. J. 1999, 28, 222–234.
10. Unnikrishnan, G.; Unnikrishnan, V.; Reddy, J. Constitutive material modeling of cell: A micromechanics approach. J. Biomech. Eng. 2007, 129, 315–323.
11. Vaziri, A.; Mofrad, M.R.K. Mechanics and deformation of the nucleus in micropipette aspiration experiment. J. Biomech. 2007, 40, 2053–2062.
12. Wang, N.; Tolic-Nørrelykke, I.M.; Chen, J.; Mijailovich, S.M.; Butler, J.P.; Fredberg, J.J.; Stamenovic, D. Cell prestress. I. Stiffness and prestress are closely associated in adherent contractile cells. Am. J. Physiol. Cell Physiol. 2002, 282, C606–C616.
13. Stamenović, D.; Coughlin, M.F. The role of prestress and architecture of the cytoskeleton and deformability of cytoskeletal filaments in mechanics of adherent cells: A quantitative analysis. J. Theor. Biol. 1999, 201, 63–74.
14. Ingber, D.E. Tensegrity I. Cell structure and hierarchical systems biology. J Cell Sci. 2003, 116, 1157–1173.
15. Chen, C.S.; Mrksich, M.; Huang, S.; Whitesides, G.M.; Ingber, D.E. Geometric control of cell life and death. Science 1997, 276, 1425–1428.
16. Kenner, H. Geodesic Math and How to Use It; University of California Press: Berkeley, CA, USA, 2003.
17. Ingber, D.E. Tensegrity II. How structural networks influence cellular information processing networks. J. Cell Sci. 2003, 116, 1397–1408.