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Peer Review

Review of: "Next-Generation Space Cardiology: Developing a COMSOL-Enabled Digital Heart Twin for Long-Duration Missions"

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Overall Assessment

This paper presents an ambitious proposal for developing a computational digital twin of the human heart specifically tailored for space medicine applications. The research addresses a genuinely important gap in aerospace medicine by focusing on microgravity-induced cardiovascular changes, which become increasingly relevant as human spaceflight activities expand beyond low Earth orbit. However, while the technical scope is impressive and the clinical motivation is compelling, the manuscript suffers from significant structural and methodological deficiencies that substantially undermine its scientific rigor and readability.

Overall Rating: C+ (Needs Major Revision)

Substantive Strengths

The paper's primary strength lies in its identification and approach to a genuinely underexplored research domain. The intersection of computational cardiology and space medicine represents a critical area for investigation, particularly given the documented cardiovascular deconditioning that occurs during long-duration spaceflight. The authors demonstrate a sophisticated understanding of multi-physics modeling by incorporating fluid-structure interaction, electromechanical coupling, and the novel concept of gravitational transitions spanning the full mission profile from terrestrial conditions through microgravity to partial gravity environments such as Mars. This comprehensive approach to modeling the complete cardiovascular adaptation cycle represents a conceptually valuable contribution to the field.

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The technical methodology, centered on COMSOL Multiphysics implementation, appears fundamentally sound from a computational perspective. The integration of finite element analysis with physiologically relevant boundary conditions and the incorporation of time-dependent adaptation parameters demonstrate appropriate consideration of the complex, dynamic nature of cardiovascular responses to altered gravitational environments. Furthermore, the proposed clinical applications spanning pre-mission screening, in-flight monitoring, and post-flight rehabilitation address genuine operational needs in space medicine that are currently inadequately served by existing diagnostic and monitoring capabilities.

Fundamental Structural Deficiencies

Despite these conceptual strengths, the manuscript is significantly undermined by severe organizational and presentation problems that compromise its scientific credibility. The paper suffers from a fundamental identity crisis, oscillating inconsistently between the format of a research proposal and that of a completed research study. This ambiguity creates confusion throughout the manuscript, as readers are presented with detailed numerical results from simulations that have not been adequately described methodologically, alongside budget projections and timeline proposals more appropriate for grant applications than peer-reviewed research articles.

The organizational structure lacks logical coherence, dispersing key methodological details throughout the document and hiding critical information within tangential discussions. The excessive use of technical jargon and acronyms, frequently without adequate definition or context, creates significant barriers to comprehension even for readers with relevant expertise. This presentation style suggests that the authors have prioritized demonstrating technical sophistication over clear scientific communication, resulting in a manuscript that fails to convey its core contributions effectively.

Methodological and Validation Concerns

The validation framework represents perhaps the most serious weakness in the proposed research. While the authors present detailed numerical results and make extensive claims about model accuracy, the methodology for validating these computational predictions against actual physiological data remains inadequately developed. The proposed validation strategy relies heavily on terrestrial analog studies, particularly head-down bed rest protocols, rather than actual spaceflight data, which raises questions about the clinical relevance of the resulting model predictions.

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The uncertainty quantification and sensitivity analysis components appear superficial, lacking the rigor necessary for a computational model intended for clinical decision-making. The authors provide insufficient detail regarding how inter-individual variability in cardiovascular adaptation will be incorporated into the model, despite the well-documented heterogeneity in astronaut responses to microgravity exposure. This limitation is particularly concerning given the paper's emphasis on personalized medicine applications and astronaut-specific risk stratification.

Furthermore, the relationship between computational outputs and actual clinical decision-making remains poorly defined. While the authors present detailed hemodynamic parameters and biomechanical metrics, they fail to establish clear thresholds or decision trees that would enable clinicians to translate these computational results into actionable medical interventions. This gap between sophisticated modeling and practical clinical utility represents a significant limitation in the proposed approach.

Technical Implementation Issues

From a technical perspective, several aspects of the computational implementation require more rigorous development. The description of the boundary conditions for microgravity simulation is incomplete, especially when it comes to the temporal evolution of physiological parameters during the adaptation process. The mesh convergence studies and numerical stability analyses, which are fundamental requirements for any finite element implementation, receive inadequate attention in the methodology section.

The material property assignments for cardiac tissues appear to rely on generic literature values rather than spaceflight-specific data, which may compromise the accuracy of the resulting simulations. Additionally, the computational efficiency and scalability considerations are insufficiently addressed, raising questions about the practical feasibility of deploying such a system in the resource-constrained environment of spaceflight operations.

The integration of multiple physics modules, while conceptually appropriate, introduces computational complexity that may compromise real-time performance capabilities. The authors' claims regarding consumer-grade hardware compatibility appear optimistic given the stated requirement for high-fidelity fluid-structure interaction simulations across multiple cardiac cycles.

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Scientific Rigor and Claims Assessment

The manuscript contains several instances of overstated claims and inadequately supported assertions that undermine its scientific credibility. The repeated emphasis on being "first" in various categories requires more careful substantiation through a comprehensive literature review. Many of the physiological parameters presented in the results tables appear inconsistent with published spaceflight cardiovascular data, yet these discrepancies receive insufficient discussion or justification.

The novelty claims, while partially justified, fail to acknowledge existing work adequately in cardiac digital twins and computational space medicine. This selective citation pattern suggests confirmation bias in the literature review process and diminishes the credibility of the authors' positioning of their contribution within the broader research landscape.

Recommendations for Fundamental Revision

The manuscript requires substantial restructuring to address its fundamental organizational deficiencies. The authors must decide whether they are presenting a research proposal or reporting completed research results and restructure the entire document accordingly. If the authors are presenting completed work, they must comprehensively expand the methodology section to include detailed descriptions of computational implementation, validation procedures, and uncertainty analysis.

The validation strategy demands complete reconceptualization with an emphasis on comparison against actual spaceflight cardiovascular data rather than terrestrial analogs. This will require establishing collaborations with space agencies or accessing existing astronaut health databases to provide meaningful benchmarking of model predictions.

The presentation quality requires dramatic improvement through simplification of language, standardization of terminology, and elimination of redundant content. The figures and tables need professional redesign with clear legends and appropriate context for interpretation.

Conclusion

This manuscript addresses an important research question with a technically sophisticated approach that has the potential to make valuable contributions to space medicine. However, the current presentation fails to meet the standards expected for peer-reviewed publication due to fundamental deficiencies in organization, validation methodology, and scientific rigor. The core research concept possesses merit, but successful development will require substantial collaboration with experienced space medicine researchers and a more focused approach to either computational methodology or clinical applications rather than attempting comprehensive coverage of both domains simultaneously.

The work would benefit significantly from external review by experts in both computational cardiology and operational space medicine to ensure that the technical sophistication is matched by clinical relevance and practical utility. This research could ultimately provide valuable tools for supporting human health during long-duration space exploration missions with comprehensive revision that addresses these fundamental concerns.

Declarations

Potential competing interests: No potential competing interests to declare.