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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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This manuscript presents an ambitious and technically sophisticated project: the development of a high-fidelity digital twin of the human heart, specifically adapted for spaceflight and interplanetary conditions. Using COMSOL Multiphysics, the authors simulate cardiovascular behavior under microgravity (0g), Martian gravity (0.38g), and post-flight orthostatic stress, addressing a pressing and largely unmet need in the fields of space medicine and human physiology. This work aligns closely with global interests in astronaut health and digital health innovation, offering substantial promise for autonomous medical assessment in extreme environments.

One of the most compelling aspects of this research is its integration of advanced computational modeling with mission-specific physiological challenges. By incorporating anisotropic tissue mechanics and coupled fluid-solid physics, the authors move beyond traditional cardiovascular simulations, which often assume terrestrial norms and fail to account for the dynamic and multifactorial stressors of space missions. This innovation significantly elevates the potential clinical and operational relevance of the model, positioning it as a valuable tool in both research and mission planning contexts.

The authors are also to be commended for designing a model that spans multiple mission phases—from microgravity adaptation to post-mission rehabilitation. This life-cycle perspective is rarely addressed in current cardiovascular modeling literature, and its inclusion strengthens the translational potential of the simulation framework. The ability to simulate orthostatic stress following re-entry is particularly important, given the known risks of cardiovascular instability in astronauts upon returning to Earth or transitioning to partial-gravity environments.

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Moreover, the manuscript successfully links its innovation to broader strategic objectives, such as those outlined by the UAE in astronaut health and digital health systems. This alignment not only enhances the societal relevance of the research but also supports its scalability and implementation potential within national and international space programs. The emphasis on remote and autonomous health monitoring is especially timely, considering the growing emphasis on long-duration missions and the increasing need for onboard diagnostic solutions.

Despite these strengths, the manuscript would benefit from greater clarity and transparency in methodological exposition. The computational approach using COMSOL is described in general terms, but key details—such as boundary conditions, mesh specifications, solver settings, and model validation—are either omitted or insufficiently elaborated. For reproducibility and scientific rigor, these aspects must be clearly presented. How was the model calibrated and validated against known physiological data under terrestrial and altered-gravity conditions?

Additionally, while the physiological assumptions embedded in the simulation appear sound, a more explicit discussion of the biological datasets used to parameterize the model would enhance credibility. Were clinical or experimental datasets from spaceflight missions used? How were microgravity-induced changes in cardiac geometry or vascular compliance quantified and incorporated into the model? Including such details would bolster confidence in the simulation's physiological realism.

The authors also state that the model supports predictions of "heart shape, muscle deformation, and pressure-flow relationships," yet these outcomes are not visualized or quantitatively discussed in the current draft. Providing representative outputs—such as strain maps, flow simulations, or pressure-volume loops—would significantly improve the reader's understanding of the model's functionality and application scope. These visual outputs are essential for demonstrating the fidelity and interpretability of the digital twin.

Furthermore, the manuscript could benefit from a clearer distinction between the novelty of the simulation framework and its potential clinical or operational use cases. For example, how might this platform be integrated into astronaut training programs or inflight health monitoring systems? Could it be adapted for personalized medicine approaches, taking into account individual cardiovascular risk profiles? A discussion of these applications would enhance the translational impact of the work.

Lastly, while the project's connection to the UAE's national priorities is important, the manuscript should also more explicitly position itself within the global context of space cardiology. How does this model compare with other existing digital heart models, such as those developed by NASA or the European

Space Agency? Discussing potential interoperability or collaboration opportunities would position this work as a key contribution to an emerging international dialogue in computational space medicine.

In conclusion, this manuscript addresses a highly relevant and underexplored problem with technical precision and creative vision. The development of a digital heart twin tailored to spaceflight conditions represents a valuable contribution to both aerospace medicine and computational physiology. With improvements in methodological transparency, output presentation, and broader contextualization, the work could become a reference in its field. The authors are encouraged to expand on these aspects to fully realize the strong potential of their innovative platform.

Declarations

Potential competing interests: No potential competing interests to declare.