

Peer Review

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

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The authors are addressing a key topic in space medicine, specifically exploring the intersection of digital health technology and computational modelling for exploration-class missions, using a COMSOL-based digital heart twin to simulate CV dynamics in microgravity. The proposal for work is commendable, as while the work is targeted for exploration-class level missions, it could also provide a structure and framework for virtual medical evaluation and pre-mission risk profiling in space cardiology.

The manuscript is well-structured, and the core idea is clear. Minor revisions requested:

1// The authors could incorporate or comment on the absence of a pre-flight Earth-normal hemodynamic state as a modeling baseline. Modeling transitional phases—Earth (1g) → microgravity (0g) → Mars partial gravity → Earth re-entry—would offer greater fidelity for simulations of long-duration spaceflight. If such transitions are outside the current study scope, a brief rationale outlining how baseline cardiac conditions (e.g., preload, ventricular compliance) affect wall strain and turbulence metrics in static microgravity simulations would be valuable. This potentially could be helpful for future validation / translational work to model hemodynamic status over the transition states envisioned.

2// It would enhance future reproducibility if the authors could briefly describe the proposed modeling codebase, solver configuration, average simulation time per cardiac cycle, and energy usage. The benchmark data (e.g., Intel i9-12900KF with PARDISO, $\Delta h < 5\%$ in strain, ΔPV -loop area $< 3\%$) may be better highlighted in the methods or supplementary materials. Further, specifying whether the COMSOL Application Builder was used for any automation or clinical deployment purposes could add translational value. A diagram of the architecture could be helpful.

3// Given the body's cardiovascular system is inherently dynamic, the authors may consider addressing the use (or planned use) of time-varying boundary conditions to better approximate physiological states (e.g., examining respiratory-cardiac coupling, baroreflex) - this would also help with future validation with microgravity-based analogues. Even if a static boundary approach was used, a short discussion on how dynamic inflow/outflow profiles might alter FSI predictions would strengthen the physiological applicability of the model.

4// The authors mention hybrid CPU workflows on consumer-grade machines, which is commendable. As cardiac simulation increasingly moves toward GPU-based acceleration, it would be helpful to elaborate on future plans for GPU twin development. Specifically:

- Will CUDA-based acceleration or streaming be implemented?
- What is the intended data layout (e.g., SoA vs AoS) to optimize memory throughput?
- Will mesh partitioning be adapted for parallel GPU cores?

5// The authors could also clarify whether the model has been benchmarked (or envisions benchmarking or validating) against temporally stratified cardiovascular data collected from real or analog microgravity environments - whether from parabolic flights, ISS datasets, or head-tilt testing; head-tilt testing has also been used in capturing cardiac pulse parameters and reported on in the literature; this may be helpful for future translational work based on this work.

Correct minor typos, for example in Figure 2 (Impaired Relaxation, Hemodynam Redistribution)

Declarations

Potential competing interests: No potential competing interests to declare.