Topology-Optimized Phalangeal Prostheses with Improved Stiffness-to-Weight Ratio using SIMP-GA.

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Introduction

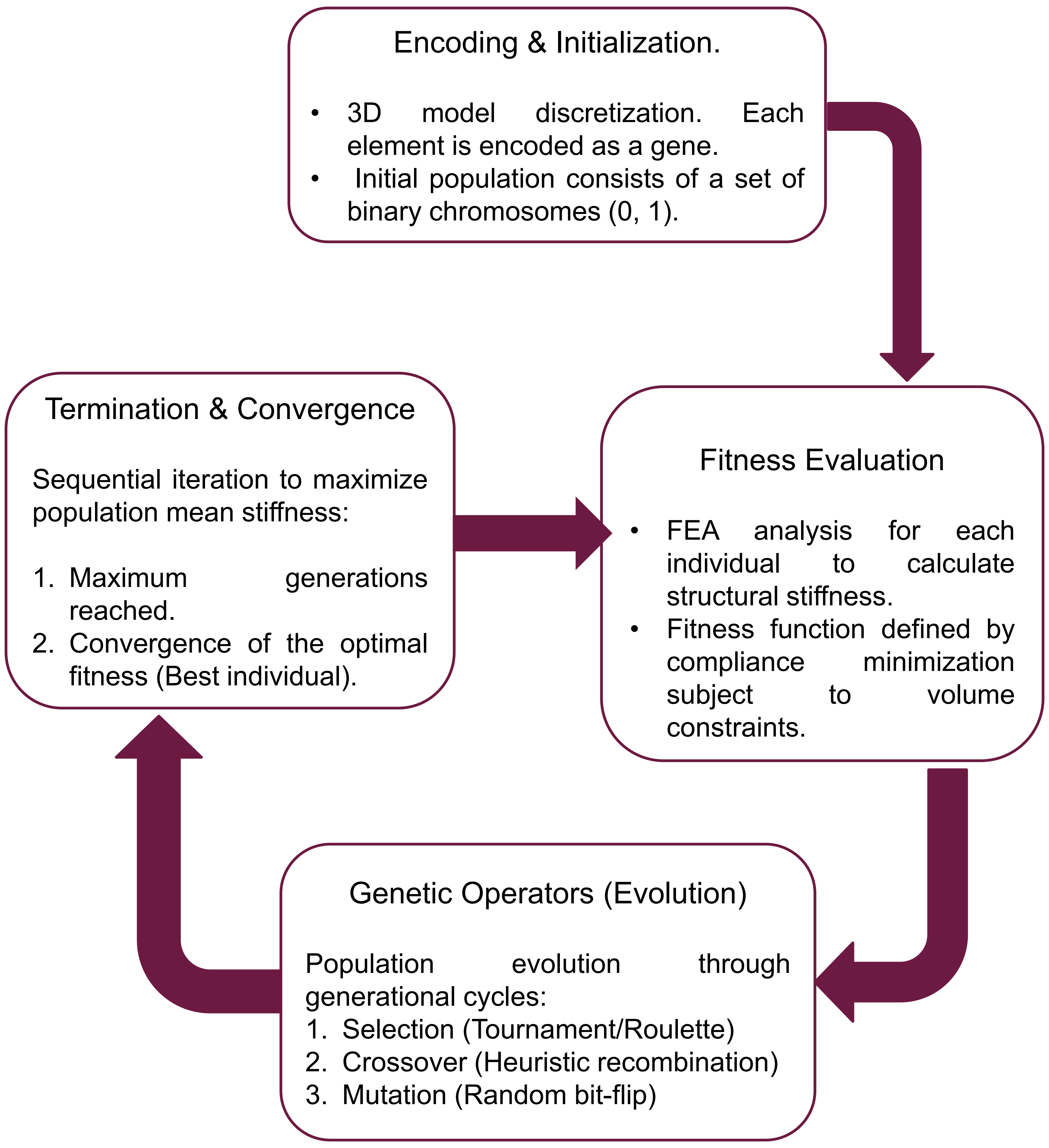
- The Biomechanical Challenge: Achieving an optimal balance between mass reduction and structural integrity in prosthetic design frequently leads to significant numerical complexity.
- Integration of Hybrid Methods: To improve the robustness of 3D material distribution, the SIMP method is coupled with a Genetic Algorithm (GA), moving beyond the limitations of traditional linear schemes.
- From FEA to Bio-inspiration: By transitioning from fundamental stiffness matrix (K) assembly toward the emulation of trabecular bone porosity, a more biomimetic structural response is achieved.
- Performance and Energy Absorption: Special emphasis is placed on maximizing the stiffness-to-weight ratio, ensuring that the resulting components can effectively handle impact energy.
- Additive Manufacturing Validation: The proposed framework is ultimately validated through the fabrication of patient-specific components, bridging the gap between computational optimization and functional solutions.

Figure 1. Initial morphological model of a human metacarpal, utilized as the design domain for structural synthesis.

Figure 2. Topologically optimized projection exhibiting a bio-inspired lattice with hierarchical porosity to maximize the stiffness-to-weight ratio.

Methodology

The methodology consists of the following steps:



Encoding & Initialization.

- 3D model discretization. Each element is encoded as a gene.
- Initial population consists of a set of binary chromosomes (0, 1).

Fitness Evaluation

- FEA analysis for each individual to calculate structural stiffness.
- Fitness function defined by compliance minimization subject to volume constraints.

Genetic Operators (Evolution)

Population evolution through generational cycles:

1. Selection (Tournament/Roulette)
2. Crossover (Heuristic recombination)
3. Mutation (Random bit-flip)

Termination & Convergence

Sequential iteration to maximize population mean stiffness:

1. Maximum generations reached.
2. Convergence of the optimal fitness (Best individual).

Experimental Results

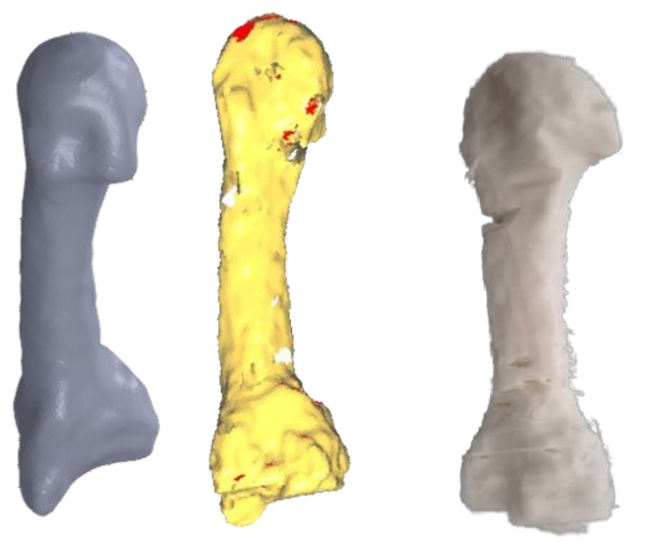


Figure 3. Morphological evolution: (Left) Initial 3D domain; (Center) Topologically optimized model via GA-SIMP; (Right) Final physical prototype.

The robust assembly of the Global Stiffness Matrix (K) ensured physical consistency in the displacement fields (U) across the 3D tetrahedral elements, preventing numerical divergence during the iterative optimization (Fig. 3).

By coupling the SIMP method with the Genetic Algorithm, a 20% mass reduction was achieved with optimal evolutionary stability, verified by a controlled volume convergence between 4.98 and 5.02 over 200 generations (Fig. 4).

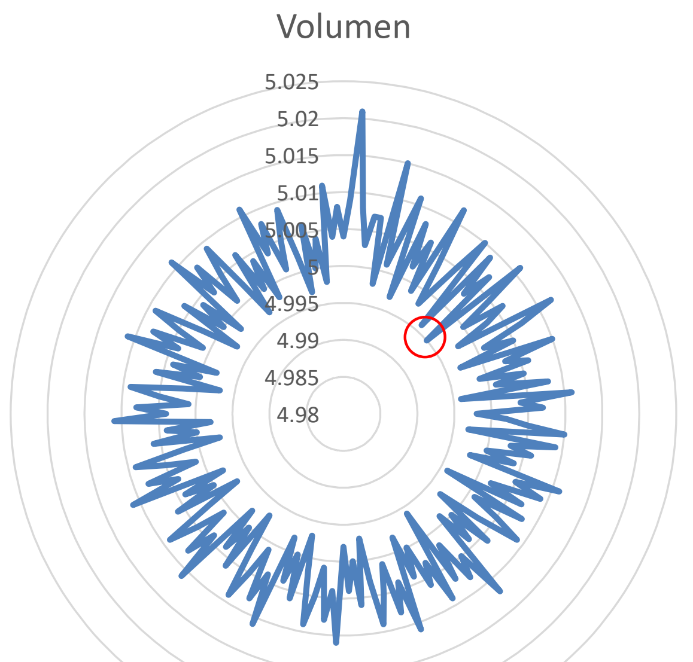


Figure 4. Volume oscillation tracking across 200 generations, demonstrating algorithmic robustness and convergence stability between 4.98 and 5.02.

Finally, the implementation of a regularization filter enabled a seamless transition from numerical density fields into high-fidelity .STL geometries for functional additive manufacturing (Fig. 5).

Figure 5. Manufacturing pipeline showing the base model (left), the optimized structural lattice (center), and the final 3D-printed metacarpal component (right).

Conclusions

- A functional hybrid framework was developed by successfully integrating SIMP optimization and Genetic Algorithms within a Python environment.
- A 20% mass reduction was achieved in phalangeal prosthetic designs without compromising structural mechanical integrity.
- The seamless transition from numerical simulation to additive manufacturing was ensured through high-fidelity .STL model generation.
- The proposed methodology was validated as a robust solution for producing lightweight, patient-specific biomechanical components.
- The scalability of this hybrid approach was demonstrated, showing potential for more complex 3D prosthetic applications.

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