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Design, Kinematic Analysis, and ANSYS Simulation of a 21-DOF Biomimetic Prosthetic Hand with SMA Actuation

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INTRODUCTION

Traditional prosthetic hands face limitations in biomimicry, fabrication complexity, and actuation efficiency. 4D printing, additive manufacturing that produces structures capable of controlled shape transformation over time offers a paradigm shift in prosthetic design.

Research Objectives:

- Anatomically accurate skeletal & skin structures
- 21-DOF kinematics via ANSYS simulation
- Grasping and pinching motion characterization
- Electrical muscle-like actuation integration
- 4D printing as fabrication direction

DESIGN METHODOLOGY

2.1 Biomechanical Analysis

Anatomical mapping of hand kinematics, joint ROM, and ADL force requirements.

2.2 Skeletal Structure Design

The skeletal framework replicates human hand osteology with 27 bones: carpals, metacarpals, and phalanges. Each bone is modeled with anatomically correct geometry and mechanical properties.

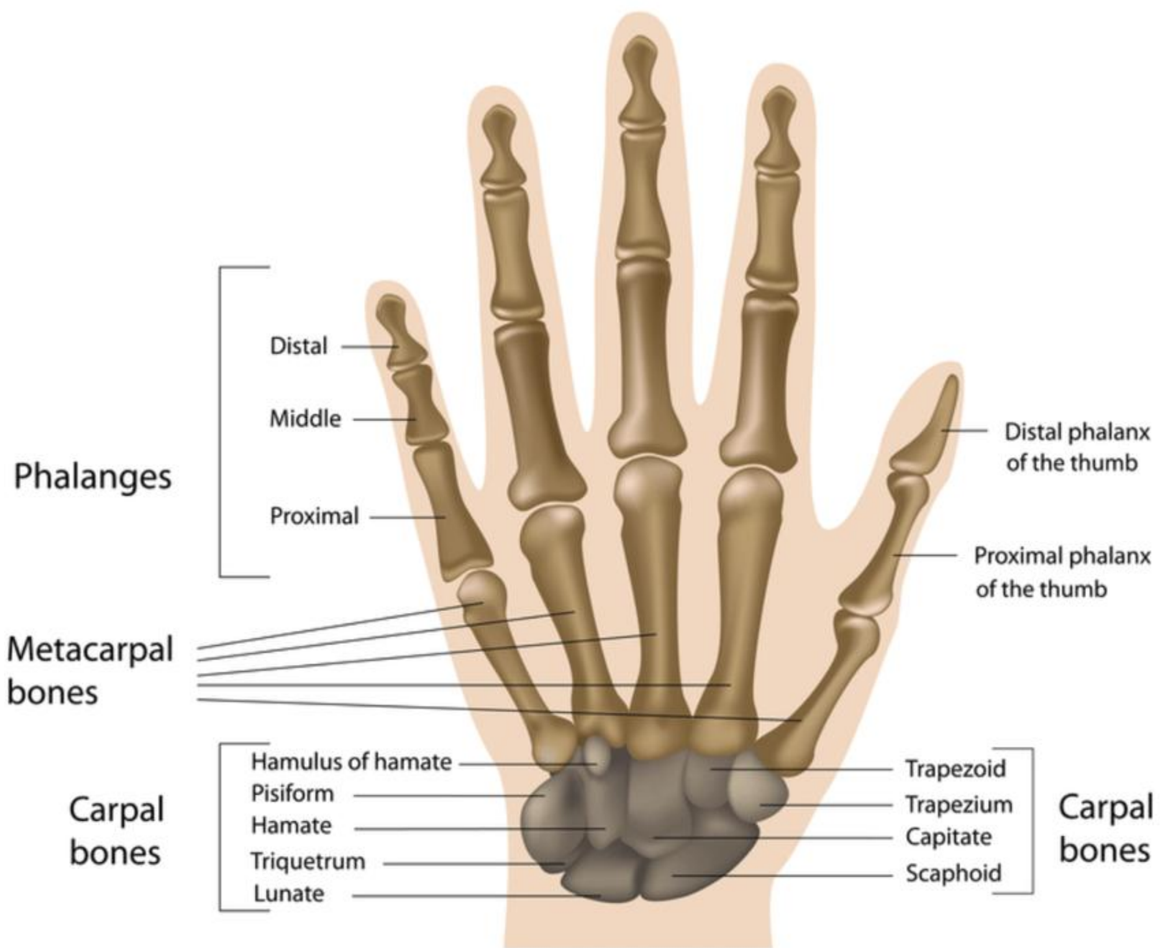


Figure 1 : *Human hand skeletal structure* [1]

Figure 2 :*Human hand skeletal CAD model*

2.3 Bone Geometry and Material Properties :

Material: High-strength thermoplastic (PLA composite)
Elastic Modulus: 3 G Pa
Density: 1.2 g/cm³
Design: Solid structure

2.4 Joint Articulation

Each joint incorporates ball-and-socket or hinge mechanisms with constrained DOF matching anatomical ranges. Joint surfaces include low-friction coatings to minimize wear during cyclic motion.

Figure 3 : *3D Printed Bone structure*

Joints	Degrees of freedom	Joint Type
Distal phalanx – Mid phalanx	1 DOF	Hinge
Mid phalanx – Proximal Phalanx	1 DOF	Hinge
Proximal Phalanx – Metacarpal	2 DOF	Universal Joint

2.5. Skin Structure Design

The skin system consists of multiple compliant layers that replicate the mechanical behavior of human dermis and epidermis, providing both protection and tactile interface.

2.5.1 Skin Multi-Layer Architecture

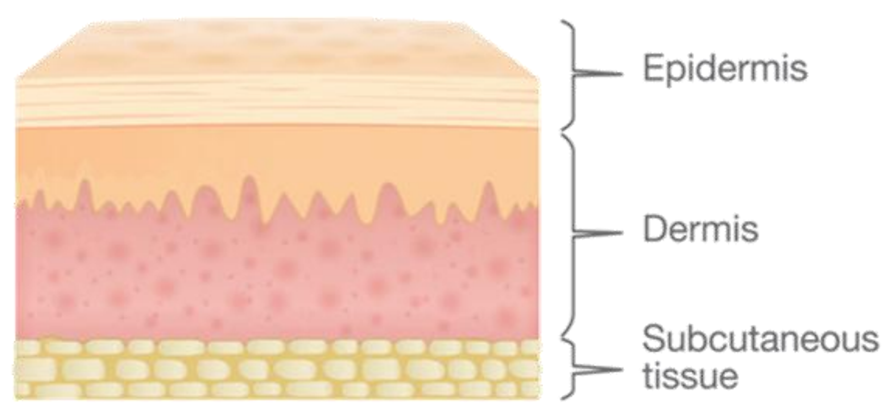


Figure 4 : *Skin Multi-layer architecture* [2]

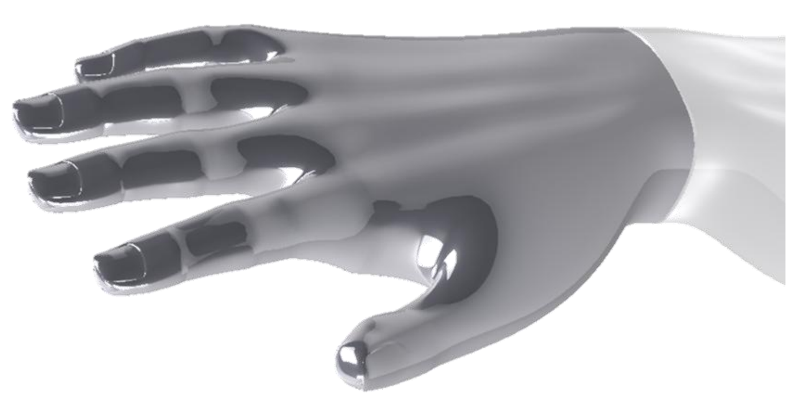
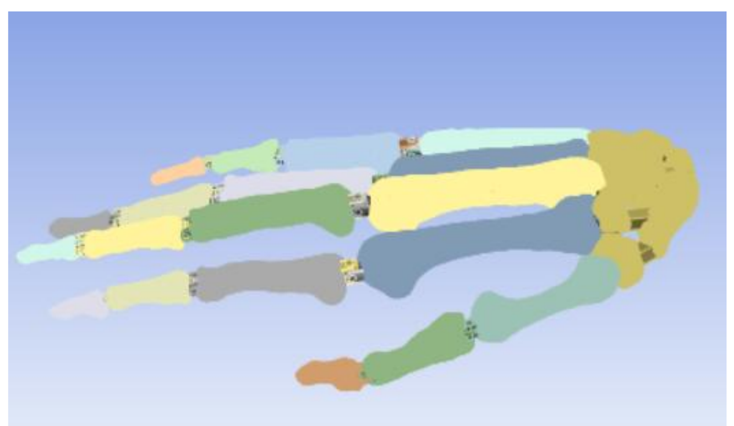


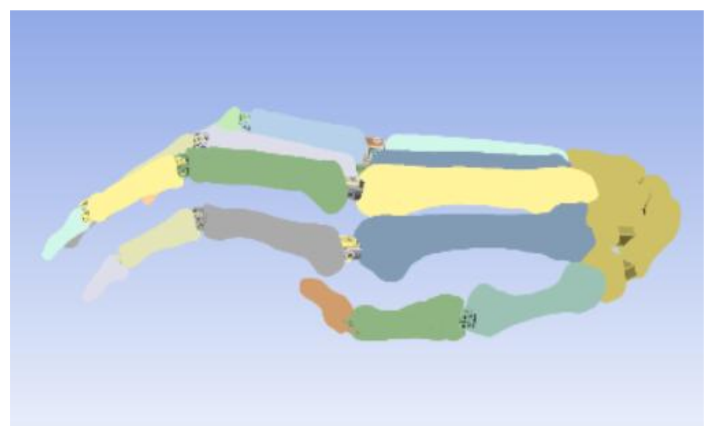
Figure 5 : *Human hand skin CAD model*

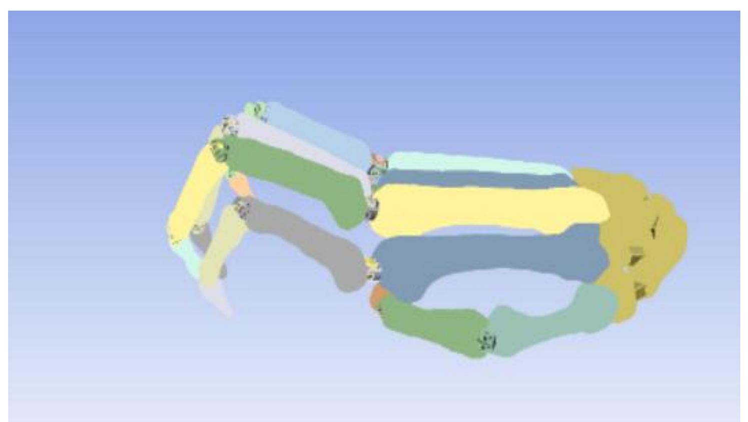
2.5.2. Mechanical Characterization

Elastic Modulus: 0.5 MPa (hyperelastic behavior)
Coefficient of Friction: 1.2 (dry contact)
Contact Stiffness: Matches human fingertip compliance

ANSYS MOTION SIMULATION







Setup

- Rigid-body dynamics with contacts
- Hyperelastic skin models
- Anatomical DOF constraints
- Tendon actuator force profiles

Figure 6 : *Time-sequenced ANSYS simulation of grasping motion showing (left to right) initial open position, mid-grasp finger flexion, and final closed configuration with object contact*

Current Refinement Phase

Fine-tuning motion control parameters based on simulation feedback. Iterative optimization of actuator timing, force modulation, and joint coupling to achieve smooth, natural transitions between grasp configurations.

RESULTS & DISCUSSION

We demonstrate a biomimetic prosthetic hand with anatomically accurate skeletal structure, compliant multi-layer skin, and 21-DOF kinematics validated through ANSYS simulation. Grasping motions achieve human-like force profiles and contact mechanics. Future integration of 4D printing technology will enable streamlined fabrication and enhanced functionality for next-generation prosthetic devices.

FUTURE WORK

Advanced Fabrication Integration

- Single-step fabrication of complete assembly
- Embedded shape-memory capabilities
- Eliminates manual assembly
- Enables complex geometries

References ;-

[1] Iglovikov, V. R. A. K. A. S. A. Pediatric Bone Age Assessment Using Deep Convolutional Neural Networks; 2017.

[2] Tamatam, S. SkinKraft. https://skinkraft.com/blogs/articles/layers-of-skin (accessed 2021-11-10).