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# BIOMECHANICS-DRIVEN DEVELOPMENT OF PROSTHETIC FINGERS: A TWO-PHALANX APPROACH

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**Abstract.** This study presents a biomechanics-driven approach to develop two-phalanx prosthetic fingers replicating essential human finger motions. A detailed biomechanical analysis of joint trajectories, anatomical constraints, and functional coordination for tasks like grasping identifies key motion features to guide design. Two underactuated prosthetic finger mechanisms are proposed, balancing anatomical realism with structural simplicity. Each employs mechanical couplings and passive elements to achieve coordinated phalanx flexion and extension using minimal actuation, enhancing manufacturability and integration into upper limb prostheses. Kinematic modelling using Denavit–Hartenberg parameters in MATLAB generates motion trajectories and assesses fingertip path accuracy under various actuation conditions. Integrated biomechanical constraints ensure realistic motion ranges and joint coordination. Comparison with natural finger behaviour shows both mechanisms closely approximate intended motion patterns, delivering satisfactory trajectory fidelity, smoothness, repeatability, and reproducibility. These results demonstrate the effectiveness of biomechanics-informed design and hybrid kinematic modelling for practical, anatomically relevant prosthetic fingers and potential for customization of prosthetics.

**Keywords:** Prosthetic finger, biomechanical analysis, underactuated mechanism, workspace analysis, motion trajectories.

## 1. Introduction

The human hand's ability to perform a vast array of tasks, from gripping tools to typing on a keyboard, stems from its complex kinematic structure, which combines multiple joints, muscles, and tendons in a highly coordinated manner. For individuals who have lost this capacity, the development of a hand prosthesis that can replicate these functions is critical for restoring independence and improving quality of life.

Traditional prosthetic hands often fall short in replicating the full range of motion and dexterity of the natural hand, highlighting the need for more sophisticated designs.

The integration of advanced technologies in upper-limb prosthetics has revolutionized the field, enabling the development of prosthetic devices that closely mimic natural movements. This is particularly important for individuals with trans-ulnar, trans-humeral, and trans-scapular amputations, where the goal is to restore as much functionality as possible through precise replication of movements and the incorporation of neural interfaces [9]. However, achieving this level of functionality presents significant challenges, primarily due to the intricate biomechanics of the hand and the difficulty of mimicking natural kinematics in artificial devices [1].

The human hand's remarkable versatility is a result of its complex kinematic structure, which includes over 20 degrees of freedom (DoF) distributed across various joints, that include metacarpophalangeal (MCP) joints, located at the base of each finger that allow for both flexion/extension and abduction/adduction movements, proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints located within the fingers which enable flexion and extension being crucial for grasping and pinching movements. A key component is the thumb's carpometacarpal (CMC) joint, a saddle joint that provides the thumb with its unique range of motion, including opposition, essential for gripping objects. Key principles of natural finger biomechanics, such as joint movement and tendon mechanics, are essential for understanding and replicating the dynamic interplay of forces and motions. Tendons play a crucial role in transmitting forces from muscles to bones, enabling precise and coordinated finger movements. Furthermore, the viscoelastic properties of tendons contribute to the hand's adaptability and efficiency during various tasks. Understanding the interplay of these joints and tendons is critical for designing prostheses that can replicate natural hand movements. Each joint contributes to specific hand functions, and their coordination allows for the execution of complex tasks, such as manipulating small objects or exerting forceful grips.

The versatility of the human hand is also evident in the variety of grasp types it can perform, including power grasp used for holding large objects, requiring maximum contact area between the hand and the object with significant force applied primarily by the fingers, precision pinch, involving the thumb and one or more fingers, used for holding small objects with fine control, and lateral pinch that employs the thumb and the side of the index finger, often used for holding flat objects. Research in literature underscores the importance of accurately replicating these grasp types, highlighting the correlation between grasp functionality and user satisfaction. Additionally, the integration of biomimetic neuronal tissues serving as mechanoreceptors into prosthetics [2, 3] offers the potential to enhance sensory feedback and improve the user's ability to interact with their environment. These artificial mechanoreceptors mimic the natural sensory capabilities of the hand, enabling more intuitive control and improved dexterity. The incorporation of such advanced features represents a critical step toward creating prostheses that closely replicate the natural hand in both function and sensation.

This paper presents a methodology that sets the stage for advanced prosthetic devices that prioritize both functionality and user experience. Simulations provide essential reference for evaluating the functionality and practicality of the biological and the proposed prosthetic finger. The analysis highlights the design's ability to achieve a robust balance between manufacturability, simplicity, and functional performance, establishing a strong foundation for further refinements in prosthetic technology. This model is crafted to replicate the natural biomechanics of the human hand.

Our approach has the aim to integrate advanced interfacing strategies. By integrating biomechanical insights and innovative designs, this study lays the foundation for advanced prosthetic solutions that enhance user experience and restore essential hand functions.

## 2. Methods

Designing prosthetic hands involves replicating the human hand kinematics [4]. Key considerations include modelling fingers as three segments (phalanx) connected by joints, using universal joints for MCP joints and hinge joints for PIP and DIP, actuation systems that provide torque and speed for realistic motion.

### 2.1. Biomechanical analysis of the human finger

To replicate natural finger motion [5], it is essential to model and simulate the trajectories of finger joints during flexion and extension, that reveal the coordination of joints and tendons, offering key insights for designing prosthetics that mimic realistic and functional hand movements.

A simplified kinematic chain representation forms the basis for modeling the fingertip's trajectory during movement, resulting from the synchronized motion of the MCP, PIP, and DIP joints. Using the following equations, we can describe the fingertip's 2D path:

$$x = L_1 \cos(\theta_1) + L_2 \cos(\theta_1+\theta_2) + L_3 \cos(\theta_1+\theta_2+\theta_3) \quad (1)$$

$$y = L_1 \sin(\theta_1) + L_2 \sin(\theta_1+\theta_2) + L_3 \sin(\theta_1+\theta_2+\theta_3) \quad (2)$$

where:

x, y represents the coordinates of the fingertip,

$L_1$, $L_2$, $L_3$ are the lengths of the phalanges,

$\theta_1$, $\theta_2$, $\theta_3$ are the angles of the MCP, PIP, DIP joints.

These joints, in combination with the phalanges, exhibit a cascading motion, where movement at the MCP joint propagates to the PIP and DIP joints, creating a coordinated and natural motion trajectory [6].

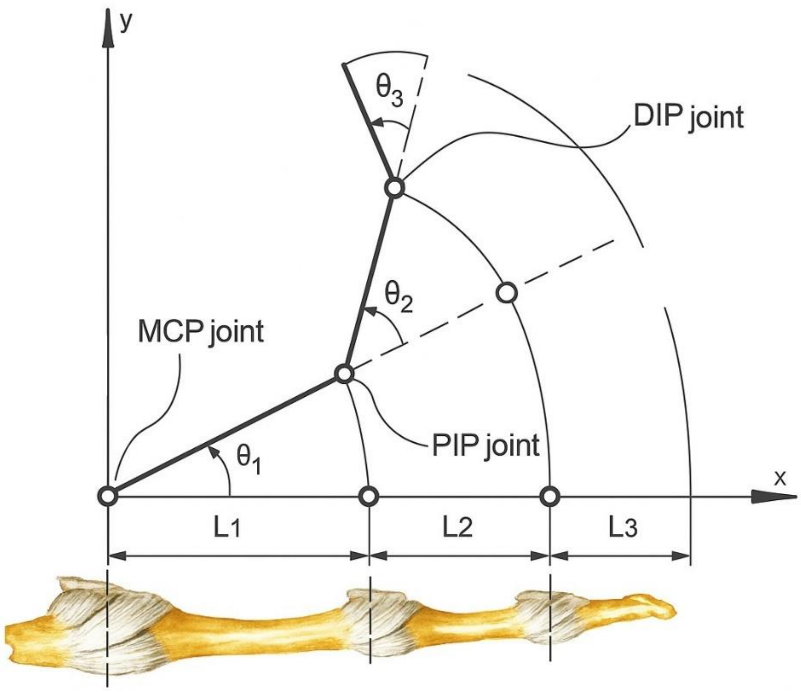


Fig. 1. Joints of the human finger.

The workspace of a finger represents the region within which the fingertip can move, dictated by the range of motion (ROM) of each joint. The trajectory of the fingertip, i.e. the path traced during motion, provides critical data for the prosthetic. By analyzing these trajectories, we can optimize the positioning and movement of prosthetic joints to mimic natural motion patterns.

By modeling the fingertip's trajectory during a power grasp, we can align prosthetic joint movements to ensure consistent contact with objects, improving grip stability and functionality [7, 8].

The simulations for workspace and trajectory of a finger have been calculated using MATLAB, using phalanx dimensions detailed in Table 1, and Eq. (1), (2).

**Table 1**

*Biologic Finger Dimensions.*

| Phalange | Length | Phase 1 Angles | Phase 2 Angles | Phase 3 Angles |
|---|---|---|---|---|
| MCP | $L_1 = 55\ mm$ | $\theta_1 = 0°$ | $\theta_1 = 45°$ | $\theta_1 = 90°$ |
| PIP | $L_2 = 33\ mm$ | $\theta_2 = 0°$ | $\theta_2 = 45°$ | $\theta_2 = 100°$ |
| DIP | $L_3 = 25\ mm$ | $\theta_3 = 0°$ | $\theta_3 = 30°$ | $\theta_3 = 80°$ |

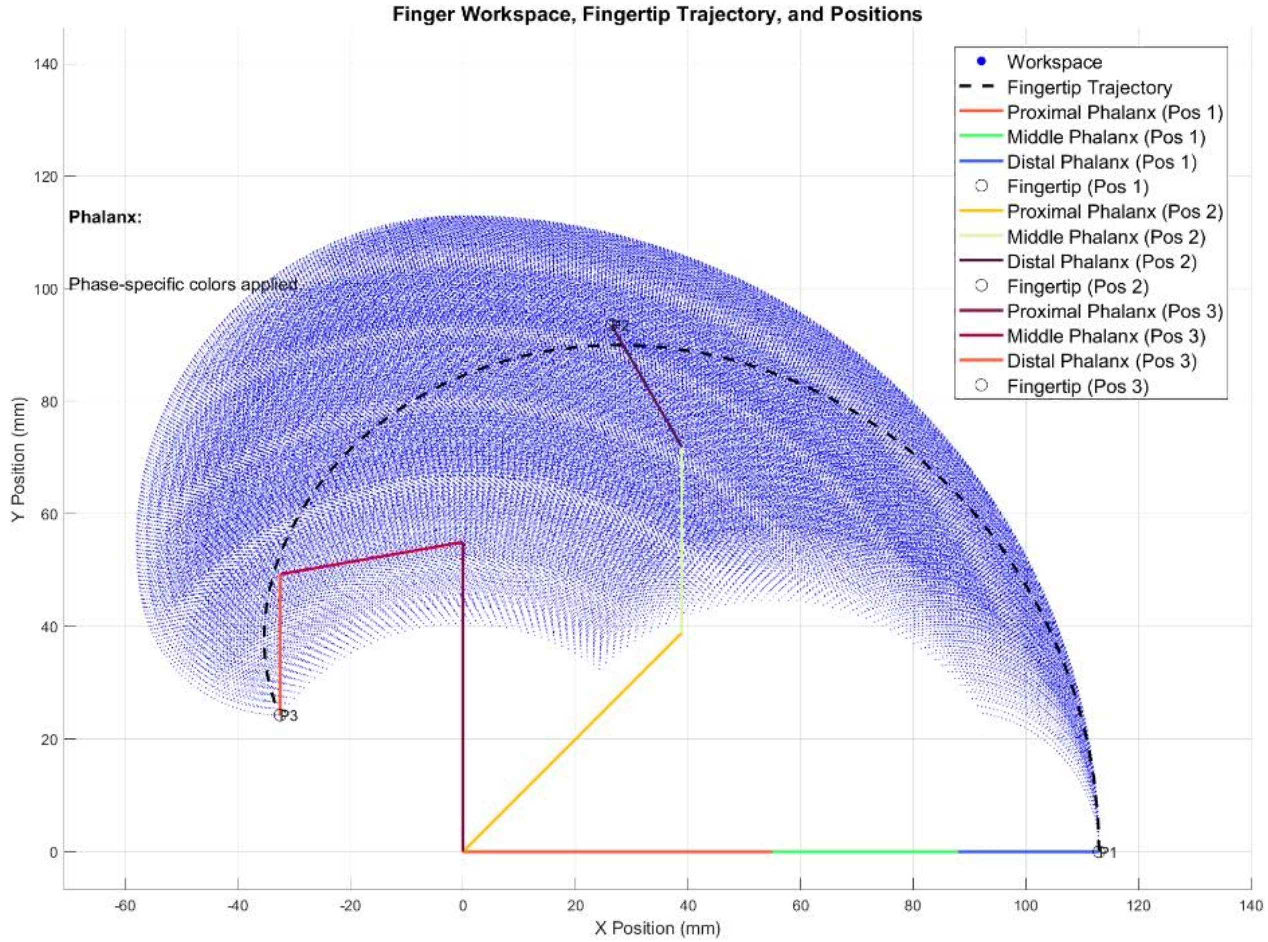


Fig. 2. The simulated trajectory of the fingertip during coordinated flexion and extension. It showcases the cascading motion of the finger joints, which is vital for grasping and manipulation tasks. The workspace points are shown in blue, while the fingertip trajectory during flexion-extension is represented by a black dashed line.

Understanding the biomechanical properties of the finger is essential for developing advanced prosthetics [9]. These properties are particularly challenging due to the intricate coordination required between multiple joints and tendons, the compact yet highly mobile structure of the phalanges, and the wide range of forces exerted during diverse tasks such as precision gripping and power grasping. Unlike other body parts, the finger's biomechanical complexity stems from its dual role in fine motor skills and force application, making its replication in prosthetics both a mechanical and neurological challenge. Key insights include:

- Joint Alignment: Prosthetic joints must replicate the ROM and mechanical behavior of natural joints to ensure smooth and coordinated motion.
- Trajectory Optimization: By analyzing the fingertip's trajectory, designers can ensure that prosthetic fingers move intuitively, enhancing user satisfaction.
- Mechanical Efficiency: Simplified models, such as merging the PIP and DIP joints, can reduce mechanical complexity while maintaining functional capabilities.

By integrating these principles into the design process, prosthetic fingers can achieve greater biomechanical fidelity, enabling users to perform daily tasks with improved precision and comfort.

## 2.2. Proposed Prosthetic Finger

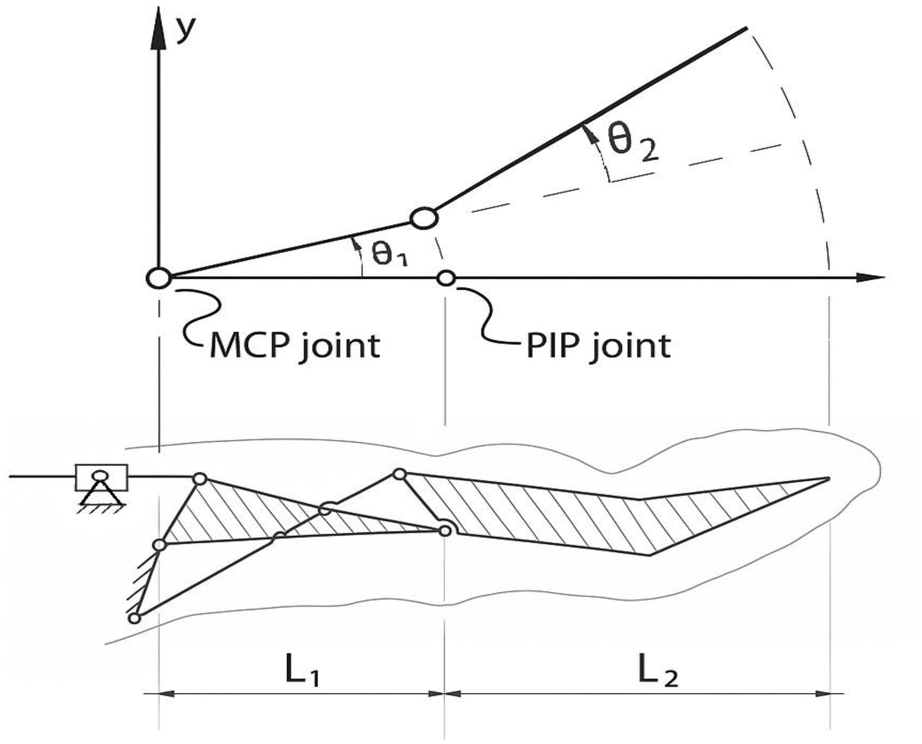


Fig. 3. The model used in the simulations (top), and the kinematic model of the proposed mechanism (bottom) for prosthetic fingers.

The kinematic model used in the following simulations, as shown in Fig. (3), is a planar underactuated mechanism connected sequentially by revolute joints, actuated by a single motor located at the base, through which synchronized movement of the distal joint (DIP) is ensured. The mechanism simplifies control by relying on predefined kinematic relationships between the joints [5]. In these simulations, the model assumes a simplified structure, where the geometry and constraints of the actual passive mechanism are neglected. Instead, the analysis focuses exclusively on the trajectory of the fingertip, which is modeled as a two-link serial kinematic chain.

The workspace and fingertip trajectory are fundamental parameters for assessing the functional performance of prosthetic finger designs. A comprehensive visualization of the motion capabilities of the proposed prosthetic finger is shown in Fig. (4). This subsection presents an analysis of the insights derived from the graph and evaluates its implications for the overall design methodology.

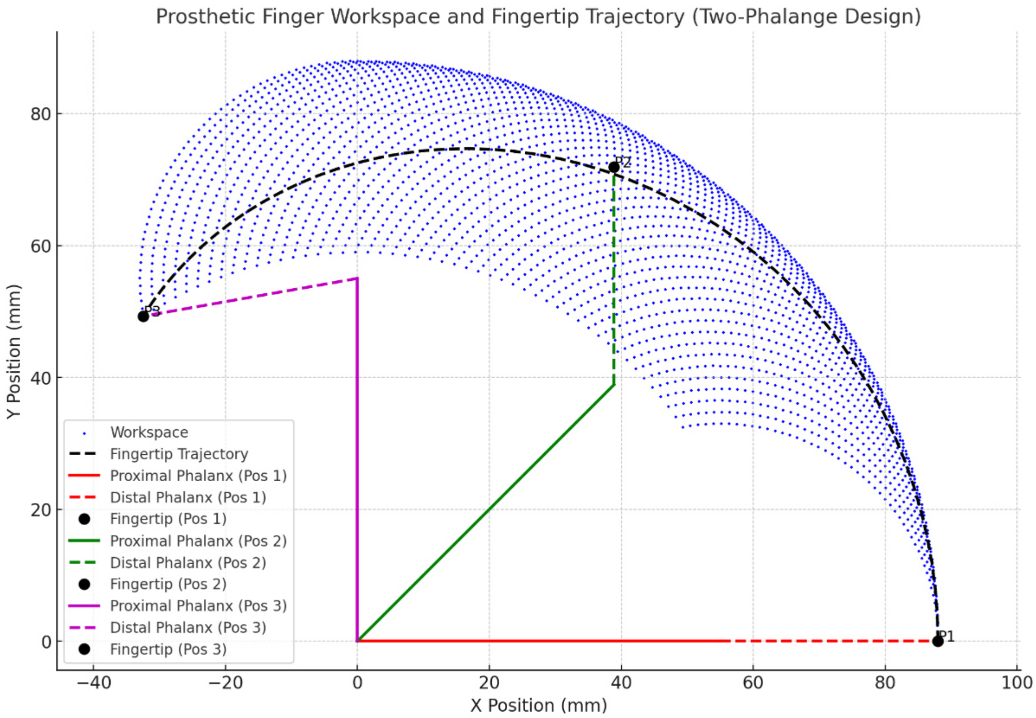


Fig. 4. Proposed prosthetic finger workspace and fingertip trajectory using the same angles for MCP and PIP joints as in Fig. (2).

The proposed two-phalange prosthetic finger simplifies the anatomical structure of the human finger by combining:

- Proximal Phalanx (65 mm), responsible for primary motion and contributing significantly to the finger's workspace.
- Distal Phalanx (40 mm), serving as an analog to the biological distal phalanx, employing passive coupling to simplify actuation.

This configuration excludes the middle phalanx and its associated PIP joint, thereby reducing mechanical complexity and manufacturing costs while retaining essential functional characteristics for object manipulation and grasping. The prosthetic finger generates a compact yet effective workspace that aligns with the spatial requirements for performing activities of daily living (ADLs), such as grasping and holding objects.

The trajectory forms a smooth, curved arc, closely approximating the natural flexion-extension motion of a biological finger. The absence of a middle phalanx results in a reduction in trajectory length compared to the biological counterpart; however, this trade-off is justified by the enhanced manufacturability and mechanical simplicity of the two-phalange design. The graph serves as a critical validation tool for the proposed design, providing evidence for the significant overlap between the biological and prosthetic workspaces substantiates the capability of the prosthetic design to replicate key functionalities. The trajectory closely aligns with the natural motion patterns, demonstrating the efficacy of the two-phalange configuration in preserving essential motion characteristics. The simplified two-phalange structure strikes a balance between functionality and manufacturability, a crucial consideration for prosthetic devices. The trajectory analysis confirms the ability of the prosthetic finger to perform various grasp types, including cylindrical, spherical, and planar grasps, which are fundamental to daily tasks.

### 2.3. Comparative Analysis of Fingertip Trajectories and Workspaces

These computational models ensure that prosthetic designs align with the natural biomechanics of the human hand [9], providing a foundation for functional and ergonomic prostheses.

The design of a prosthetic finger aims to balance functionality, manufacturability, and biomechanical resemblance to the biological finger. To evaluate the efficacy of the proposed two-phalanx prosthetic finger, comparative analysis of its fingertip trajectory and workspace against a biological finger was conducted. The results are summarized in Fig. (5) and Fig. (6), with supporting data presented in Table 2.

The fingertip trajectories of the biological and prosthetic fingers were analyzed for their shape, length, and functional coverage. In Fig. (5), the biological trajectory represents a natural flexion-extension motion enabled by three phalanges (proximal, middle, and distal) and three independent joints (MCP, PIP, and DIP). The prosthetic trajectory, while slightly shorter, effectively captures the critical motion pattern needed for activities of daily living (ADLs), achieving 85.4% of the biological trajectory length.

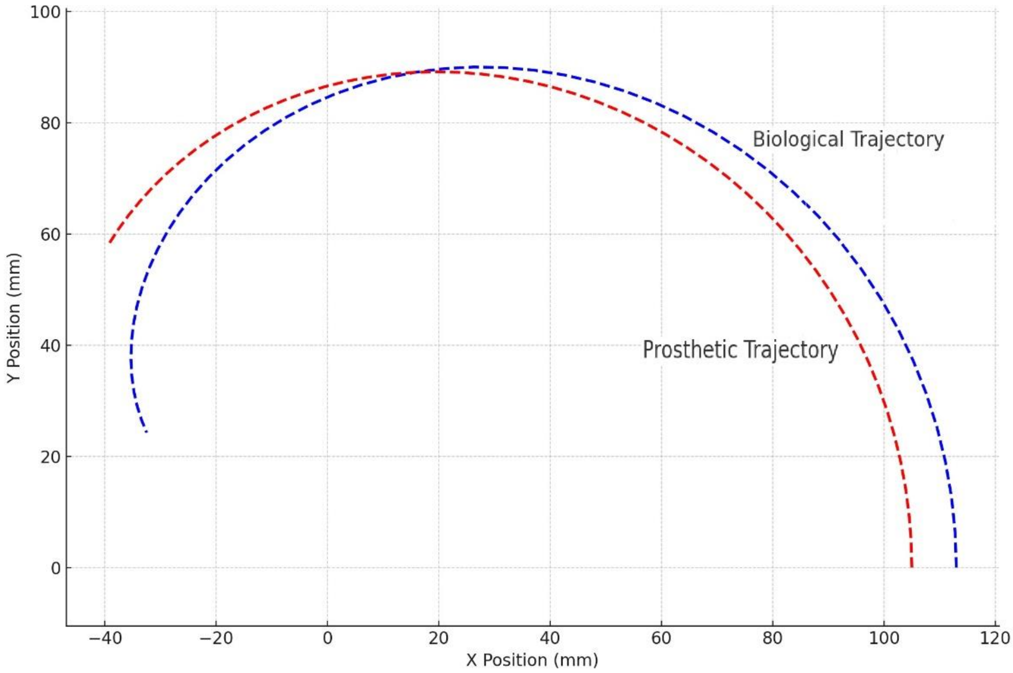


Fig. 5. Fingertip trajectories of the biological finger and the proposed prosthetic finger.

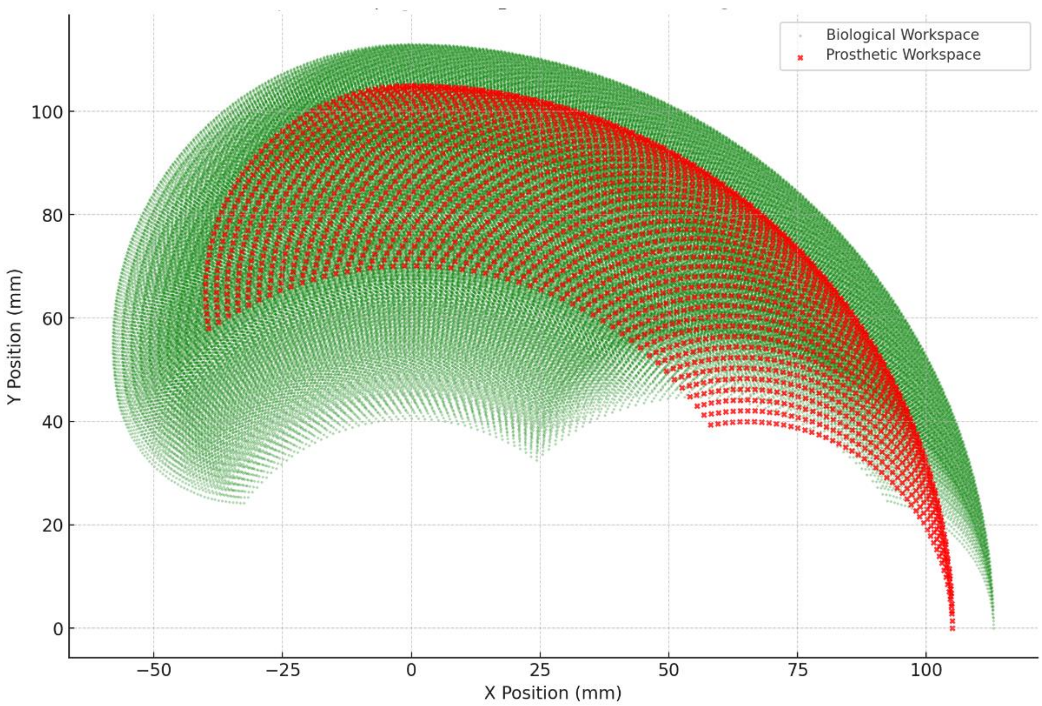


Fig. 6. Workspace of biological and proposed prosthetic finger.

This result demonstrates that the simplified two-phalanx design sufficiently replicates the key motion arcs required for grasping and manipulation. The slightly reduced trajectory length stems from the absence of a middle phalanx and adaptive coupling of distal phalanx motion to the proximal joint.

The workspace analysis in Fig. (6) reveals that the two-phalanx prosthetic design covers 62.1% of the biological workspace area. The overlap between the two workspaces highlights that the prosthetic finger achieves functionality within a critical subspace, corresponding to practical grasping and manipulation tasks.

However, the biological workspace includes additional regions due to the independent motion of the DIP joint, which enhances precision and adaptability. To further improve the prosthetic design, incorporating adaptive phalanx actuation could bridge the gap in workspace coverage while maintaining simplicity.

**Table 2**

*Comparative metrics for Biologic and Prosthetic Finger.*

| Metric | Biological Finger | Prosthetic Finger | Comparison (%) |
|---|---|---|---|
| Fingertip Trajectory Length (mm) | 241.88 | 206.60 | 85.4% |
| Workspace Area (mm²) | 13,352.13 | 8,285.91 | 62.1% |
| MCP Joint Range (°) | 90.0 | 90.0 | 100% |

| | | | |
|---|---|---|---|
| PIP/Equivalent IP Joint Range (°) | 100.0 | 100.0 | 100% |
| DIP Joint Range (°) | 80.0 | N/A | - |
| Workspace-to-Trajectory Ratio (mm) | 55.21 | 40.12 | 72.7% |
| Proximal Phalanx Length (mm) | 55.0 | 65.0 | - |
| Middle Phalanx Length (mm) | 33.0 | N/A | - |
| Distal Phalanx Length (mm) | 25.0 | 40.0 | - |

The primary motivation for selecting a two-phalanx prosthetic finger lies in its simplicity and ease of manufacturability. By reducing the number of phalanges and joints, the design:

- Minimizes mechanical complexity having fewer components that reduce potential points of failure and simplify assembly.
- Improves reliability through simplified actuation mechanisms enhancing robustness during repeated use.
- Reduces cost through the absence of a dedicated DIP joint and actuator that allows for a more affordable prosthetic device.
- Decreases weight resulting in a lighter prosthetic that is more comfortable for users, reducing fatigue and improving wearability.

Despite these advantages, the reduced functionality relative to a three-phalanx design is acknowledged. The three-phalanx prosthetic, while closer in resemblance to the biological finger, introduces challenges such as:

- Increased weight, through the additional phalanx and joint that adds to the overall mass, potentially making the prosthetic cumbersome for some users.
- Higher cost and complexity, considering the additional components and actuators that will drive up manufacturing and maintenance costs.
- Control complexity, that demands sophisticated control algorithms, which can be challenging for users to operate effectively.

To bridge the gap between the two-phalanx design and the biological finger's functionality, adaptive actuation mechanisms can be implemented. Examples include:

- Coupled Four-Bar Linkages: Integrating a linkage mechanism that passively couples the motion of the distal phalanx to the proximal joint can replicate natural motion patterns without requiring additional actuators.
- Tendon-Driven Systems: A compliant tendon system could enable adaptive flexion of the distal phalanx during object contact, mimicking the behavior of human tendons.
- Spring-Assisted Flexion: Adding springs to the distal phalanx can provide resistance during extension and assist in flexion, enhancing the natural feel of motion.

The two-phalanx prosthetic finger demonstrates a robust balance between functionality, manufacturability, and simplicity. While a three-phalanx design may more closely mimic the biological finger, its increased complexity, cost, and control challenges make it less practical for widespread use. Future iterations of the two-phalanx design can incorporate adaptive mechanisms to further enhance its resemblance to the biological model while retaining its simplicity and reliability. This iterative approach ensures that prosthetic technology remains both functional and accessible to users.

## 3. Conclusions

The kinematic modelling and integration of advanced prosthetic technologies into the human body represent a significant advancement in prosthetic fingers.

This study presents a comprehensive approach to the kinematic modeling and biomechanical analysis of prosthetic fingers, emphasizing the importance of replicating natural finger movement. By leveraging engineering principles and focusing on metrics such as workspace coverage, range of motion, and fingertip trajectory, the proposed model successfully mimic key aspects of human finger functionality. The analysis demonstrates that this mechanism provides a viable pathway for achieving functional prosthetics, with distinct advantages depending on the intended application. The model offers a simpler, more robust solution ideal for scenarios prioritizing control efficiency and reduced complexity.

Future work should expand upon the findings of this study by incorporating dynamic analyses, material optimization, and user-centered testing to validate and refine the proposed designs further. Additionally, exploring advanced control strategies and actuation systems could enhance the overall functionality

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