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Design and Fabrication of a Body-Powered 3D-Printed Finger Prosthesis for Trans-Phalangeal Amputation

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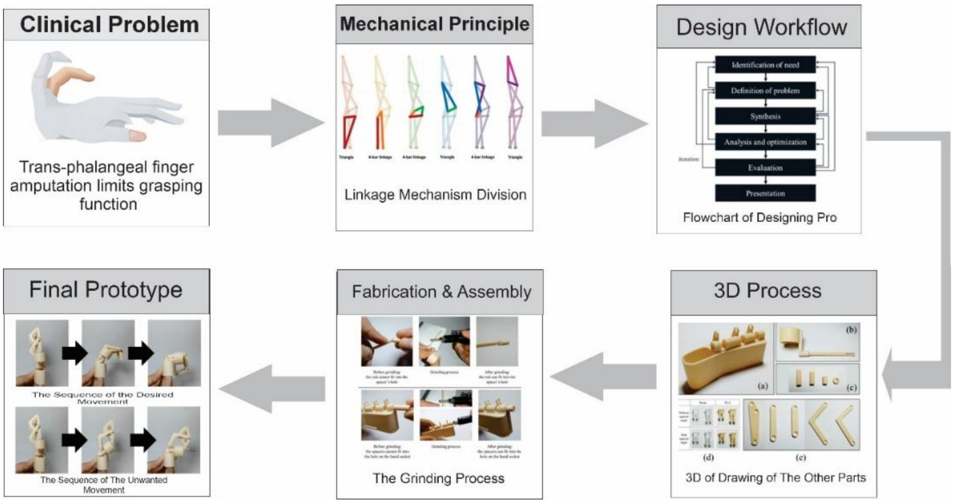
Graphical Abstract



Highlights

- This study presents a low-cost, body-powered prosthetic finger designed specifically for trans-phalangeal amputees.
- A single-DOF four-bar linkage mechanism was optimized to mimic natural finger flexion using 3D-printed components.
- The device is lightweight, customizable, and easy to operate using residual finger motion.
- Prototype testing showed effective range of motion and the ability to perform basic gripping tasks.

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ABSTRACT

High-cost and ongoing maintenance requirements keep many finger amputees in underdeveloped nations from accessing prosthetic devices. The most prevalent upper-limb amputation, trans-phalangeal amputation (accounting for about 78% of cases), is addressed in this paper as requiring a low-cost, effective finger prosthesis. Using a single degree-of-freedom (1-DOF) connection mechanism and additive manufacturing, a body-powered prosthetic finger was designed and built. Aiming to restore fundamental grip function, the device is customisable to the user's hand size. Defining user needs (affordability, simplicity of use, comfort), investigating several four-bar linkage designs, and kinematic analysis optimisation of the mechanism constituted the design process. Using fused deposition modelling (FDM) 3D printing with polylactic acid (PLA), a prototype was created and evaluated for range of motion and load capacity. With a straightforward tether actuation by the remaining finger, the last prosthesis effectively simulates natural finger bending from extended to curled states. Lightweight and easy to wear, it survived lifting items up to a particular weight—on the order of a few kilograms—before mechanical slip occurred. The 3D-printed finger prosthesis shows that a low-cost, body-powered device can restore fundamental grasp abilities for trans-phalangeal amputees. Further studies will include user trials to assess long-term comfort and function as well as material enhancements for durability.

1. Introduction

Loss of fingers due to amputation can significantly impair hand function, yet many amputees cannot obtain prosthetic devices. In developing regions, an estimated 40 million people live with limb amputations, but only about 5% have access to prosthetics [1]. The primary barrier is cost – conventional prosthetic fingers and hands can cost $4,000 to $100,000 each, with a lifespan of only 3–5 years requiring periodic replacement [2]. For growing children, devices may need replacement every few years, compounding the expense. As a result, there is a pressing need for more affordable prosthetic solutions. Trans-phalangeal amputation (loss of one or more finger segments) is the most common upper-limb amputation, comprising roughly 78% of cases [3]. These cases often involve the loss of finger parts at various joint levels. A case study with 24-year-old woman with multiple finger amputations at different joints of the left hand, which severely affected her ability to grasp objects and increased self-consciousness in social situations [4]. Conventional treatment for such partial hand loss often involves passive cosmetic prostheses made of silicone that restore appearance but not function. There is a clear opportunity to improve functional outcomes with an engineered solution that enables basic finger motion for grip [5].

Sophisticated myoelectric or multi-jointed prosthetic hands can be too pricey and complicated for many users' requirements, which presents yet another difficulty. In contrast, body-powered devices, which harness the user’s own residual motion (for example, using wrist or remaining finger movement to actuate the prosthetic), can be much simpler and cheaper. Additive manufacturing—also known as 3D printing—promises a production technique to enable customisation and help to down cost even more. Especially for unique designs, 3D printing usually has cheaper production costs than conventional manufacturing [6]. It also allows quick prototyping, and the design of complicated shapes suited to an amputee's anatomy. 3D printers' ubiquity allows people in low-resource or distant areas to perhaps acquire devices without centralised mass manufacturing [7].

In recent years, several designs for prosthetic fingers have been explored e.g., motor-driven mechanisms in patented designs which have aim to provide robust function but can be heavy or costly [8]. Body-powered designs which utilize the user’s residual finger motion to actuate the prosthetic; these offer ease of use (the user simply wears it like a ring) and modularity (each finger device can function independently), making them lightweight and customizable to different amputation levels [9]. Other research has explored soft pneumatic actuators and shape-memory alloy driven fingers to more closely mimic biological motion [10, 11]. However, such approaches may require complex fabrication or control, which can raise costs [12]. In this study, 3D-printed prosthetic finger for trans-phalangeal amputees that restores fundamental grasp function was designed at low-cost. It applies body-powered linkage mechanism with one degree of freedom, prioritizing simplicity, durability, and user comfort. The device should be easily operated using the motion of the remaining finger segment, be lightweight, and fit the user's hand securely.

2. Materials and Methods

2.1 Design Requirements and Specifications

At the outset, design specifications based on user needs and anatomical considerations has been established. The primary requirements were that the prosthetic finger be body-powered—operated by the user's own movement without requiring electronics—with a single degree of freedom (DOF) to mimic natural finger flexion and extension. It was also essential that the device be fabricated via 3D printing to ensure low cost and ease of customization, and that it be custom fit to the user's residual finger and hand dimensions. Additional criteria included comfort, ease of donning and doffing, intuitive operation, and a lightweight form factor with mass and size comparable to a natural finger to prevent discomfort or awkwardness. The prosthesis needed to be capable of exerting sufficient grip force to hold everyday objects, with a target holding capacity of approximately 25 kg as an upper bound based on manual handling guidelines, recognizing that a single finger would realistically support a much smaller load in practical use. An amputee case from literature indicated the need for a prosthetic that could restore opposition (pinching and gripping) for tasks like holding a phone or carrying light objects [8]. The device should also address suspension (staying securely on the finger stub without slipping) and not impede any remaining joint movement of the hand.

2.2 Anthropometric Measurements

Designing a custom finger prosthesis requires accurate measurements of the user's hand and residual digit. In this study, dimensions on an individual without an amputation (for prototype sizing) and planned to adjust for a specific amputee's dimensions in a future iteration. Figure 1 illustrates the joints of the human hand [13] and indicates typical measurement points for finger length (distal, middle, and proximal phalanx lengths) and width, as well as palm width. For a trans-phalangeal case (partial finger), the critical measurements include the length of the remaining finger segment and the circumference of the finger at the amputation site (for socket fitting). The average ranges of motion of human finger joints (metacarpophalangeal, proximal and distal interphalangeal joints), which are about 0–90° at the PIP joint and 0–130° at the MCP joint for flexion/extension [14]. These ranges provided targets for the prosthetic's motion. Using callipers, the finger phalange measured lengths and diameters on the prototype model hand. These values guided the scaling of our mechanism. For instance, the total length of the prosthetic finger was set to match the length of an average index finger (about 11 cm from MCP to fingertip), and the linkage dimensions were adjusted accordingly.

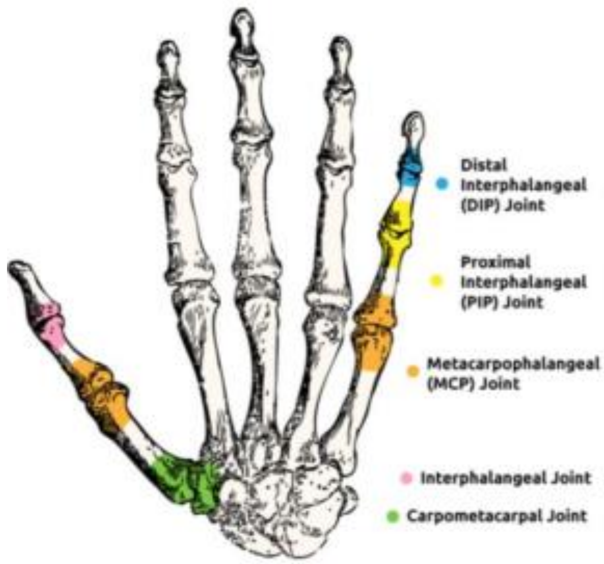

Figure 1. The Joints of The Human Hand

2.3 Conceptual Design – Four-Bar Linkage Mechanisms

The mechanical design of the prosthetic finger as a kinematic linkage problem. The challenge was to create a mechanism that could convert a single input motion (from the user's residual finger or an attached cable) into a coordinated bending of a finger-like structure. A four-bar linkage was chosen as the foundation because it can produce approximate anatomical flexion with a simple pin-jointed assembly. The multiple four-bar linkage configurations, drawing inspiration from classical mechanism synthesis techniques. This study used on linkage designs for prescribed positions, which provided four candidate linkage schemes (labelled Techniques 1-4 in Figures 2-5) [15]. Technique 1 was a rocker-output linkage tuned for two positions; Technique 2 used a three-position coupler curve; Technique 3 employed a two-position coupler; and Technique 4 was a dyad linkage approach. Each concept and qualitatively evaluated how well it could mimic finger motion.

Technique 1 (Figure 2) had a rocker link that would serve as the "finger" and an input crank attached to the user's knuckle movement. This design was straightforward but initially produced an output rotation that did not achieve full curl of the finger. Technique 2 and Technique 3 tried alternate linkage geometries aiming to improve the trajectory of the fingertip. Technique 4 introduced a serial linkage (dyad) to better approximate the multi-joint nature of a finger. After generating these concepts, then selected the best-performing sketch (visually and by quick kinematic analysis) as the basis for further development. The chosen design was a variant of Technique 4 (linkage mechanism with a dyad), as it allowed the fingertip to move through a larger arc and could accommodate multiple joint rotations within one mechanism. It essentially breaks the finger into several four-bar sub-mechanisms connected in series, one for each phalange segment.

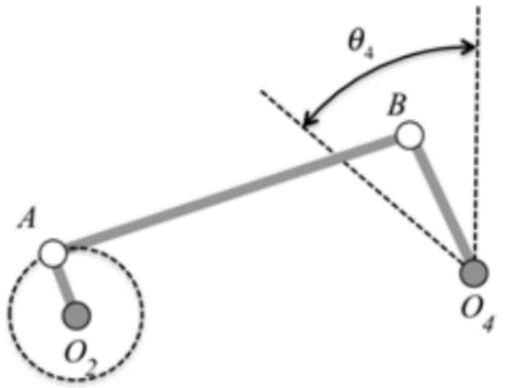

Figure 2. Technique 1: Rocker Output Two Position

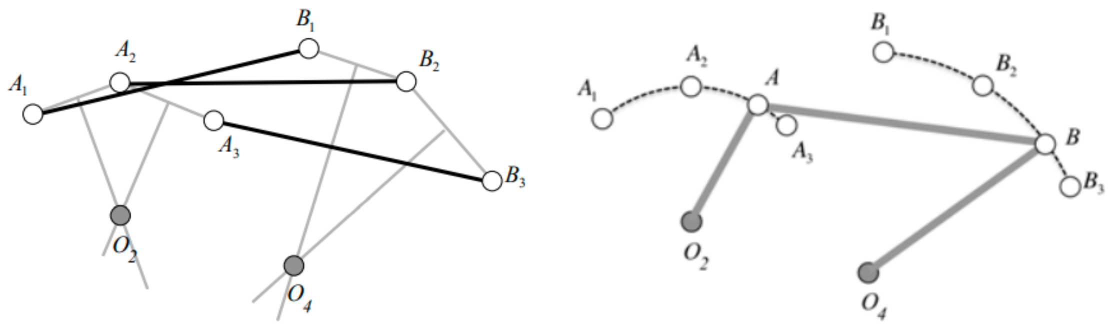

Figure 3. Technique 2: Three Position Coupler

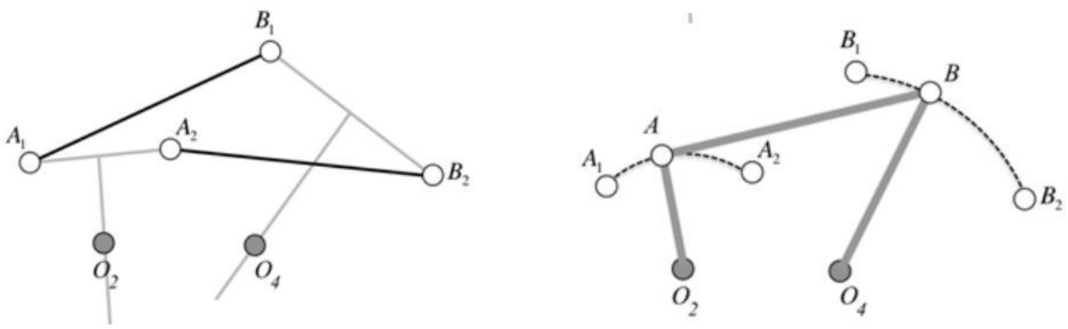

Figure 4. Technique 3: Two Position Couplers

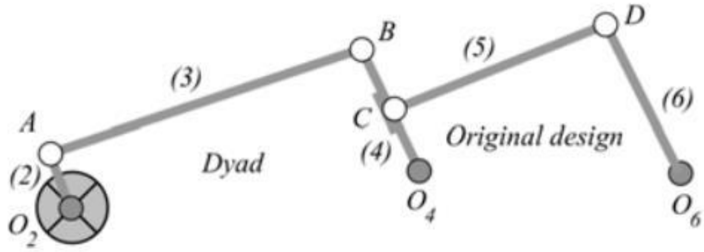

Figure 5. Technique 4: Linkage Mechanism: Dyad

2.4 Detailed Design and Kinematic Analysis

The conceptual mechanism chosen, detailed design proceeded to using analytical and computational tools. The finger linkage was divided into six segments corresponding to different parts of the finger mechanism as shown in Figure 6. By dividing the mechanism into sections, each part's motion can analyse separately and then integrate them to understand the overall finger motion. The input link (coloured red in diagrams) represents the actuation link that the user moves; when this link rotates, it drives the connected linkages through the series of four-bar chains, resulting in the prosthetic finger curling. To determine the precise geometry (link lengths, pivot locations), we performed kinematic simulations. MATLAB has been used to run an optimization on the linkage dimensions so that the output positions approximated the natural finger postures at initial (finger extended), half-bent, and fully bent (fingertip to palm) positions. The desired angular rotations for each joint were based on average human finger flexion angles. Simple loop closure equation for the four-bar and solved for link lengths that achieved approximately 45° flexion at half position and 90° at full flexion of the prosthetic's "PIP" joint equivalent. A flowchart of the design process is shown in Figure 7, summarizing the steps from identifying the need through conceptual design, analysis, fabrication, and testing. then modelled the final linkage geometry in CAD software (SolidWorks). This CAD model included not only the linkage bars (the "mechanism parts") but also a mounting **socket** to attach to the residual finger, a connector rod and ring to capture the user's input motion (worn around the neighbouring finger or wrist to pull the linkage), and small spacer components to maintain alignment of the linkage plates. After the CAD design was completed, the detailed dimensions extracted to ensure everything could be fabricated within the tolerances of our 3D printer. Key design parameters included linkage thickness of 2 mm thickness for each link, making them thin enough to stack in a finger-width space) and joint pin diameters (3 mm, to use readily available small screws or printed dowels as pins).

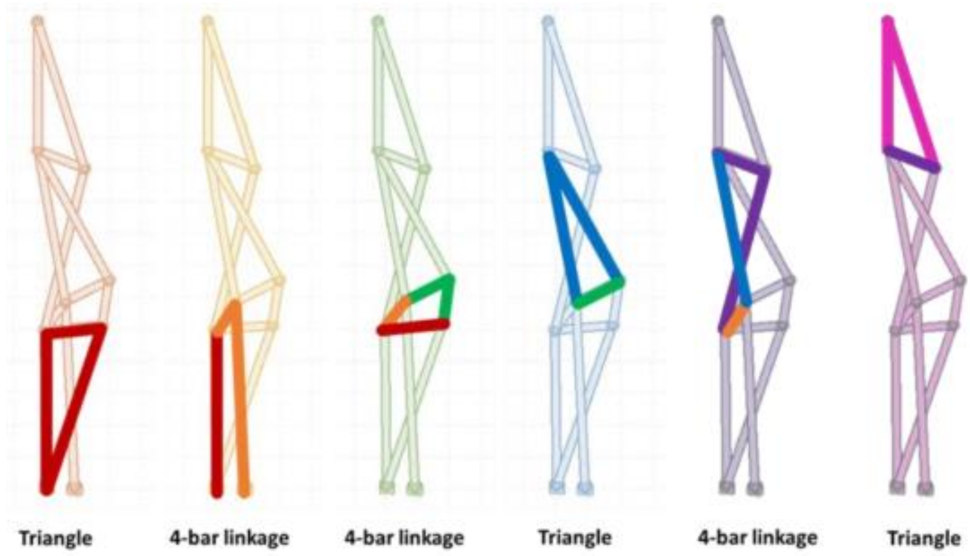

Figure 6. Linkage Mechanism Division

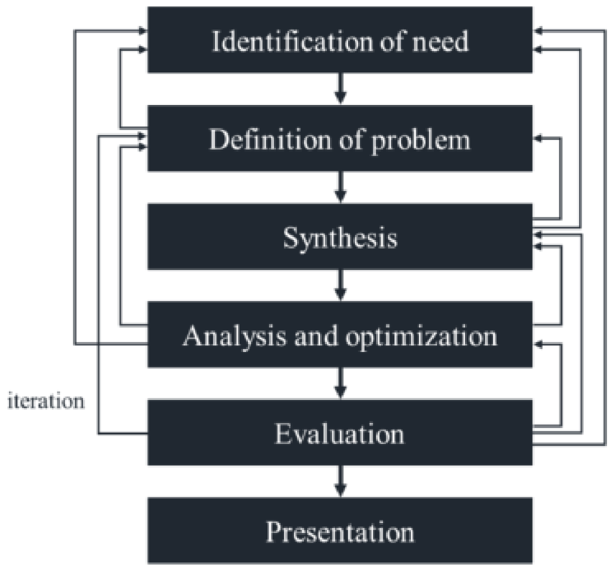

Figure 7. Flowchart of Designing Process

2.5 Fabrication via 3D Printing

Additive manufacturing created fabricated components of the prosthetic finger. The mechanism links, socket, ring, connector rod, spacers, and joint pins were first designed in 3D CAD software and then exported as STL files for printing. Two printing techniques were used. Most components were printed in PLA plastic using Fused Deposition Modelling (FDM), chosen for its simplicity of printing and sufficient strength for prototyping goals. Printed with a 0.2 mm layer height and 20% infill, these structural pieces and linkages. The size of each component was checked post-printing against the CAD model to offset any fit problems or shrinking or fit concerns. We also used Stereolithography (SLA) printing with photopolymer resin for the joint pins, which are tiny and need more accuracy and strength. When printing tiny, complex parts like hinges, this resin material provides more resolution and maybe more strength than PLA. After printing, some minor post-processing was required. In our initial assembly attempt, we discovered that certain parts did not fit together perfectly due to small printing inaccuracies. For instance, the circular holes in the spacers were slightly tight for the mating pins, and the ring connector didn't fully insert into the socket openings. We performed a grinding and sanding process (see Figure 8) to remove excess material and achieve proper fit. This step was manual and took only a few minutes per part. Finally, all parts were assembled according to the design. The assembly procedure involved inserting the joint pins through the aligned holes of the linkage parts (in their stacked configuration) and securing them.

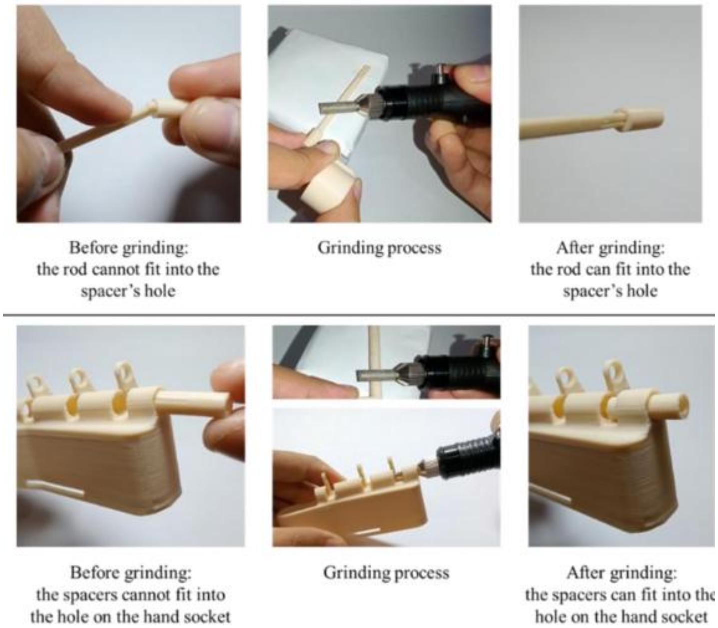

Figure 8. The Grinding Process

2.6 Testing Methods

The complete prosthetic finger prototype was preliminarily tested to assess its range of motion, strength, and ergonomic fit. The prosthetic finger was manually operated by sliding the input ring or link across its full range, and the resulting finger curl was noted. To determine if the prosthesis could reach both a completely extended posture and a suitably flexed position to grasp items roughly 3 cm in diameter, such as a cylindrical handle, the motion was qualitatively compared to that of a human finger. Aiming at about 90 degrees, a protractor was also used to measure the angle at the "PIP" joint in the completely closed position. Strength was assessed by means of a straightforward load test done by attaching the prosthetic to a solid support to mimic hand connection. Weights (100 g increments of rice) were put progressively under a little bucket suspended from the fingertip. Observations were done to see whether the device could support the weight without distortion or detachment by flexing the finger to raise the bucket. The prosthetic either failed or could no longer handle the load as it was increased. As seen in Figure 9 of the thesis, which depicts the configuration for torque measurement using weights, this approach was modified from the intended minimum torque test. Finally, an able-bodied person wore the device on their finger under a sleeve simulating an amputated stump, allowing for informal ergonomic and fit assessment. Though a complete ergonomic trial with an amputee was not feasible during this phase, subjective evaluations were conducted on the device's comfort, adjustability (e.g., padding or lining in the socket), and general weight.

Figure 9. Prosthetic Position to Measure Minimum Torque

3. Results and Discussion

3. 1 Prosthetic Finger Design Overview

The final design of the prosthetic finger is a single-DOF linkage mechanism that bends like a natural finger when actuated by the user's residual finger motion. The device consists of a set of interlinked plastic pieces forming three pseudo-joints corresponding to the MCP, PIP, and DIP joints of a finger. Figure 10 shows an assembled view of the prosthetic finger from the side, illustrating the linkage mechanism in the extended (straight) position and highlighting the key components.

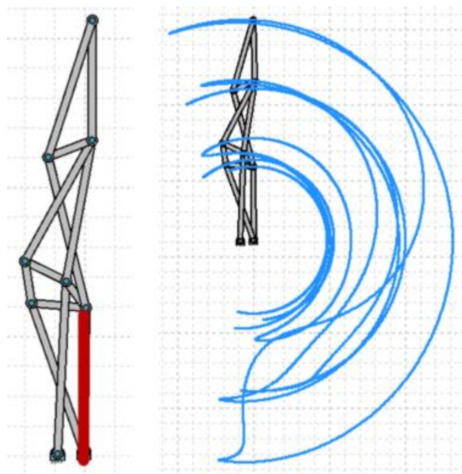

Figure 10. The Finger Linkage Mechanism and Its Movement

In the extended position, all linkage segments are aligned, making the prosthetic finger appear straight. When the input link (mounted near the base) is pulled, the linkage segments rotate relative to each other, causing the finger to curl. The red-colored link in our design (see thesis diagrams) served as the input; in the physical prototype, this input is connected to a ring worn on an adjacent finger. By bending that finger or pulling the ring, the user causes the prosthetic to flex. The mechanism was tuned such that the fingertip follows a roughly anatomical path. The linkage division approach (six four-bar sub-mechanisms) ensured that when the input rotated by ~90°, the tip of the prosthetic finger moved to a position touching the hypothetical palm, achieving a closed fist posture. The overall length of the device matched the user's other fingers, and the appearance was discreet enough – although not lifelike cosmetically, it has a slim profile.

3. 2 Fabrication and Assembly Outcomes

All components were successfully 3D printed and assembled. Figures 11 and 12 illustrates the CAD models of the mechanism parts and other parts, as well as the 3D printed pieces before assembly. We found that printing the linkage in PLA yielded sufficiently rigid parts; however, the PLA joint pins were fragile. The resin-printed pins were used in the final assembly due to their higher strength and better fit. After minor grinding of a couple of parts, the prosthetic finger was assembled. Figure 13 shows the 3D printing results of all the parts: (a) the hand socket that fits over the finger stump, (b) the ring and connector rod for actuation, (c) spacers, (d) joints (pins), and (e) the linkage mechanism parts. These parts together weigh only a few tens of grams (the entire device weighs approximately 50 g). The assembly process was straightforward, beginning with the insertion of the joints to sequentially connect the linkages, followed by the attachment of spacers and the securing of the socket, ring, and connector components. Once fully assembled, the prosthetic finger was mounted on a test hand for evaluation. To enhance comfort and improve grip on the skin, the socket was lined with a thin layer of foam. The ring was adjusted to loop comfortably around the adjacent finger of the tester, ensuring stable operation. During assembly, some joints exhibited tightness, likely due to residual roughness from the 3D printing process. This was resolved by applying a small amount of lubricating oil to each pin, which noticeably improved the smoothness of movement. However, when using PLA pins, several broke during the press-fit assembly, indicating that the material may be too brittle for load-bearing joint applications. Figure 14 shows an example of PLA pins that broke into pieces during assembly. In contrast, the resin pins (particularly those printed without a taper angle) inserted cleanly but tended to loosen under load. The resin pins with a slight taper held more firmly after assembly and were ultimately chosen for the prototype. This result indicates that material choice for critical small components is important – switching to a tougher material (or even small metal screws) for pins could greatly enhance durability in future iterations.

Figure 11. 3D Drawing of the Mechanism Parts

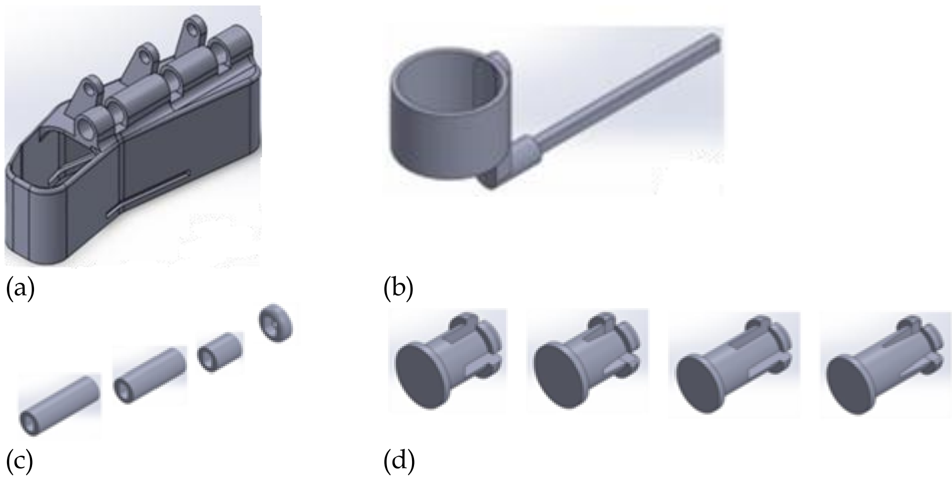

Figure 12. Three Dimension (3D) of Drawing of the other parts. a) Hand Socket, b) Ring and Connector Rod, c) Spacers, d) Joints

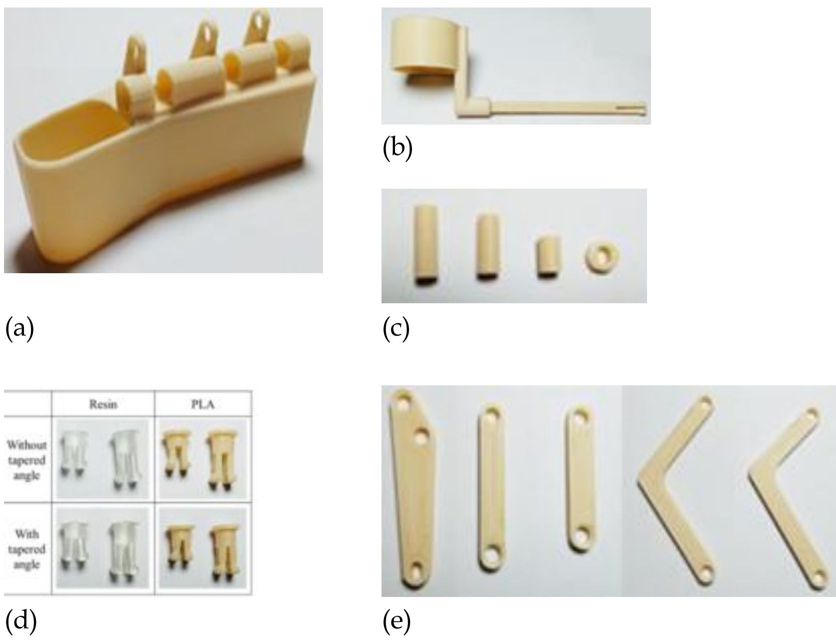

Figure 13. Three Dimension (3D) of Printing Result. a) Hand Socket, b) Ring and Connector Rod, c) Spacers, d) Joints, e) Mechanism Parts

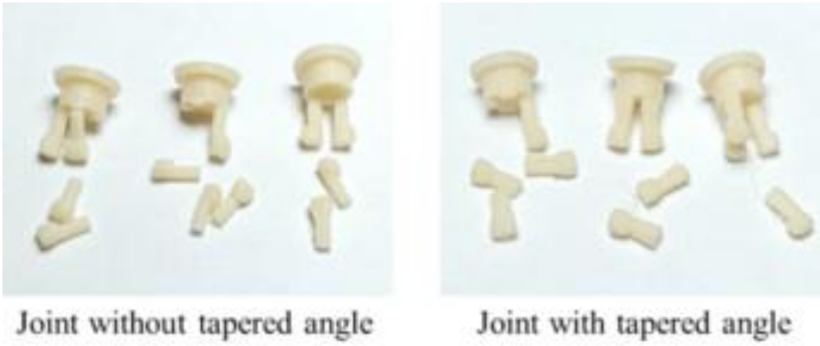

Figure 14. PLA Joints Breaks into Several Pieces

Range of Motion and Functional Testing

In functional tests, the prosthetic finger prototype demonstrated the intended range of motion. Starting from full extension, the user (tester) could flex the device through approximately 90 ° of motion to a curled position. Figure 15 shows a sequence of the prosthetic finger's desired movement: initial (straight), half-flexed, and fully flexed positions. The motion was smooth, albeit with a somewhat abrupt stop at the final position due to the mechanical limits of the linkage. There was a minor issue of unwanted hyperextension – when fully extended, the linkage tended to slightly bow backward if forced (likely due to a small slack in the joints). Figure 16 illustrates this unwanted movement beyond the intended range. By adding a physical stop in the design to prevent hyperextension and protect the mechanism. When the prosthetic finger was attached and the input ring tethered to the tester's finger, a natural coordination could be achieved: by bending the controlling finger, the prosthetic finger flexed simultaneously. This indicates the body-powered control concept is feasible. The tester could, for example, hook the prosthetic finger around a light object and lift it by flexing her intact finger.

In the strength test, the prosthetic finger could lift around 500 g before the mechanism started to slip. The slipping occurred at the attachment of the socket to the tester's finger (essentially, the whole device began to slide off when overloaded). Structurally, the linkage itself did not break under these loads, which is promising. When the device was manually held in place (to isolate mechanism strength), it managed to curl and hold about 1.0 kg of weight at the tip before we observed significant deformation of the plastic links. This corresponds to roughly 9.8 N of force at the fingertip. While this is far below the ambitious 25 kg target (which would actually require involvement of multiple fingers or a whole hand grasp), it is sufficient for many daily tasks like holding eating utensils, a toothbrush, or a TV remote. The minimum torque needed to actuate the finger (to overcome joint friction) was low – the tester reported it was easy to move, requiring only a gentle motion of the controlling finger. This suggests that, in terms of user effort, the prosthetic is convenient to operate. However, the trade-off is that because it is easy to move, it cannot exert very large forces (without the user's finger slipping out or the device coming off, as mentioned). Ergonomic test with an amputee user, but we did evaluate comfort qualitatively. The test has been evaluated with device's lightweight nature made it almost unnoticeable after a few minutes of wearing. There were no pressure points from the socket during our short trials, although for a custom fit on an amputee, the socket shape would need to be exact to their finger stump to avoid any pressure sores. The open-frame design (mostly linkage bars rather than a solid mass) means it is ventilated and does not significantly trap heat on the user's hand – a common issue with cosmetic silicone prosthetics.

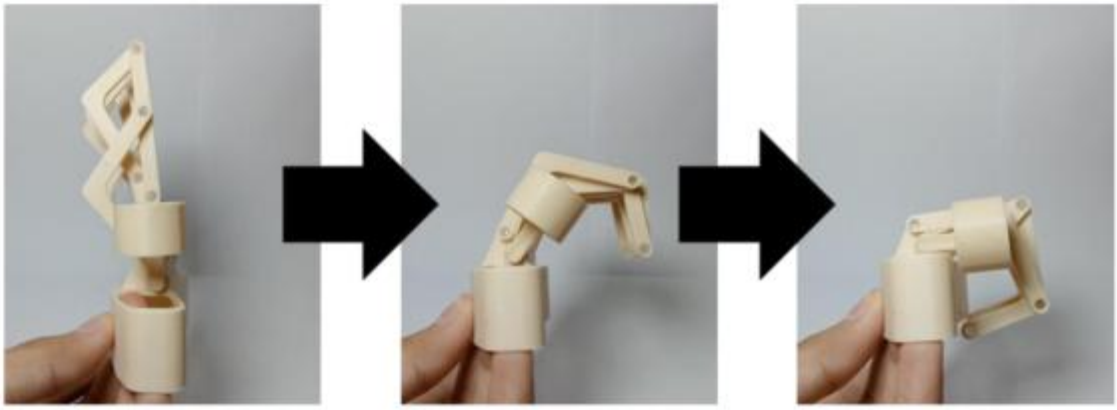

Figure 15. The sequence of the desired movement

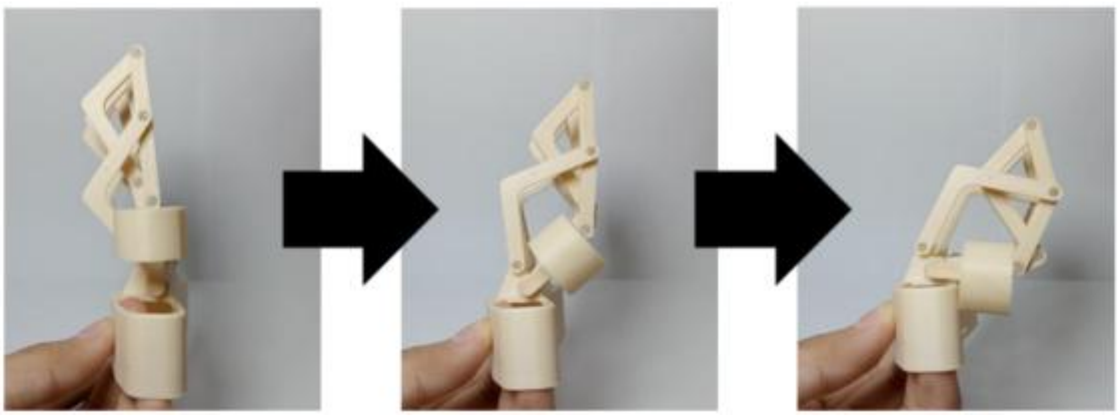

Figure 16. The sequence of the unwanted movement

Integrating of classical mechanism design with modern fabrication to address a biomedical challenge. The body-powered finger prosthesis achieved basic functionality at a fraction of the typical cost of commercial devices. By leveraging consumer-grade 3D printing, the prototype was produced with only a few dollars' worth of material. Such affordability could make prosthetic fingers accessible to a wider population, particularly in low-income settings. Compared to externally powered prosthetic fingers (which often use motors and complex linkages or cable systems), our design is much simpler, although it provides only one degree of freedom. This limits the range of possible motions (for instance, no independent control of different finger joints), but it also greatly simplifies use – there is no electronics or battery to maintain, and the user's own proprioception can control the finger. Body-powered control is intuitive and often preferred in some scenarios (as evidenced by many amputees continuing to use cable-driven hooks or body-powered split-hooks for reliability). The ring-actuated design we implemented is similar in spirit to Macduff's (2012) concept of a ring that the residual finger can move to drive a prosthetic. Our prototype confirmed that this approach can indeed produce a useful motion [16]. The prototype's ability to hold around 1 kg in a static lift test is modest, but for a single finger, it is not insignificant. A human finger can typically exert around 5–10 kg of force in a strong pinch or hook grip; achieving higher forces would likely require either a sturdier construction (perhaps using metal linkages) or distributing load across multiple fingers. Since our aim was to enable everyday light activities, the current strength may suffice for tasks like typing, using a phone, or holding a cup (with support from other fingers).

The weakest point observed was the attachment/suspension: future designs might incorporate better strapping or moulding to the hand to prevent the device from dislodging under heavier loads. One concern identified is the durability of 3D-printed PLA parts. PLA is known to be prone to brittle failure and can degrade with time (especially under heat). Over a longer period of use, the joints and links might crack. A possible improvement is to print the device in tougher materials such as ABS or nylon, or to use carbon-fibre reinforced filament for critical parts [17]. Additionally, using metal pins for the joints could drastically improve the lifespan and reliability of the mechanism, at a slight cost increase (still very low compared to entire device cost). Comfort and cosmetic appearance are important for user acceptance, it is not cosmetically glove-like [18]. It looks mechanical, which some users might not mind, but others might prefer a covering that makes it resemble a natural finger. A silicone sheath could be designed to cover the prosthetic, providing a lifelike appearance while the internal mechanism provides function. This hybrid approach (functional core + cosmetic glove) is used in many commercial prosthetics and could be applied here without major changes to the core design [19].

The main limitations of the current design are its single degree of freedom and custom fit to a specific size. The 1-DOF linkage cannot adapt to different grasp shapes (unlike multi-articulating fingers which can conform around objects). However, it covers the primary motion needed for a simple closing grasp. Regarding size, although the design can be scaled, each user would require a personalized socket and possibly adjustments in linkage lengths to match their hand proportions. This is where the digital nature of the design and 3D printing become strengths to adjust the CAD model for different finger lengths. Ensuring the mechanism still works when scaled (especially if the user's hand is much larger or smaller) may require re-optimization of the linkage geometry. The assembly and maintenance of the device are straightforward. One advantage of a printed prosthesis is that any broken part can be reprinted and replaced [20]. In tests, if a linkage had broken, it could produce a new one in a few hours. This modular replacement could be part of a maintenance plan could be provided with one prosthetic finger, but with the digital files and instructions to print spare parts as needed.

4. Conclusion

The designed and fabricated a low-cost prosthetic finger for trans-phalangeal amputation has been successful using 3D printing and a body-powered linkage mechanism. The resulting device meets many of the design criteria: it is lightweight, easy to operate with one remaining finger, and capable of reproducing the basic flexion motion of a finger. Initial testing showed that the prosthesis can assist in simple gripping tasks and is comfortable for short-term use. By using accessible materials and manufacturing methods, the cost of the device is minimal, which is a significant step toward making prosthetic fingers more widely available to those in need. This study contributes a practical example of applying engineering design to improve quality of life for amputees, emphasizing affordability and simplicity. While the prototype is promising, further improvements are necessary to enhance its performance and user experience. In summary, the body-powered 3D-printed finger prosthesis demonstrates that even a single-degree-of-freedom device can restore meaningful function, enabling an amputee to perform everyday tasks with greater ease. With iterative refinement and user-centered design, such prosthetic solutions have the potential to significantly reduce the gap in prosthetic care availability, especially in resource-limited settings.

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CRediT Authorship Contribution Statement
Desinta Dewi Ramadani: Conceptualization, Methodology, Formal analysis, Investigation, Writing – Original Draft. Muslimin: Methodology, Validation, Data Curation. Farid Triawan: Conceptualization, Validation, Writing – Review & Editing, Supervision, Funding acquisition, Project administration.

Conflicts of Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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