Research Project 2024-2025

Defying Limb-itations: Revolutionising Accessible Prosthetics Through 3D Printing

Final Report

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Abstract

Upper-limb loss significantly impacts autonomy, mental health, and quality of life, yet prosthetic devices remain largely inaccessible due to high costs and limited practicality. This project aimed to design and prototype a functional, affordable, and personalised 3D-printed forearm prosthetic, utilising open-source tools, sustainable materials, and biomechanical understanding. The device is powered by elbow-driven articulation with potential for motorised control, enabling grasping and object manipulation through a simple fishing wire and elastic mechanism.

A key innovation lies in the generation of a personalised socket, created from user-specific 3D scans and automated via Python code to eliminate CAD skill barriers. Most components were printed using Flashforge and UltiMaker printers, using Fused Deposition Modelling and PLA filament. Without access to clinical participants, a mock stump and artificial joint system enabled prototype testing. A functionless aesthetic model as well as a functional claw distal attachment were developed, both possessing magnetic interfaces to allow interchangeable use.

Further development included a motorised control system built around an Arduino Nano, showcasing potential for wireless input and enhanced autonomy. The project also highlights the potential of sustainable production through biodegradable materials and modular design. A complete open-source guide has been published online, enabling users with access to a smartphone, computer, and 3D printer to fabricate and assemble their own prosthetic.

This project demonstrates the feasibility of low-cost, community-driven prosthetic development. It offers a scalable solution to limb loss that prioritises accessibility and personalisation. Beyond restoring function, it highlights how prosthetics can help reclaim independence, dignity, and identity.

Lay Summary

Losing an arm is a life-changing experience that affects a person's ability to work, care for themselves, and most importantly live the life they want. Prosthetic arms can help, but they are expensive, hard to get, and often uncomfortable. Many people, especially in conflict zones and poorer areas, never get one. This project aimed to change that. Using low-cost 3D printing and free software, a forearm prosthetic was developed that can be made at home with basic equipment. The device is powered by elbow movement, pulling on fishing wire to open and close a claw at the end of the arm. It's simple, but it works. Assuming access to a printer, it only costs around £25 to produce.

The project also created a free online guide for users to scan their own arms, generate a personal socket using code (no design skills needed), and print the parts at home. An electronic system was also designed to show how future devices could be controlled with a motor and possibly even wirelessly. The arm uses shin pads and Velcro for comfortable upper-arm support and can therefore be adapted to suit children or different limb shapes.

Although just a prototype, the project shows what's possible when accessibility is put first. Prosthetics shouldn't just be for those with more money, they should be tools for anyone who needs them. With limited funding and time, this project shows that prosthetics can be made cheaply and quickly, and they could easily be made for everyone. It's not just about replacing a limb; it's about reclaiming identity and independence.

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I Introduction

The human hand is one of the most functionally complex and dexterous appendages in the body, responsible for both gross and fine motor control. With 21 degrees of freedom (distinct directions a joint can move) in the fingers and 6 in the wrist, they enable delicate object manipulation and forceful gripping (Cordella et al., 2016). The loss of a hand profoundly affects an individual's independence, occupational capacity, and psychological well-being. Limb loss is often likened to the experience of bereavement, highlighting the emotional, social, and functional disruption it brings (Belon and Vigoda, 2013).

Prosthetics serve as a critical intervention in restoring autonomy and improving quality of life. Even passive prosthetics, which lack functional movement, have been shown to enhance body image and reduce social stigma (Trent et al., 2020). This is especially apparent for women, among whom studies have observed a preference for functionless but more cosmetically appealing designs (Trent et al., 2020; Resnik, Borgia and Clark, 2020). More advanced options include body-powered and myoelectric (muscle activated) devices, with some hybrid models combining both systems to maximise mobility and precision (Cordella et al., 2016; Piazza et al., 2017). Despite these technological advancements, access remains severely limited. The World Health Organisation estimates that only 10% of the 35–40 million people globally in need of prosthetic devices currently have access (Mduzana et al., 2020).

Background

In the UK, approximately 5,200 upper-limb amputations are performed each year (Cordella et al., 2016; Home, 2024). While vascular disease and diabetes are the most common causes of lower-limb amputation in high-income countries, accounting for 82% of cases (Shahsavari et al., 2020). Upper-limb loss is often due to traumatic events such as traffic collisions or workplace injuries, which make up 68.8% of such cases (Østlie et al., 2024). Many paediatric patients require prosthetics due to congenital limb differences, which presents additional challenges due to the need for regular resizing and personalisation as they grow (Trent et al., 2019).

The urgency for accessible prosthetic solutions is even greater in conflict zones. Last year in Gaza, over 24,000 individuals suffered life-altering injuries due to ongoing violence, with around 1,000 children reported to have lost at least one leg, and approximately 10 more children losing limbs every day (Knell, 2024; The New Arab, 2024). One man, after undergoing a transfemoral (mid-thigh) amputation from an Israeli tank strike, described losing "his whole life," including the ability to care for his family (Knell, 2024). Upon receiving a prosthetic, he stated, "Just getting my leg back is also giving me back my smile." This highlights how prosthetic access transcends physical function, it plays a vital role in restoring dignity, independence, and hope.

However, cost remains a major barrier. A basic body-powered hand prosthetic can cost upwards of $10,000 in the US, while myoelectric arms can exceed $120,000 (Brack and Amalu, 2020). Furthermore, discomfort, lack of personalisation, and limited functionality result in high rejection rates, with 26% of adults and 45% of children abandoning their devices (Brack and Amalu, 2020). These statistics emphasise that prosthetics must be not only functional, but also affordable, comfortable, and adaptable to individual needs.

3D printing

One promising avenue for improving prosthetic accessibility is 3D printing, which enables cost-effective, customisable, and rapid prosthetic production. Unlike traditional prosthetics that require specialised manufacturing, 3D printing reduces both production costs and waiting times with on-demand fabrication. Extrusion-based 3D printing, particularly Fused Deposition Modelling (FDM), is a widely used method for producing plastic parts (Rajan et al., 2022).

Computer-aided design (CAD) software is used to develop 3D models which are fed into a slicing software to develop instructions for the printer. Most FDMs utilise thermoplastics for printing, these are fed into a heated nozzle via a stepper motor and gear system for melting (Rajan et al., 2022). Various plastics can be used depending on the required durability and flexibility, with Polylactic Acid (PLA) offering a low-cost, biodegradable option, while Nylon and PETG provide higher durability at a slightly increased cost (Wang et al., 2024). The plastic is extruded from the nozzle and deposited layer by layer, hardening upon cooling. Actuators control nozzle movement in the X, Y, and Z axes, allowing precise material deposition. Due to the "stacked" printing, sacrificial supports are often required to stabilise overhanging structures. Variables such as infill geometry and density can be tailored, altering the physical characteristics of builds. A larger disposable base called a raft is useful to provide more stability to a print and prevent it from separating from the stage mid-print. Compared to alternative printing methods FDM lacks fine resolution, however it is very well suited to printing low-cost prosthetics due to its affordability, versatility and accessibility (Rajan et al., 2022).

The e-NABLE community develops open-source, 3D-printed, upper-limb prosthetic devices (figure 1) with a focus on affordability, functionality, and personalisation. 40,000 volunteers across 100 countries have helped deliver prosthetics to between 10,000 and 15,000 recipients in underserved communities with limited healthcare access (Enabling The Future, 2023). Most devices are mechanically controlled by an adjacent joint, with movement being translated via fishing wire or elastic cords, for example, wrist flexion augmenting finger movement. The community utilises PLA due to its cost-effectiveness and biocompatibility. The prosthetics are simply designed to allow accessible assembly with minimal tools. The modular design of the prosthetics particularly benefits children who frequently outgrow their devices; this segmented approach also allows easy replacement of damaged parts (Enabling The Future, 2023). They provide various designs such as the "Phoenix Hand" and "UnLimbited Arm", accommodating a range of limb differences (Enabling The Future, 2023). One of the most notable designs within the network is the Cyborg Beast, developed by Dr. Jorge Zuniga (Zuniga et al., 2015). Specifically created for children, its anatomical structure, bold aesthetic, and emphasis on ease of use have made it a standout option, demonstrating how child-focused, open-source innovation can empower users (Zuniga et al., 2015). While these devices do not fully replicate the complexity of natural human movement, they offer a significant boost in independence and confidence, at a fractional cost of conventional prosthetics.

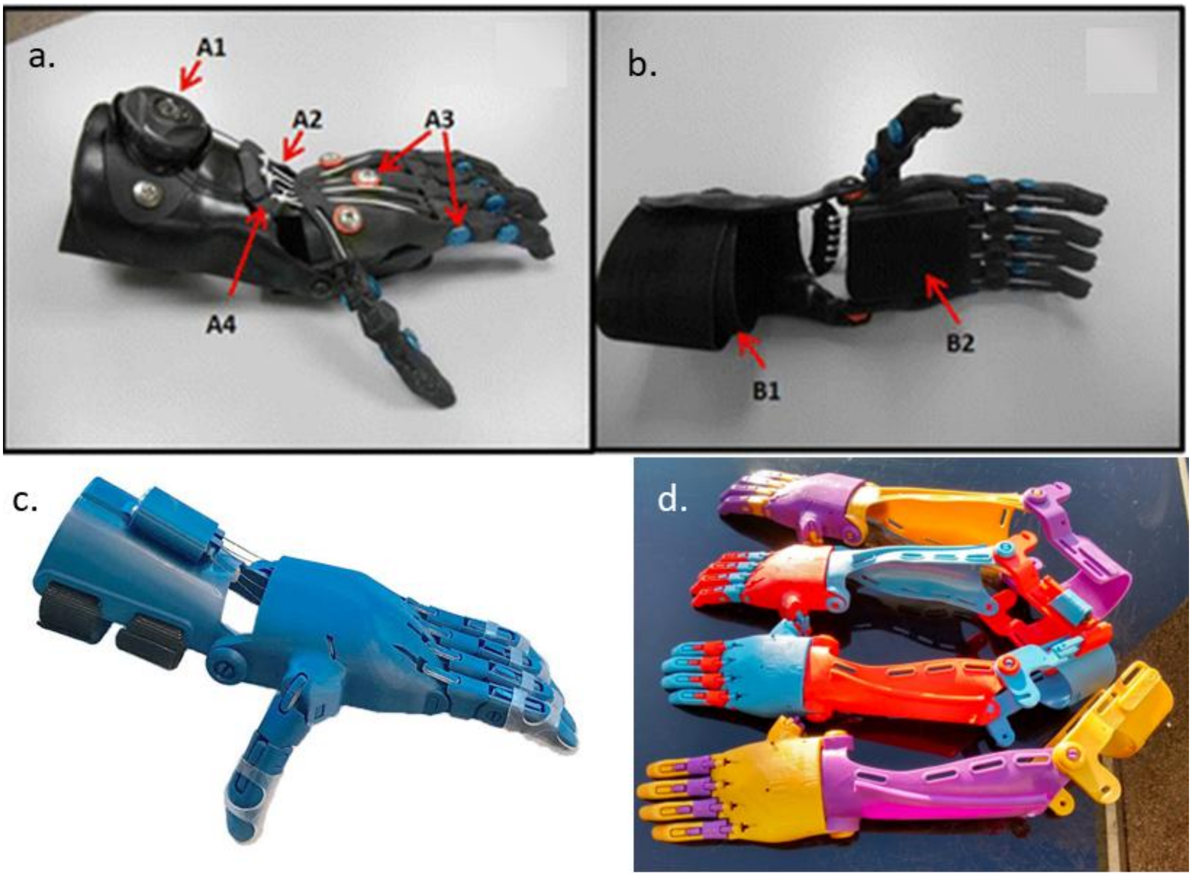

Figure 1. *E-NABLE community open-source designs.* Cyborg Beast, the top view (a) highlights the adjustment dial for tension control (A1), nylon cords for finger movement (A2), securing screws (A3), and the tension balance system (A4), while the bottom view (b) shows the adjustable Velcro straps for the forearm (B1) and hand (B2). The p*hoenix hand (c), and unlimbited arm (d) (Enabling The Future, 2023; Zuniga et al., 2015; Thingiverse.com, 2025).*

Although the project utilises FDM it's important to recognise the advancements occurring in other branches of biomedical engineering such as bioprinting in regenerative medicine. One such innovation is volumetric bioprinting (VBP) using light to cure bio-resins; it rapidly forms entire 3D structures in a matter of seconds (Placone and Engler, 2018). Unlike the traditional layer-by-layer approach, VBP facilitates more intricate, faster, and cell-compatible designs (Jing et al., 2023). Another promising technique is cryogenic 3D printing, where materials are deposited at extremely low temperatures, resulting in distinct internal structures that can impact cellular development (Placone and Engler, 2018). While these technologies aren't directly applicable to prosthetic manufacturing, they highlight the expanding capabilities and future potential of 3D printing.

II Project Aims

This report will explore the development of a functional, low-cost, 3D-printed forearm prosthetic designed to improve accessibility for individuals in underserved communities. Elbow-driven mechanical actuation will facilitate motion at the distal end of the prosthesis, allowing for basic grasping function, offering a practical and affordable alternative to expensive commercial devices. The design prioritises ease of assembly, modular adaptability, and personalisation, particularly for growing users or those with varying residual limb shapes.

The key aims of the project are to:

- Develop an accessible, cost-effective prosthetic that maintains core functionality.
- Enhance mechanical performance through elbow-powered control, enabling intuitive, body-driven movement.
- Implement personalised socket fittings, using 3D scanning to improve comfort and long-term wearability.
- Create a detailed open-source assembly guide, empowering individuals, families, and communities to fabricate and maintain their own prosthetic devices.

By leveraging open-source tools and affordable materials, this project will contribute to the expanding field of grassroots bioengineering, where prosthetics are not just tools, but symbols of autonomy, dignity, and inclusion. Prosthetics should not be a luxury; they should be a right.

III Methodology & Implementation

3D Printing Setup and Materials

A Flashforge Adventurer 3 Pro (figure 2 and appendix for specs) was initially utilised for prototype printing, with FlashPrint 5 being used as slicing software. PLA was chosen as the primary printing material due to its biodegradability, low cost, and ease of use (Kristiawan et al., 2021). A material comparison table can be found in the appendix. Derived from renewable resources such as corn starch, PLA offers an eco-friendlier alternative to petroleum-based plastics, making it a suitable choice for sustainable prosthetic production. This project mainly utilised the "branch of post" style of supports (figure 3), with a tree-like pattern due to their easy removal.

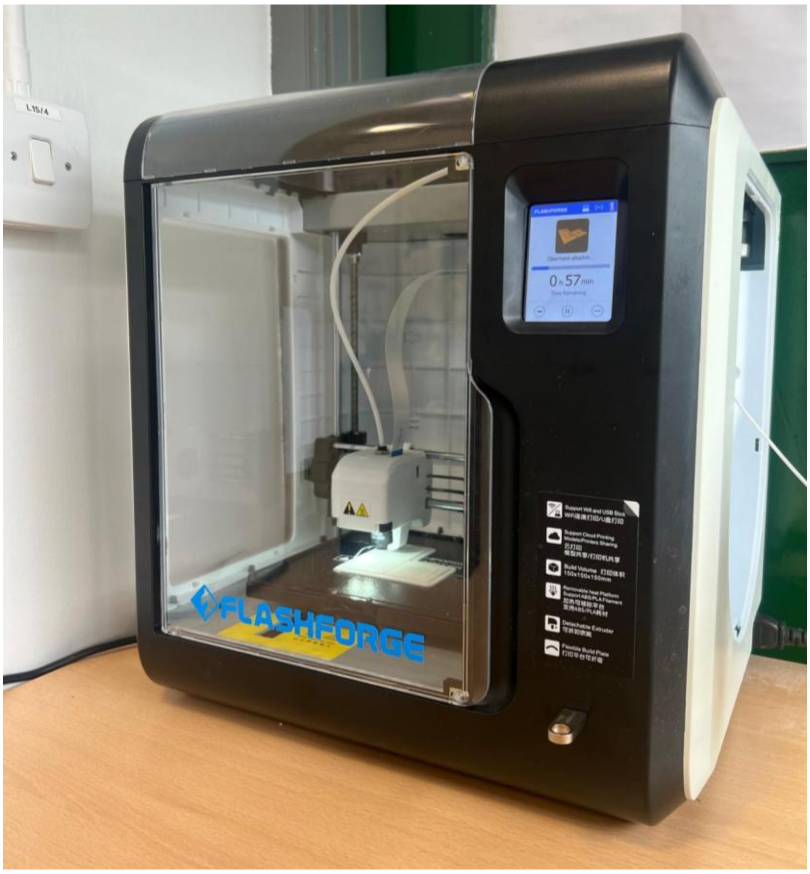

Figure 2. *Photograph of the Flashforge Adventurer 3 Pro 3D printer used for prototype production. The printer employs fused deposition modelling (FDM) and was operated using FlashPrint 5 software.*

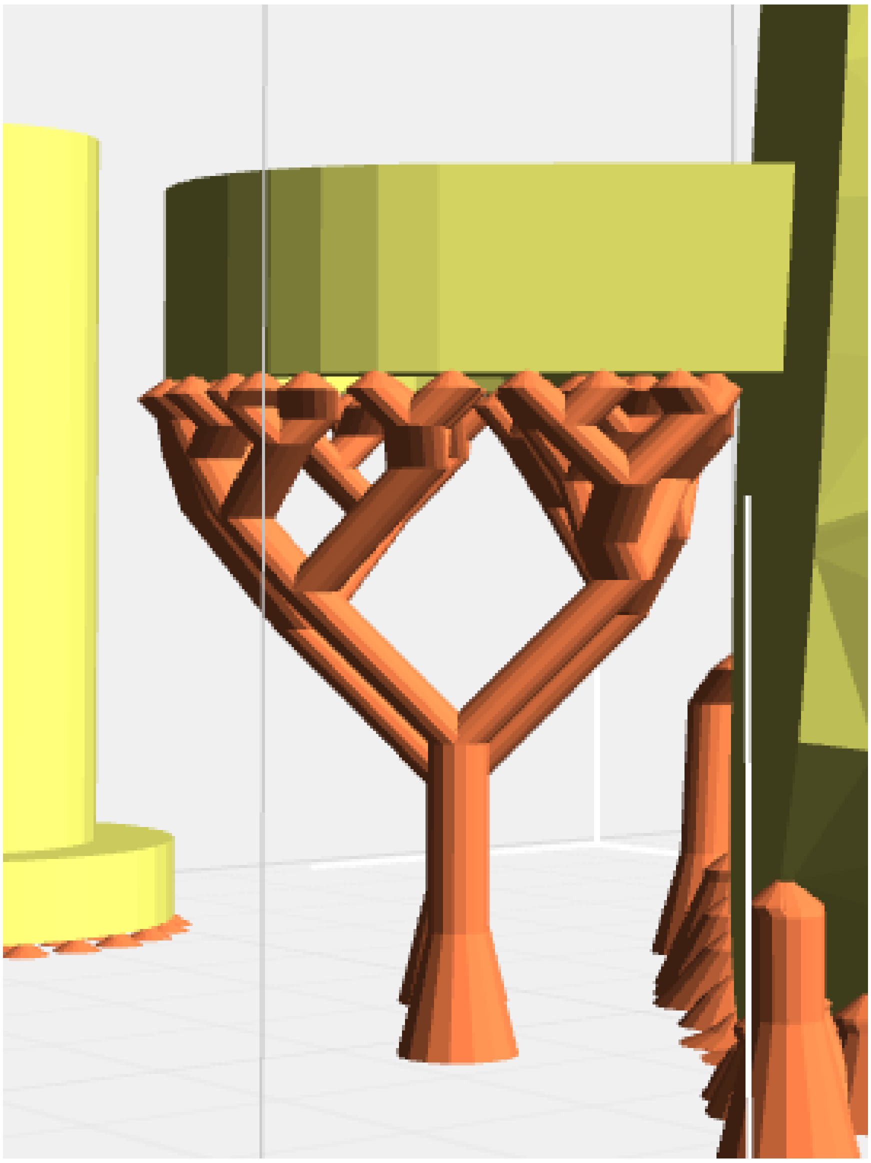

Figure 3. *Screenshot from FlashPrint 5 showing the "branch of post", tree-style, support structure used during 3D printing (FlashForge, 2025).*

Modelling with 3D Scanner App

To acquire the lifelike 3D arm model a free modelling app from the App Store (Apple, iOS), 3D Scanner App (Laan Labs, 2024), was used. An arm was suspended at the wrist with fishing wire to maintain stability and to reduce artefacts during modelling. The app was used to take images from multiple angles and then build a 3D model.

Manual Model Processing

To complete the proposed plan for the project, the models needed to be manipulated. The forearm needed to be mirrored before the stump model was cut from it. Meshmixer, a software for editing 3D meshes, allowed manual manipulation, performing a Boolean difference. A Boolean difference is a CAD operation in which one 3D object is subtracted from another. The models required rescaling on Meshmixer as scale was lost from initial scanning.

Automating Model Processing (Python)

As the project aimed to provide accessibility, patients could not be expected to learn how to perform model manipulation. The process required automation, meaning coding. Python code was utilised in Google Colab, more specifically using the Trimesh, PyMesh and NumPy packages. The forearm needed mirroring, aligning and centring before the stump could be aligned, scaled and cut from it.

Breaking down the final automated process into stages: with two models to manipulate simultaneously.

1. Import models
2. Watertight
3. Scale the models (as scale was lost when exporting from app to stl file)
4. Scale up stump by 2% (to account for silicon insert)
5. Align models with XY plane
6. Flip m1 with a vertical mirroring
7. Centre both models' centroids at 0, 0
8. Boolean difference
9. Export

Trimesh was used for most functions: Loading, manipulating, scaling, aligning, Boolean subtracting, and exporting the meshes. PyMesh was used to repair the meshes to make them "watertight" i.e. one large surface with no holes. NumPy was used to find the maximum distance across a model, supplemented scaling function. Coding this process allows users with no CAD experience to replicate modifications easily (figure 4). Many adjustments were made to the code over the temperamental process of developing the code. Running the code takes about 4 seconds.

Figure 4. *Photograph showing the first successful 3D printed prototype generated after automated mesh manipulation using Python code in Google Colab.*

Final Print Preparation

For printing the finalised prototype, an UltiMaker S5 printer (figure 5 and appendix for specs) located in the University of Liverpool Sydney Jones library was planned to be used. This printer was selected due to its larger print volume and FDM printing style.

Figure 5. *Photograph of the UltiMaker S5 printer used for prototype production. The printer employs fused deposition modelling (FDM) and was operated using UltiMaker Cura software.*

However, due to limited printer access and delays in funding, both the UltiMaker and Flashforge were utilised. This allowed direct comparison of the print qualities at the final prototype.

The prototype was made slightly differently to that of the proposed mechanism for users. Due to ethics restrictions, no amputee patients were available, so an artificial stump had to be created to design a prosthetic for. A full upper arm and forearm was 3D modelled, then manipulated on Meshmixer and cut into two sections (figure 6). The code manipulated the forearm model, and an artificial articulating elbow joint was designed to demonstrate the mechanical function of the prosthetic (figure 7). Figure 8 shows the final printed stump, elbow and upper arm assembled, figure 9 shows the socket.

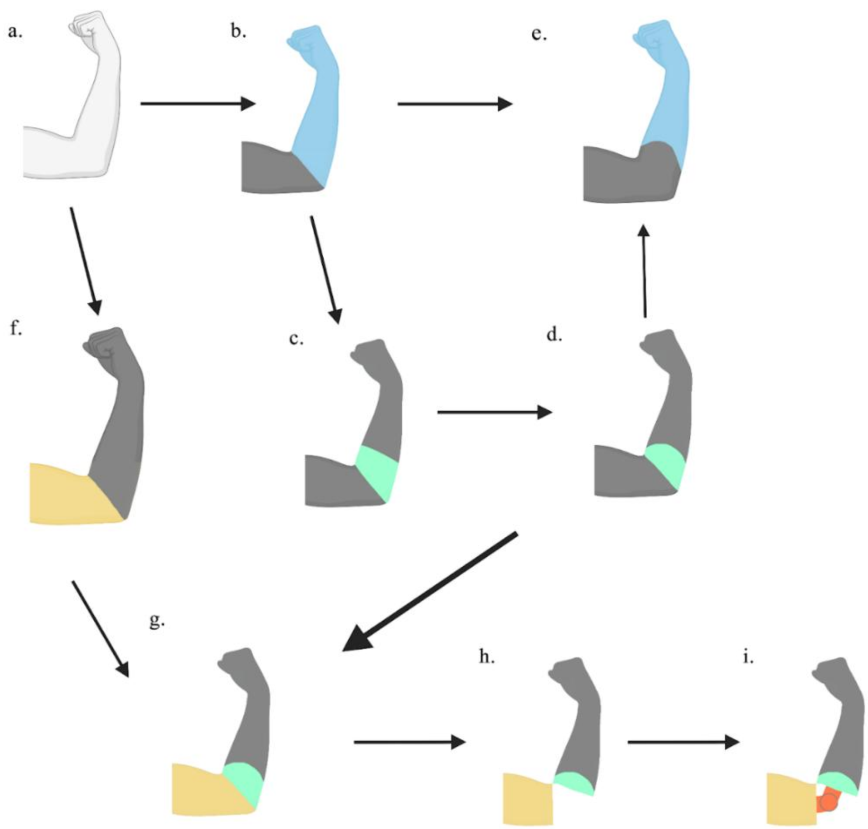

Figure 6. *Flowchart outlining prosthetic workflow. A) The original model of my arm was cut at the elbow joint to give a forearm (B) and an arm (F). B) A duplicate of the forearm was then made. C, D) The forearm was cut and moulded to create an artificial stump. E) The stump and other forearm model were then run through the python script to create a socket. G) The stump of D was then combined with F to recreate the elbow. H) For a functional test, articulation of the elbow was required so a section was removed and (I) replaced with a simple hinge joint.*

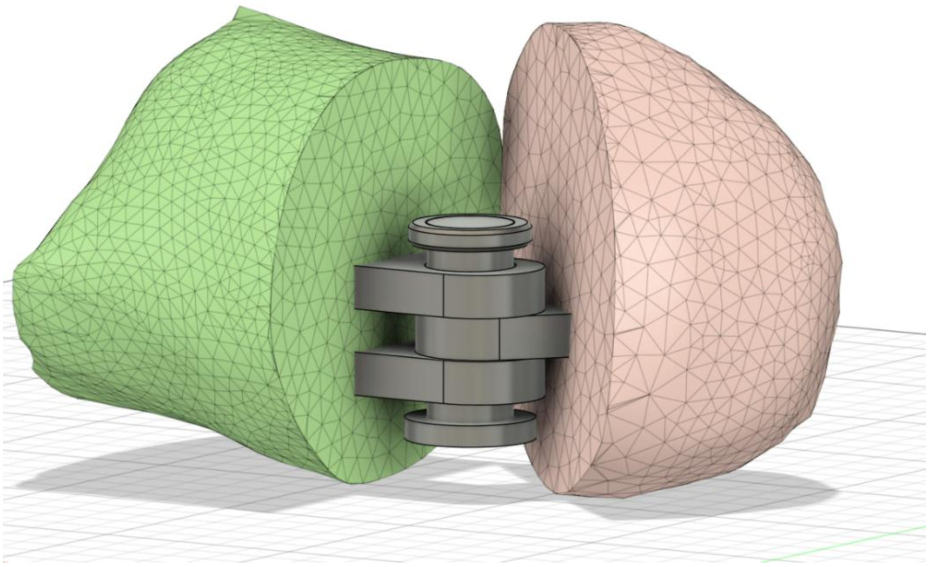

Figure 7. *Self-designed hinge joint created to enable mechanical articulation between the forearm stump and upper arm model. Created on Autodesk Fusion (Autodesk, 2025b).*

Figure 8. *Image showing the final printed artificial stump created by manipulating and sectioning the original arm scan. The elbow assembly integrates the custom hinge for articulating motion during testing.*

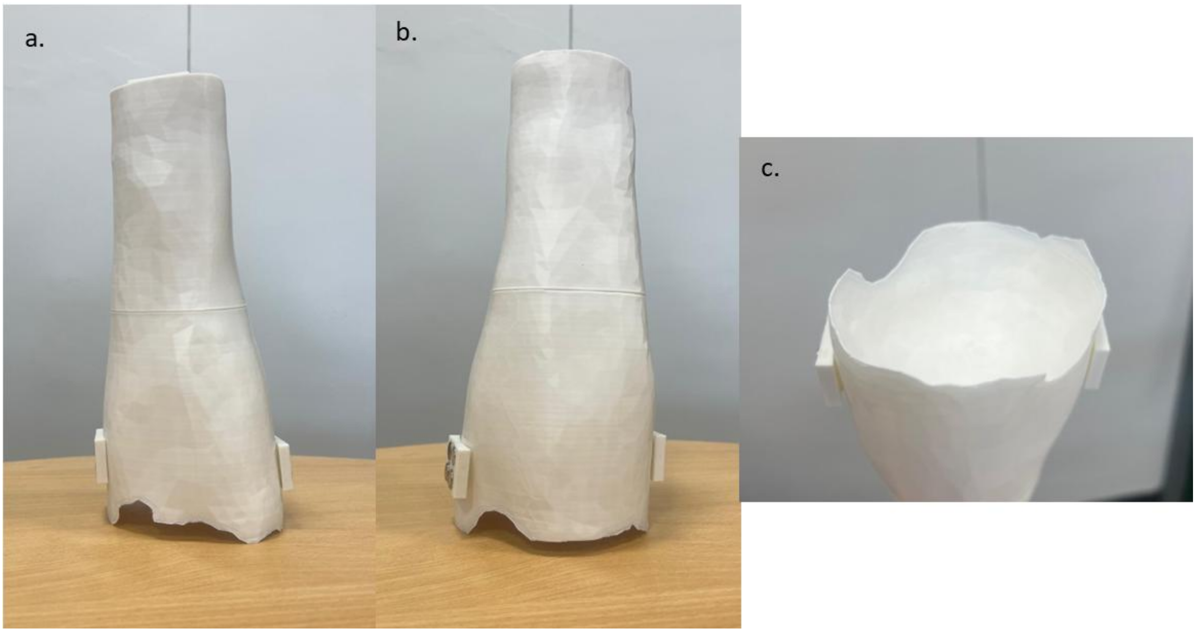

Figure 9. *Image showing the final printed socket from the anterior (a), posterior (b) and inferior (c) views.*

Hand/Claw Mechanism

Two options were developed for the distal end of the prototype, both of which possessing a magnetic interface, functioning interchangeably. The first was a static model of the scanned hand (figure 10), which unfortunately popped off the plate during printing leading to an incomplete fourth and fifth finger. The second was a claw mechanism (figure 11) modelled from a litter picker simply as a proof of concept. A simple hinge joint secured the two halves together. One half of the claw remains static, attached to the end of the forearm, the other is manipulated via an attached piece of fishing wire. The wire runs down the surface of the forearm before finally being tied off in a custom-built housing unit (figure 12) holding a magnet. This attaches to the upper arm. This action is resisted by a loop of elastic string. Most suitable open-source prosthetic hand designs required printing flexible joints from materials not compatible with accessible printers.

Figure 10. *Image of printed hand model.*

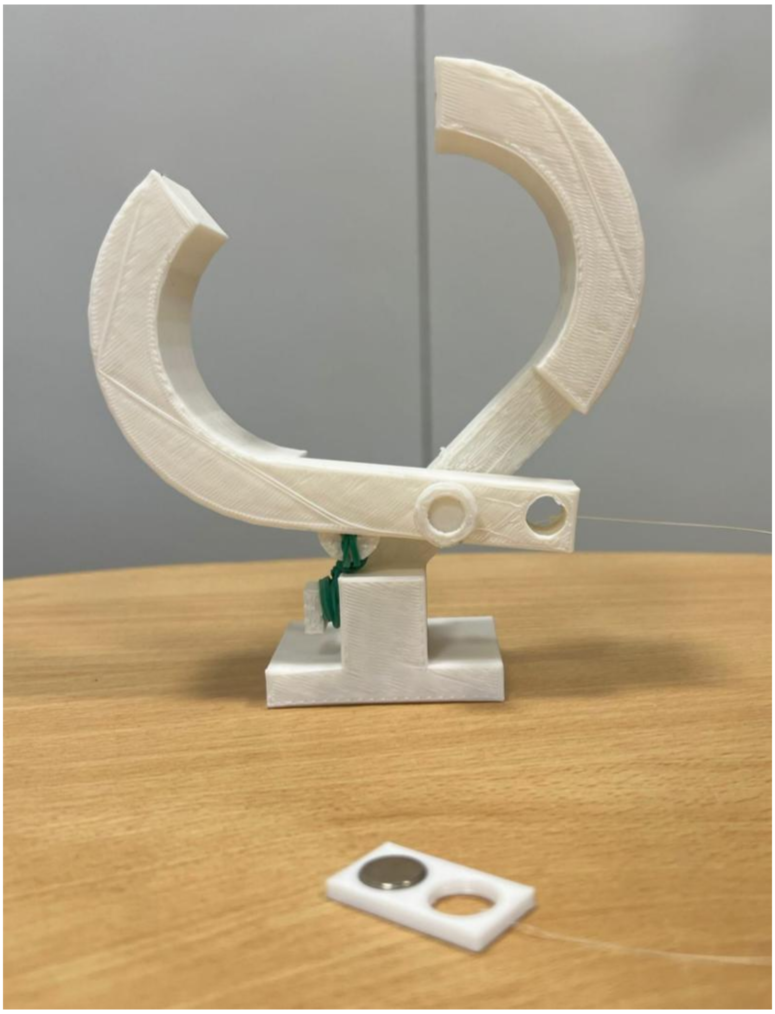

Figure 11. *Prototype claw mechanism designed for the prosthetic system. The claw comprises a fixed half attached to the forearm and a mobile half actuated by fishing wire, with elastic resistance to enable opening and closing.*

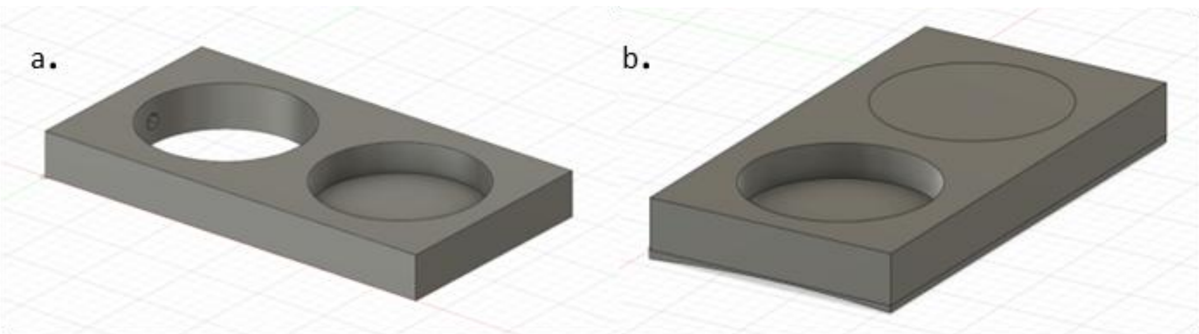

Figure 12. *3D models of (a) the custom housing unit designed to anchor the fishing wire cable and embed a magnet for connection to (b) the attachment site for the upper arm brace. Created on Autodesk Fusion (Autodesk, 2025b).*

Upper Arm Attachment System

Continuing with the theme of affordability and personalisation, another aim was to create an upper arm brace (figure 13) that was both low-cost and adaptable to a wide range of arm shapes. Shin pads were selected as the main body, rigid yet ergonomically shaped, inexpensive, and widely available. These were securely fastened to the upper arm using Velcro straps, ensuring both a snug, custom fit and user comfort. Initially, elastic webbing was used to connect the upper arm section to the forearm socket. However, it proved too strong, creating excessive resistance during elbow extension. To resolve this, it was with a weaker sewing elastic, which provided the necessary flexibility without compromising control. To secure the elastic to the socket and upper arm brace, a custom two-part attachment system (figure 14) was designed. The first part featured a curved surface to maximise contact area for gluing onto the socket or brace. Its upper surface contained four recessed grooves to hold magnets, allowing it to attach to the second component. This second part mirrored the magnet layout, and its upper surface included four pins to anchor the elastic. However, the base of these pins proved structurally weak and broke under minimal force. In response, this component was redesigned as a clasp mechanism. This not only allowed adjustable tension for a more personalised fit but also significantly improved the structural integrity and reliability of the elastic attachment.

Figure 13. *Photograph showing the completed upper arm attachment system made from repurposed shin pads and Velcro straps.*

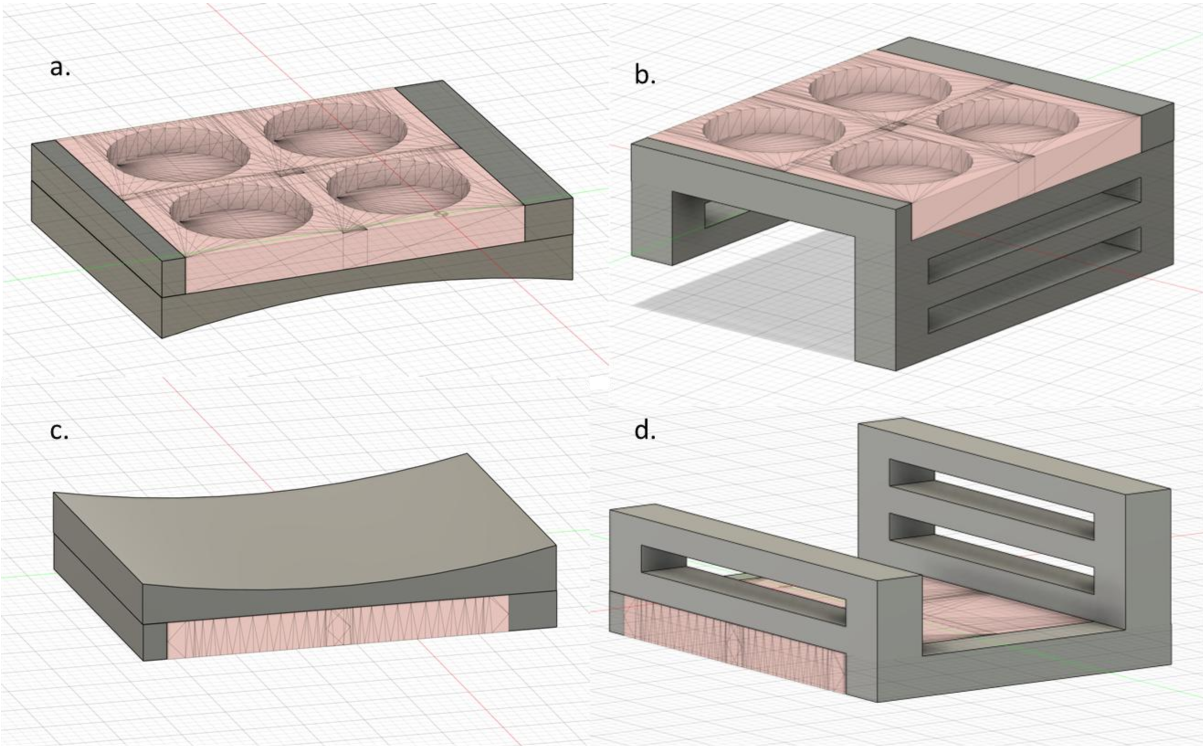

Figure 14. *Images of two custom-designed components: (a, c) original attachment piece featuring a curved adhesive surface and magnet recesses, and (b, d) improved elastic clasp mechanism. Created on Autodesk Fusion (Autodesk, 2025b).*

Considering the magnet-ending fishing wire cable, its attachment piece was adhered to the upper arm brace. Attaching the cable to the upper arm means the distance of said attachment piece from the claw determines the length of the cable and therefore the opening/closing of the claw. The state of flexion of the elbow determines the state of the claw. Pythagoras' theorem explains why the cable will experience the most tension in an extended state, therefore inducing claw closure.

Safety Considerations

When prints are initially completed, care must be taken around any sharp edges printed at the cusps of the socket. Some post-printing processing could be done to smooth the edges, sandpaper is recommended. The use of magnets in this project must also be considered, they shouldn't detach easily but care should be taken.

Holistic Workflow for End-User

A step-by-step public plan has been created (appendix) and published on reddit so anyone can simply scan both their stumped and full other arm with the 3D scanner app and easily follow the rest of the instructions to print their own arm. A specific example of instruction is details the accurate acquisition of arm measurement - “extend your elbow fully with the inside of your forearm facing upwards, you should feel a bony protuberance on the inside of your arm (this is your medial epicondyle), mark this point with a small horizontal marker line”. The plan talks them through modelling their arm, simply manipulating it before exporting them as stl files from the app into the python script in Google Colab. Their measured length will then be used to scale both the forearm and stump model before cutting the latter from the former to produce a personal fitting socket. The output file can then be opened in a software associated with their chosen 3D printer, sliced and exported to the printer. This whole process should take a few hours plus print time which could last up to 4 days assuming access to only one printer and no print errors. Users just need access to a smart phone, PC, and a 3D printer. If a printer’s build plate size is insufficient, models can be segmented in Meshmixer using the plane cut tool and reassembled post-print with a PLA-compatible adhesive. Assuming access to a 3D printer, costs will be limited to sourcing PLA (~£12), elastic, shinpads, and magnets.

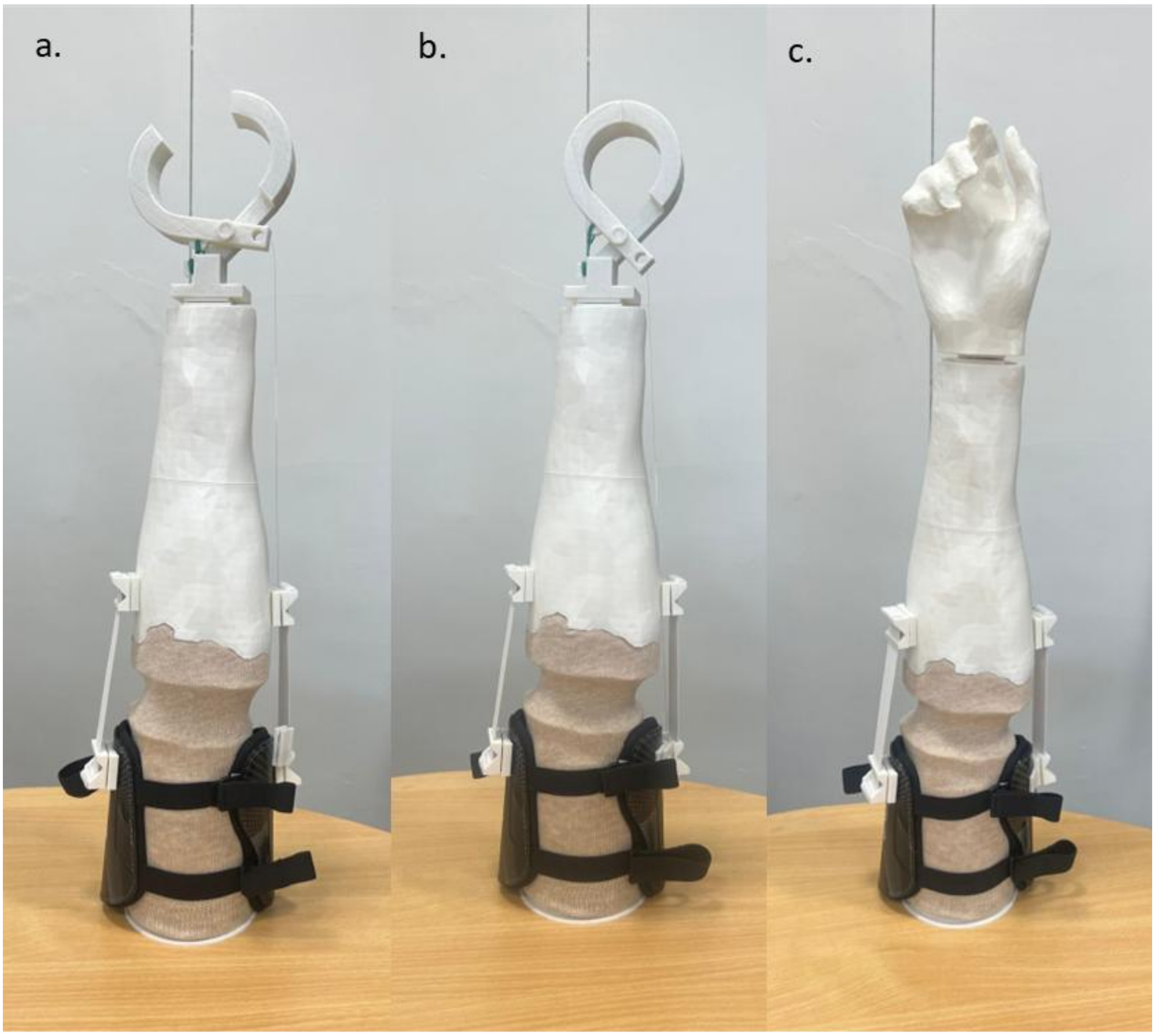

Figure 15. *Images of finished prosthetic. Open claw with detached wire pulley (a), closed claw with attached wire pulley (b) and the functionless aesthetic-focused hand attachment (c).*

IV Testing

To evaluate the performance and usability of the prosthetic prototype, a series of simple tests were carried out. These focused on assessing basic fit, function, and the accuracy of the final printed model in comparison to design expectations. A limited array of tests was performed due to delayed prototype production. The difference in build quality was noticeable between printers, the UltiMaker models proving smoother and hosting improved definition.

Fit Testing on Mock Stump

The printed prosthetic was tested on a mock stump to assess the general fit. This allowed for an initial evaluation of socket dimensions and alignment. Although the prototype was not fitted to a real user, this basic check ensured that key contact points and form contours aligned approximately with the stump shape.

Grip and Object Handling Scenarios

Simple object interaction tests were carried out using lightweight items such as plastic bottles and pens. These scenarios assessed the prosthetic's ability to grip, hold, and release items with minimal strain. While the mechanical movement was basic and limited, it provided an initial proof of concept.

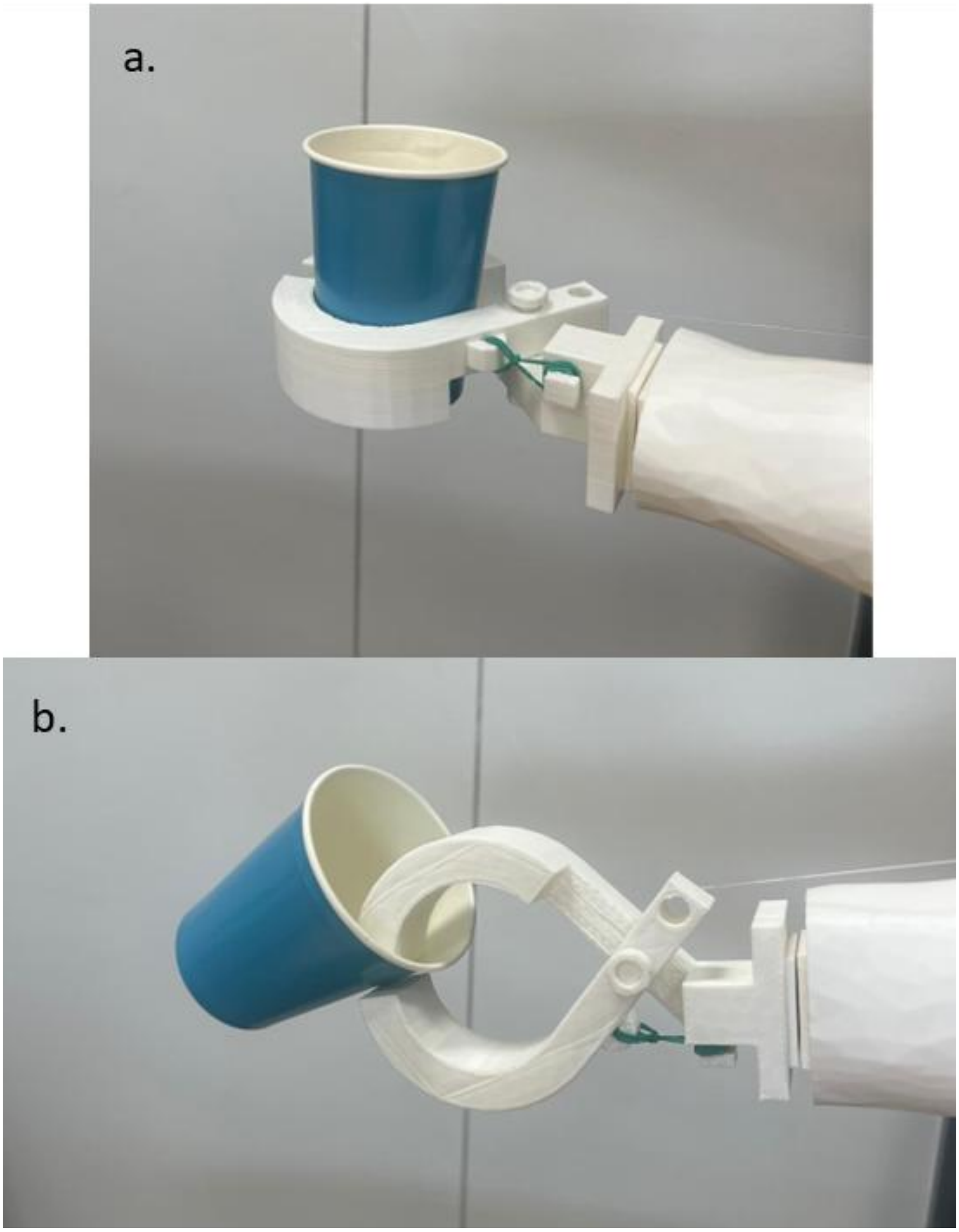

Figure 16. *Images of horizontal (a) and vertical (b) grip tests proving prosthetic functioning as necessary.*

V Electronics

Motorised Prosthetic Concept

To explore alternative functionality and increase user independence, a motorised control system was developed in collaboration with Derek Neary of the Engineering department. The aim was to create a simple mechanism for actuating claw articulation independent of another biomechanical movement i.e. elbow joint. The concept centres around using a small motor to pull or release a cable (figure 17). Remaining focused on sustainability, remnants of an old RC car project were repurposed meaning no new parts were purchased.

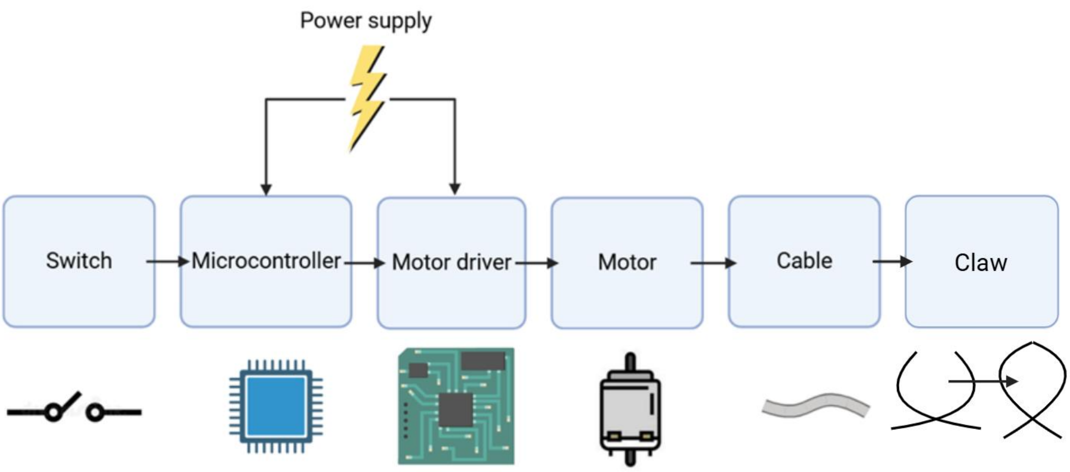

Figure 17. *Simplified flowchart illustrating the control logic of the motorised prosthetic system. Created on Biorender (BioRender, 2025).*

Circuit Design

The system was built around an Arduino Nano microcontroller, a geared DC motor, and a basic H-bridge motor driver circuit, powered by a 9V battery. A circuit diagram can be seen in figure 18 followed by the final circuit construction in figure 19. The user operates the motor through a spring-loaded toggle switch (figure 20).

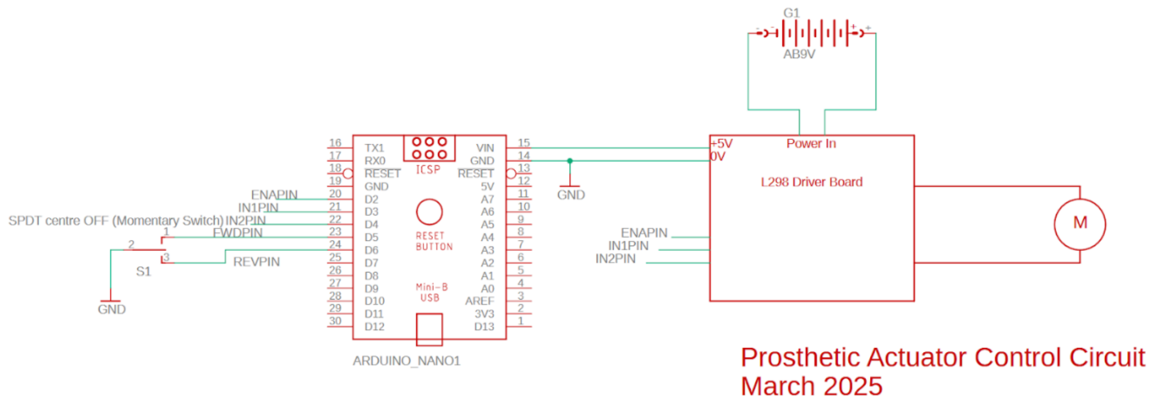

Figure 18. *Detailed schematic of the electronic circuit controlling the motorised prosthetic claw. Created on Eagle (Autodesk, 2025a).*

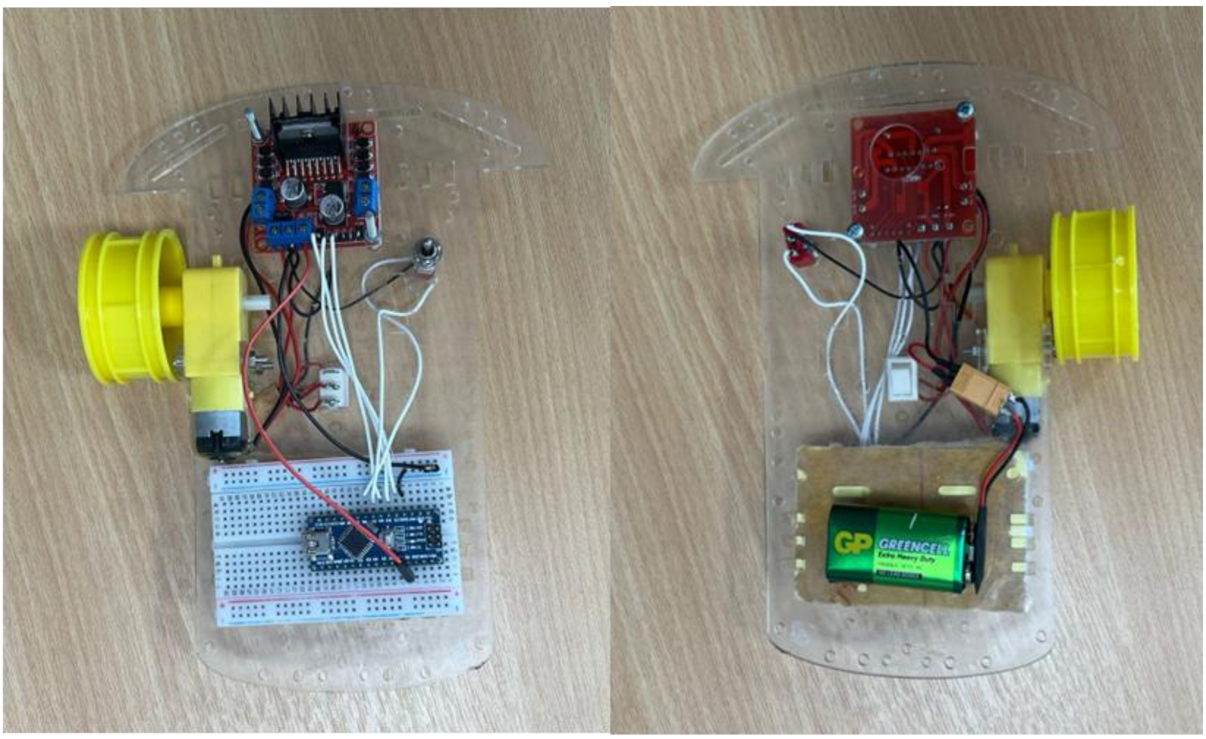

Figure 19. *Photograph showing the repurposed RC car platform used to construct the prosthetic control system prototype.*

Figure 20. *Close-up image of the SPDT (single pole double throw) momentary toggle switch employed in the prosthetic control system. The spring-loaded mechanism enables temporary manual input: pressing one side causes claw closure (motor forward), while pressing the other side triggers claw opening (motor reverse). Releasing the switch automatically returns it to the neutral centre-off position, halting motor activity*

Circuit Function and Component Roles

The Nano is a compact, affordable microcontroller serving as the “brain” of the system and costing around £15. Its size and simple programming make it especially well-suited for prototyping purposes. User input is provided through a switch, and instructions are output to commencing parts. A simple program runs the Nano, allowing it to recognise when the switch is activated and respond by directing the motor to move forward, reverse, or halt.

The L298 H-Bridge motor driver can manipulate resistance to push current through a motor one way or the other, turning it in both forward and reverse directions from a single power supply. It takes instructions from the Nano, regarding which direction to spin the motor, and delivers the required current to the motor.

A DC geared motor is an electric motor combined with a set of gears to manipulate speed and torque (rotational force). In this project, the motor pulls or releases the cable that causes the claw to close. It is well-suited for this task in which controlled, strong movement is needed.

The power supply provides the electrical energy to both the Nano and the H-bridge. The supply must be stable and sufficient to handle both the logic control and the mechanical load from the motor. A 9V battery was selected as although only 5V are required for the circuit, fitting four AA batteries with a combined output of 6V would soon drop off below the required threshold.

The current setup had been constructed separate to the prosthetic, intended for conceptual demonstration and testing. Introducing electronic components raises safety considerations including battery handling and heat.

Arduino Nano Control Logic

The Nano was programmed to respond to the state of the toggle switch. When the switch is pushed in one direction, the Nano sends a signal to spin the motor forward, causing claw closure. When pushed the other way, the motor spins in reverse, opening the claw. In the central position, the motor remains off. Motor speed is controlled using a method called pulse-width modulation (PWM), allowing the motor to receive quick pulses of power. A fixed speed is used for simplicity and safety, but future versions could allow variable speed control if needed. The speed can be set anywhere between 0-225, 180 was selected.

The motor control system is derived from five pins on the Nano, which are established during the setup phase of the program. Three of these pins are assigned as outputs: one to control the motor's speed and two to control its direction. EnaPin (Pin 2) uses PWM to regulate how fast the motor turns, while in1Pin (Pin 3) and in2Pin (Pin 4) determine whether the motor spins forwards or in reverse, depending on which is labelled as HIGH and which as LOW. These outputs communicate with a H-bridge motor driver to instigate movement based on user input. The remaining two pins, fwdPin (Pin 5) and revPin (Pin 6), are configured as inputs using Nano's INPUT_PULLUP mode. This setup applies a small internal resistance that causes each pin to read as HIGH (off) by default when no external current is applied (figure 21).

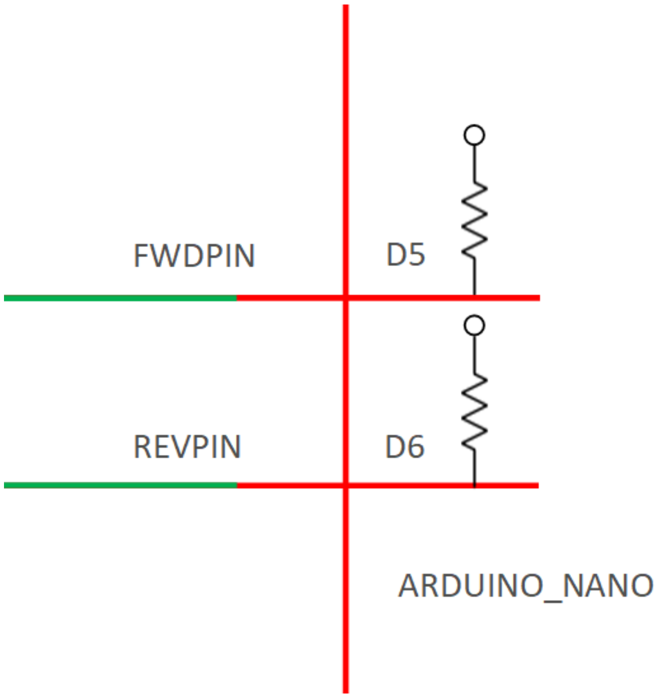

Figure 21. *Illustration of the internal pull-up resistor configuration used for the Arduino Nano's input pins. When the toggle switch is in the neutral centre-off position, the inputs fwdPin and revPin are pulled HIGH by internal resistance, preventing floating values and unintended motor activation. Pressing the switch forces one input LOW, allowing the Nano to detect user intent for forward or reverse motor control. Self-created diagram.*

Summary

This straightforward, low-cost, and user-friendly control setup enables the motor to run in either direction using a physical switch. When the switch is not pressed, the motor stays inactive, promoting both safety and energy conservation. While the system does support variable speed control via PWM, a constant speed was chosen for this project to keep the design simple and ensure uniform performance during testing. The flexible nature of the code provides a solid platform for future enhancements with expanded functionality, such as incorporating variable input tools like force-sensitive resistors or wireless controls.

VI Discussion

VI.I Limitations & prototyping steps

Despite successful prototyping, several limitations were encountered throughout the design and production process. The printing stage presented numerous technical challenges that required iterative troubleshooting and optimisation. Early prints frequently detached from the print bed mid-process, resulting in spiralled failures. This was resolved by fine-tuning the extruder and build plate temperatures to 207 °C and 55 °C respectively. Conversely, over-adhesion also occurred, making prints difficult to remove post-print; a fine layer of hairspray was applied to the stage to facilitate clean separation. Raft-model adhesion presented similar issues, where increasing the raft distance from the standard 0.15 mm to 0.3 mm improved separability, though further increases interfered with support placement. The nozzle would periodically clog and require manual unclogging, while the system needed regular recalibration across nine points on the build plate to maintain even printing.

Filament issues were also frequent, prints failed due to either exhausted spools or breakages caused by sun-exposed filament. New filament spools were obtained but were too large for the built-in holder, prompting the 3D printing of an external spool support. This highlights the practical ingenuity involved in printing custom tools to overcome unforeseen hardware limitations. Printing durations ranged from 40 minutes to over 35 hours, which, combined with supply chain delays (notably a three-week delay for upper arm components), limited the number of iterations achievable within the project timeframe. A 15% infill setting was used consistently without issue, but due to time constraints the density was dropped to 10%. The Adventurer's maximum print height of 150 mm required some larger components to be printed in parts and adhered together post-print using epoxy, potentially compromising structural integrity. Additionally, material testing was limited to a single filament type, preventing evaluation of strength or flexibility offered by alternatives such as PETG or carbon fibre composites. As aforementioned, most suitable open-source prosthetic hand designs required printing flexible joints from materials not compatible with accessible printers, prompting the designing of an original claw model.

Beyond printing challenges, the prototypes were not subjected to mechanical stress testing. As such, their durability under real-world forces, such as grip strength or drop impact, remains unknown. No formal user testing or ergonomic assessments were conducted either, limiting insight into comfort, usability, or adaptability for different users. This lack of feedback also restricted the opportunity to iteratively improve the design based on real-world function. Initial scan-modelling quality of arm could be improved on subsequent runs via slower more precise imaging. Coding the model manipulation presented further constraints, as STL files were often flawed and functions failed unpredictably. These tasks were assisted through ChatGPT (OpenAI, 2024), though reliance on AI without extensive coding knowledge may have limited deeper debugging and understanding. Together, these challenges reflect the realities of first-time prototyping with limited resources and experience, while also highlighting the importance of adaptability and incremental learning throughout the design process.

VI.II Future Prospects

Electronics Integration

While this project focused primarily on the mechanical design of a low-cost forearm prosthetic, future iterations could incorporate electronics to significantly enhance functionality. Next-generation prosthetics often include features such as temperature and force sensors, as well as wireless communication systems for more seamless and intuitive control. One aim that remained unfulfilled in the current project was the implementation of wireless motor control.

The concept was inspired by the Third Thumb project, a wirelessly controlled prosthetic digit, involved embedding a force-sensitive resistor in the user's shoe to enable pressure-based control (Ayvali, Wickenkamp and Ehrmann, 2021). This pressure-based input device would detect variations in foot pressure, which would then be translated into electrical signals. These signals would be wirelessly transmitted via Bluetooth from a transmitter located in the shoe to a receiver embedded in the prosthetic limb. The strength of the foot press would determine the contractive force generated by the motor within the prosthetic hand, enabling graded, user-controlled finger flexion without the need for physical wires.

This kind of wireless system not only reduces bulk and improves comfort but also opens the door to more intuitive and discreet control schemes, especially valuable for users with limited residual limb mobility. With further development, integrating electronics could allow for real-time responsiveness, personalised control parameters, and even the possibility of integrating feedback systems, e.g., haptic or tactile cues, to close the sensory loop.

Interchangeable Attachments

Magnetic connectors at the distal end of the prosthetic limb have proven useful for quick and secure attachment changes. This system is intuitive and requires no specialist tools, allowing the user to independently adapt their device to suit different environments and activities.

Future designs could incorporate more specific interchangeable attachments for a wide range of tasks and hobbies. Users could swap in task-specific tools such as a drumstick adapter for musicians or a basketball plate for sports activities (figure 22). These attachments would enhance adaptability and provide meaningful opportunities for participation in activities that standard prosthetics may not support. This reaffirms that prosthetics are not only medical devices but also personal tools for expression, recreation, and empowerment.

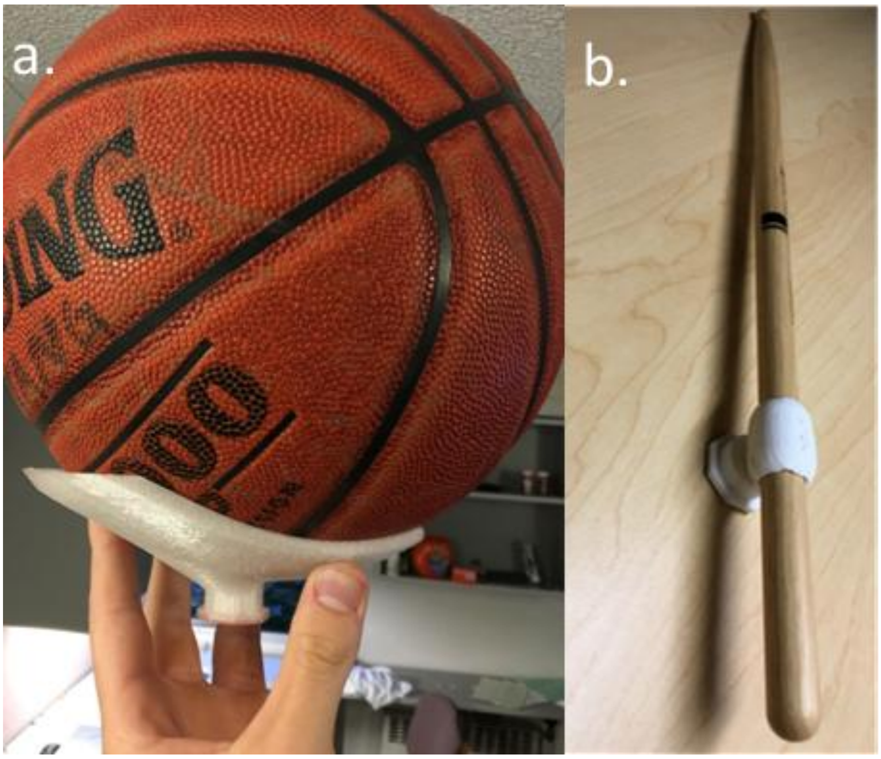

Figure 22. *Photographs of open-source designs created on Thingiverse. A. drumstick attachment. B. basketball shooting attachment (Thingiverse.com, 2025).*

Clinical Scalability and Open-Source Expansion

The open-source workflow developed during this project presents promising opportunities for clinical scalability, particularly within public healthcare systems such as the NHS. By standardising and openly sharing the design and fabrication process, prosthetic production could become significantly more decentralised, reducing reliance on large manufacturers and instead empowering clinics, technicians, and even patients themselves to take part in the fabrication process.

While this project focused on forearm limb differences, the same design principles are transferable to other regions of the body. With further development, the approach could be adapted for use in lower-limb prosthetics, partial hand designs, or even facial prosthetics. Additionally, incorporating virtual reality (VR) or augmented reality (AR) into the design and fitting phase, could enable more accurate, patient-specific customisation and greater comfort in final fittings (Hauschild, Davoodi, and Loeb, 2007).

This open-source model lays the groundwork for a more inclusive and sustainable future in prosthetics, one in which accessibility, adaptability, and collaboration are prioritised.

Sustainability

Sustainability is a crucial consideration in the development of accessible prosthetics, particularly as demand increases and 3D printing becomes more widespread. One of the key advantages of additive manufacturing is its ability to minimise material waste, especially when paired with thoughtful material selection (Kristiawan et al., 2021).

PLA's limited flexibility and lower heat resistance may constrain its use in long-term or high-stress components, suggesting the need for future exploration of alternative biodegradable filaments (figure 23) (Freeland et al., 2022). PHA (polyhydroxyalkanoates) is the second largest biodegradable, bioplastics produced worldwide behind PLA and balances environmental impact with mechanical performance (Freeland et al., 2022; Kovalcik, 2021).

Property	PLA	ABS	PETG	PHA
Renewable Source	Yes (plant-derived)	No (petroleum-based)	No (petroleum-based)	Yes (microbial fermentation)
Biodegradability	Biodegradable under industrial conditions	Non-biodegradable	Non-biodegradable	Fully biodegradable in soil and marine environments
Recyclability	Limited	Limited	High	Limited
Greenhouse Gas Emissions	Moderate	High	Low	Varies (depending on production)
Water Usage	High	Moderate	Low	Moderate to high
Overall Environmental Impact	Moderate	High	Low	Low

Figure 23. *Table showing the environmental impact comparison of four 3D printing materials: PLA, ABS, PETG, and PHA. Key environmental indicators assessed include source material, biodegradability, recyclability, greenhouse gas emissions, water usage, and overall environmental impact (Kumar et al., 2022; Zhong, Song and Huang, 2009; Stecuła et al., 2024).*

By incorporating biodegradable materials and principles such as modularity and part replacement rather than full-device disposal, prosthetics can be developed in a way that meets users' needs whilst reducing their environmental burden. As innovation in sustainable materials continues, the prosthetics field can pair technological advancement with environmental responsibility.

Bionics and Identity

As bionic limbs become increasingly advanced, with sensory feedback, AI-driven movement, and seamless bio-integration interfaces, the future may blur the line between medical necessity and elective enhancement. What begins as a solution for limb loss could evolve into a choice made in pursuit of superhuman capabilities. This raises profound ethical and philosophical questions highlighted by an ancient thought experiment: the Ship of Theseus. If every plank of a wooden ship is replaced over time, is it still the same ship? If not, when did it cease to be? In the same vein, if a person gradually replaces their biological limbs with artificial ones, at what point do they stop being entirely human?

While this project is firmly grounded in improving lives through accessible, functional prosthetics, it sits at the edge of a future in which human enhancement becomes a choice. The potential is both exciting and unsettling, reminding us that innovation must be guided by ethical foresight as much as engineering brilliance.

VI.III Conclusion

With limited funds and time, this project has demonstrated the potential of 3D printing to deliver low-cost, functional, sustainable, and personalised prosthetics. The open-source guide lays the foundation for a scalable approach that could be adopted in hospital clinics and community settings alike, helping to revolutionise prosthetic access on a global scale. A wide berth of future development remains, including the incorporation of electronic control systems and increased personalisation. With continued refinement, this approach offers not just a device, but dignity, autonomy, and hope.

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