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INTEGRATION OF ARTIFICIAL INTELLIGENCE, 3D PRINTING AND INTELLIGENT AUTOMATION IN PROSTHETIC LIMB DEVELOPMENT

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ABSTRACT

Artificial limbs are specially developed medical and engineering devices that help individuals overcome functional limitations resulting from limb loss or congenital limb conditions. The development of these devices involves much more than the fabrication and joining of mechanical components. Engineers must consider several aspects, including the user's physical requirements, the condition of the remaining limb, comfort, structural strength, material properties, component selection and ease of operation. The prosthesis should also provide dependable performance during everyday activities while remaining convenient to maintain and adjust. Recent developments in artificial intelligence (AI), digital design and automated manufacturing are creating new opportunities to improve the way prosthetic devices are designed, fabricated and assembled. These technologies can support customised product development, improve manufacturing accuracy, assist movement control and help identify possible component failures. This paper explores the application of modern engineering technologies in the development and assembly of upper- and lower-limb prosthetic devices. It discusses the construction and functions of major prosthetic components, suitable engineering materials, computer-aided design (CAD), additive manufacturing and the integration of mechanical and electronic systems. Particular attention is given to the use of AI and intelligent automation in prosthetic development. Applications such as digital image processing, finite element analysis (FEA), intelligent material selection, interpretation of muscle-generated electrical signals, robotic assembly and digital manufacturing records are considered as important tools for improving design and production processes. The integration of advanced manufacturing methods with AI-based engineering tools has the potential to make prosthetic development more personalised, efficient and accessible. However, the ultimate objective should remain the creation of devices that address real user requirements and deliver dependable performance. A systematic approach combining sound mechanical design, controlled manufacturing, proper assembly, experimental verification and professional fitting can help transform emerging engineering technologies into practical prosthetic solutions.

KEYWORDS: Artificial limbs; prosthetic device development; prosthetic arm assembly; artificial intelligence; intelligent manufacturing; myoelectric control; additive manufacturing; computer-aided design; finite element analysis; digital twin; rehabilitation engineering.

INTRODUCTION

An artificial limb, commonly known as a prosthesis, is a specially designed assistive device developed to help individuals regain certain physical abilities affected by limb loss or congenital limb conditions. The development of a prosthetic device requires a clear understanding of the user's physical condition, daily activities and functional expectations. Rather than selecting mechanical components or manufacturing methods at the beginning, the design process should focus on the specific needs of the individual. Important factors include the shape and condition of the remaining limb, muscle strength, joint mobility, body weight, activity level and the type of tasks the person wishes to perform. Environmental conditions, comfort, affordability, maintenance and ease of operation must also be considered. Involving the user throughout the design process helps engineers develop a prosthesis that is practical, comfortable and suitable for everyday use.

From an engineering perspective, a prosthetic system consists of several interconnected components that work together to achieve the desired movement and functionality. These components can be broadly classified into five major sections:

1. Body Interface System: This section connects the prosthesis to the user's body. It generally includes the socket, cushioning liner and suspension arrangement. Proper fitting is essential to minimise discomfort and ensure stable attachment.

2. Structural Support System: This consists of the main supporting frame, connecting brackets, adapters and other load-transmitting elements. These parts provide the required mechanical strength and maintain the alignment of the prosthetic assembly.

3. Movement and Functional Mechanism: This section is responsible for producing the required movements. Depending on the type of prosthesis, it may include artificial fingers, hands, wrists, elbows, knees, ankles or feet.
4. Control and Power Unit: In electrically operated prostheses, this subsystem includes sensors, electronic controllers, batteries, motor drivers and actuators. It receives control signals and converts them into the required mechanical movement.
5. Protection and Maintenance Components: Covers, fasteners, protective enclosures and serviceable joints protect internal mechanisms and make inspection, repair and component replacement easier.
The engineering requirements vary considerably between upper- and lower-limb prostheses. Artificial legs are primarily designed to support body weight and assist activities such as standing, walking and maintaining balance. In contrast, artificial arms are developed to support hand movements, object handling, gripping and other activities involving upper-limb coordination. Consequently, their structural configurations, operating mechanisms and performance evaluation methods must be selected according to their intended applications.

LITERATURE REVIEW

Recent research in prosthetic engineering has increasingly focused on integrating additive manufacturing, artificial intelligence (AI), computer-aided design and advanced control technologies to improve the functionality, affordability and customisation of artificial limbs. Traditional prosthetic manufacturing methods often involve considerable manual operations and require individual adjustments to achieve suitable fitting. The emergence of three-dimensional (3D) printing and digital engineering has provided new opportunities to manufacture customised prosthetic components with improved design flexibility. Bhatla et al. [1] examined the clinical outcomes associated with additively manufactured prosthetic devices and highlighted the importance of evaluating their practical effectiveness alongside manufacturing developments. The World Health Organization [2] also emphasised the need for appropriate prosthetic products, trained personnel and quality rehabilitation services to improve the overall delivery of prosthetic and orthotic care.
The design and selection of prosthetic components have also received considerable attention in recent studies. Speckman and Biggs [4] discussed the different components used in upper-limb prosthetic restoration, highlighting the importance of selecting suitable mechanical and functional arrangements. In particular, myoelectric control has emerged as an important technology for improving the operation of artificial hands. Chen et al. [5] reviewed different approaches to myoelectric hand manipulation and discussed the role of muscle-generated electrical signals in controlling prosthetic movements. Similarly, Igual et al. [6] and Geethanjali [7] investigated various control techniques for upper-limb prostheses, demonstrating the significance of reliable signal processing and control strategies in achieving effective prosthetic operation.
The application of 3D scanning and additive manufacturing has further expanded the possibilities for developing customised prosthetic devices. Chainando et al. [8] presented a bibliometric analysis and scoping review of 3D scanning and printing applications in upper-limb prostheses. Dababneh et al. [9] examined the potential of 3D printing in advancing upper-extremity prosthetic technologies. Rossi and Chown [10] reported a case study examining hand function and quality of life associated with a 3D-printed prosthesis. Dimintiyanova et al. [11] investigated the experiences and acceptance of 3D-printed prostheses among children with congenital upper-limb differences in India, highlighting the importance of user perspectives in prosthetic development. These studies indicate that manufacturing innovation should be accompanied by proper consideration of usability, accessibility and individual requirements.
Artificial intelligence and machine-learning techniques have created additional opportunities to improve prosthetic control and movement recognition. Rolandino et al. [12] investigated the use of high-density electromyography and machine learning for estimating hand positions. Their work demonstrates the potential of data-driven methods in interpreting muscle activity for prosthetic applications. Similarly, Shabbir et al. [20] explored the development of a six-degree-of-freedom prosthetic hand integrating voice commands, electromyography and machine-learning-based control. Such approaches provide opportunities for developing more responsive and multifunctional artificial hands.
Material selection and structural performance are equally important in prosthetic manufacturing. Plesec et al. [13] investigated the numerical behaviour of a transtibial prosthetic socket manufactured using bio-based PLA material. Ramlee et al. [14] examined the mechanical performance and microstructural characteristics of 3D-printed prosthetic leg sockets with different reinforcement materials. Ozmen and Surmen [15] explored finite element analysis and topology optimisation for the design of a below-knee prosthesis. Jindal et al. [16] investigated the mechanical characteristics of 3D-printed lower-limb socket materials under static loading conditions. Dolgikh et al. [18] further studied the influence of internal microarchitectures on pressure distribution and mechanical performance in printed prosthetic sockets. In a related area, da Silva et al. [19] reviewed the application of 3D printing in upper-limb exoskeletons and orthoses, providing additional insights into customised assistive-device manufacturing. Choo et al. [17] also reviewed the application of 3D printing technology in prosthesis production.

Upper-Limb Prosthetic Architecture

An upper-limb prosthesis is designed to assist individuals who have lost part or all of an arm. Its construction generally includes a custom-fitted socket, suspension arrangement, connecting structure, wrist assembly and an artificial hand or terminal device. The design becomes more advanced when electronic control and powered movement are incorporated.
In a myoelectric prosthetic arm, electrodes positioned at suitable locations detect electrical signals generated by muscle activity. These signals are processed by an electronic control unit, which interprets the user's intended movement and sends commands to the actuators. Servo motors or other suitable drive mechanisms then operate the fingers, wrist or gripping assembly. A rechargeable battery supplies the necessary electrical energy.
Different operating approaches are available for upper-limb prostheses:

- Body-powered prosthesis: Uses cables, harnesses and mechanical linkages to transfer movement generated by the user.
- Myoelectric prosthesis: Uses electrical signals from muscle activity to control powered movements.
- Passive prosthesis: Mainly provides cosmetic appearance, support or stabilisation without actively powered movement.
- Hybrid prosthesis: Combines mechanical and electrically operated mechanisms to provide multiple functional capabilities.

The selection of an appropriate arrangement depends on the user's functional requirements, residual muscle activity, comfort, affordability and ability to operate the device.

Lower-Limb Prosthetic Architecture

A lower-limb prosthesis is developed to support body movement and provide stability during standing, walking and other mobility-related activities. Its major components generally include a socket, suspension mechanism, structural pylon, connecting adapters, knee joint where required, and an artificial foot with an ankle mechanism. An external protective cover may also be provided to improve appearance and protect the internal components.

The socket acts as the primary connection between the user's residual limb and the prosthetic structure. The pylon transfers mechanical loads between the upper and lower sections, while the knee and ankle mechanisms assist the movement required during walking. The artificial foot provides ground contact and contributes to stability and load distribution.

Several engineering factors must be considered during the development of a lower-limb prosthesis. These include body-weight distribution, structural strength, joint alignment, impact resistance, torsional loading, fatigue behaviour and movement clearance during the walking cycle. Improper alignment or unsuitable component selection may affect stability, comfort and walking performance.

Therefore, the final configuration should be determined through individual clinical assessment and functional evaluation. Mechanical test classifications and standardised component ratings provide useful engineering information, but they cannot independently establish the most suitable prosthetic arrangement for every user.

Mechanical, Electrical and Software Interfaces

The successful operation of an artificial limb depends not only on the performance of individual components but also on the quality of the connections between them. These connections form the interfaces of the complete prosthetic system. Poorly designed or incorrectly assembled interfaces can lead to vibration, loosening, electrical malfunction, inaccurate movement or premature component failure.

Mechanical interfaces: These connections join structural and moving components such as brackets, adapters, shafts, bearings and joints. Proper dimensional accuracy, alignment, thread engagement and fastener tightening are necessary to maintain structural stability. The specified assembly torque and connection requirements should follow the relevant component manufacturer's instructions.

Electrical interfaces: These are used to connect sensors, actuators, batteries, controllers and other electronic devices. Correct voltage ratings, current capacity, wiring arrangement, connector compatibility and insulation are important for reliable operation. Electrical connections should also be protected against moisture, accidental disconnection and mechanical damage.

Software and control interfaces: Modern prosthetic systems may use embedded software to process sensor information and regulate actuator movement. Each control unit must communicate using compatible signal ranges, sampling frequencies and operating protocols. Software versions, calibration parameters and fault-handling procedures should be properly documented.

For effective maintenance and future improvements, a complete record of the assembled prosthesis should be maintained. This record should include component descriptions, manufacturer details, model numbers, identification or batch numbers, calibration settings, software versions and service history. Such documentation helps engineers identify faults, replace damaged parts and maintain consistency during future modifications.

Engineering significance

The architecture of an artificial limb must be developed by considering the complete interaction between the human body, mechanical structure, electronic control and manufacturing process. A well-designed system should provide the required functionality while maintaining comfort, durability, safety and ease of maintenance. Integrating CAD modelling, finite element analysis, additive manufacturing and intelligent control technologies can further support the development of customised prosthetic devices.

Materials, Components and Design Considerations

Material selection is a multi-criteria engineering decision. The designer must balance strength, stiffness, fatigue resistance, density, corrosion behaviour, manufacturability, skin-contact suitability, repairability and cost. No single material is ideal for every prosthetic component. The load-bearing frame, socket, flexible liner, cosmetic cover and electronic enclosure perform different roles and should be specified separately.

Component / part	Common material options	Key design considerations
Socket / structural shell	Thermoplastics, laminated composites, selected 3D-print polymers	Fit, pressure distribution, stiffness, durability, edge finish

Pylon / adapters	Aluminium alloys, titanium alloys, stainless steel	Strength-to-weight ratio, fatigue, corrosion, connection compatibility
Foot / flexible elements	Composite laminates, polymers, elastomers	Energy storage, deformation, fatigue, ground interaction
Hand / fingers / housing	Engineering polymers, aluminium, elastomers	Grip geometry, impact resistance, mass, serviceability
Liner / interface	Medical-grade silicone or other specified elastomers	Skin compatibility, comfort, hygiene, friction and wear
Electronics enclosure	Engineering thermoplastics, sealed housings	Ingress protection, heat dissipation, access and cable routing

Design for Assembly and Maintenance

While developing a prosthetic device, engineers should give considerable attention to how easily its individual components can be assembled, inspected, adjusted and replaced. A well-planned design can reduce the number of separate parts and avoid complicated joining procedures. The arrangement of components should also make it easier to identify their correct positions during assembly and prevent errors caused by improper fitting or orientation. Using compatible and standardised connecting arrangements can simplify the replacement of damaged components and reduce maintenance time. However, these common connections should be selected carefully so that they do not affect the customised dimensions or functional requirements of the prosthesis.

Mechanical fasteners, such as bolts, nuts and screws, should be positioned in locations where technicians can access them without difficulty during inspection and servicing. Proper tightening is equally important because loose connections may cause vibration, movement or premature failure. Therefore, the recommended tightening values provided by component manufacturers should be followed and recorded during assembly. Adhesive bonding and other permanent joining techniques may also be considered for selected components. Before adopting these methods, engineers should evaluate their bonding strength, resistance to ageing, durability under repeated loading and the possibility of future repair or replacement. Overall, the design should support convenient assembly, safe operation and long-term maintenance.

CAD and Engineering Analysis

Computer-aided design (CAD) plays an important role in developing the geometry and arrangement of artificial limb components. Three-dimensional modelling allows engineers to examine the shape, dimensions and relative positions of individual parts before manufacturing begins. It also helps identify possible interference between moving components and provides a clear understanding of how the complete prosthetic assembly will function. By using parametric modelling techniques, important design dimensions can be modified systematically to accommodate different anatomical requirements, socket shapes, connector positions and component configurations.

Finite element analysis (FEA) can be used to investigate the mechanical behaviour of prosthetic components under selected loading conditions. Through numerical simulation, engineers can study the distribution of stress, deformation and regions that may experience excessive loading. These results are useful when comparing alternative designs and identifying areas that may require additional reinforcement or geometric modification. However, the accuracy of an FEA study depends on the quality of the material properties, loading conditions, boundary constraints and mesh configuration used in the analysis. Therefore, simulation findings should be supported by suitable experimental tests before a design is considered reliable.

For prosthetic systems containing movable joints and mechanical linkages, multibody dynamic analysis provides another useful engineering approach. It helps examine joint movement, linkage behaviour, angular displacement and the possibility of unwanted contact between adjacent components. Such analysis is particularly valuable when developing artificial fingers, wrist mechanisms, elbow joints, knee assemblies and ankle-foot systems.

Before finalising the design, engineers should also examine several practical aspects of the complete assembly. These include the overall weight, centre of gravity, component alignment, movement restrictions, sharp edges, potential finger-trapping locations, electrical cable arrangement and accessibility of the battery and electronic units. Cleaning, inspection and replacement procedures should also be considered during the design stage. In addition, materials that come into direct contact with the human body must be carefully selected and evaluated according to their intended application, duration of contact and relevant safety requirements.

Engineering outcome: Integrating design-for-assembly principles with CAD modelling, FEA and dynamic simulation helps engineers develop prosthetic systems that are easier to manufacture, assemble, inspect and maintain while addressing mechanical performance and user requirements.



Fig.1.Prosthetic arm for paralyzed person

Manufacturing and Pre-Assembly Preparation

The fabrication of an artificial limb should be carried out through a properly planned manufacturing procedure to ensure dimensional accuracy, structural reliability and suitability for the intended user. The initial stage involves collecting the necessary anatomical measurements and preparing a detailed design based on the individual's physical characteristics and functional requirements. Depending on the type of prosthesis and the available manufacturing facilities, the shape of the residual limb can be obtained through conventional plaster moulding, direct dimensional measurement, digital measurement instruments or advanced three-dimensional scanning techniques.

Modern 3D scanning technology provides an effective way of capturing the external geometry of the residual limb and converting it into a digital model. This information can subsequently be used for developing customised socket designs and other prosthetic components through CAD software. Digital measurement also makes it possible to store anatomical data, modify designs and reproduce geometries when required. However, the accuracy of the final model depends on several factors, including the positioning of the individual during scanning, movement during data acquisition, surface irregularities and variations in soft-tissue shape. Therefore, the scanned model must be carefully examined and corrected before it is used for manufacturing.

The final design should be reviewed by a qualified prosthetist or appropriate clinical professional to confirm that the proposed geometry provides a suitable interface with the user's body. Particular attention should be given to comfort, pressure distribution, suspension and the functional requirements of the device. Only after the necessary measurements, design modifications and professional approvals have been completed should the manufacturing process proceed.

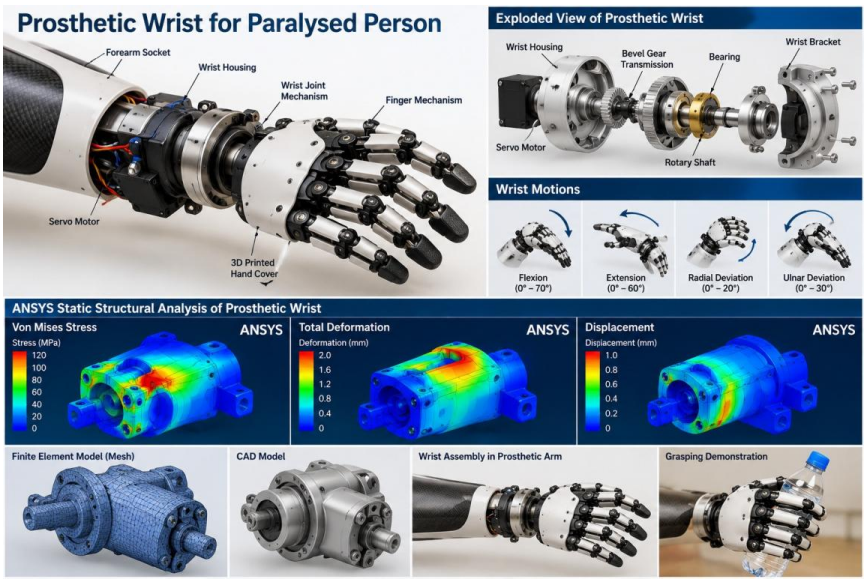


Fig.2.Prosthetic wrist for paralyzed person

Additive manufacturing

Additive manufacturing (AM) can produce customised sockets, covers, fixtures and selected structural parts with complex geometry. Fused filament fabrication is accessible for prototyping and some non-critical applications; powder-bed and other polymer processes may provide different surface and mechanical characteristics. Composite and metal AM may be considered for suitable parts, subject to process qualification. Build orientation, layer adhesion, infill, porosity, anisotropy, surface finish and post-processing influence performance. A printed component should not be assumed to be clinically suitable merely because its CAD geometry is correct.

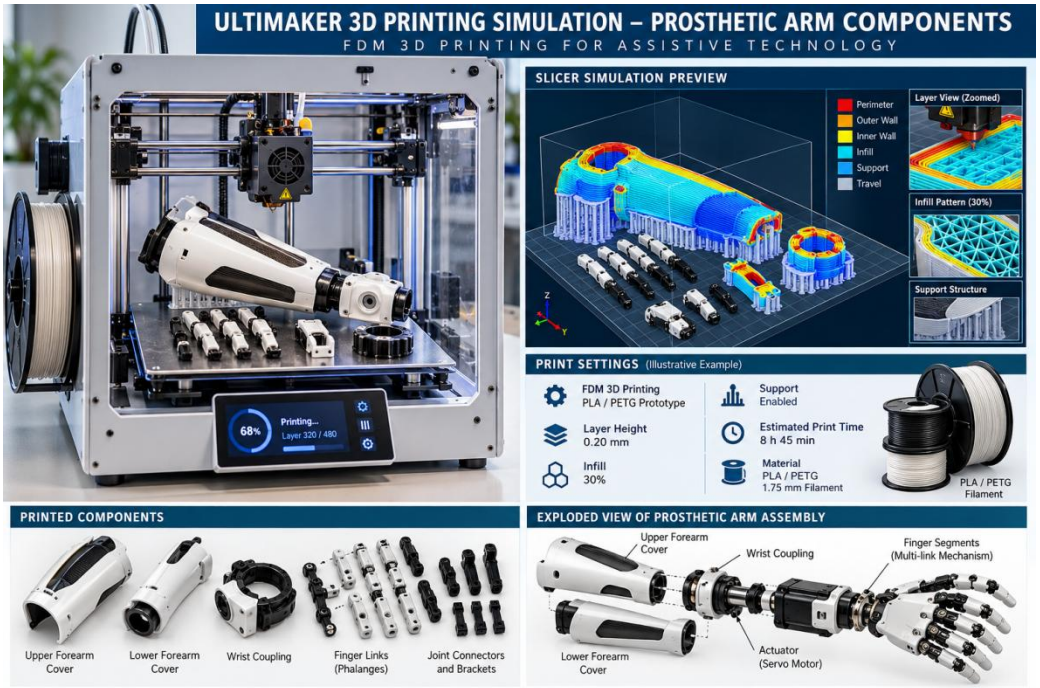


Fig.3.Prosthetic arm 3D printed component

Pre-Assembly Inspection

Before beginning the final assembly of a prosthetic device, every manufactured component should undergo a detailed quality check to confirm that it meets the required design specifications. This inspection helps identify manufacturing errors that could affect the strength, fit or operation of the completed prosthesis. Important parameters to be examined include dimensional accuracy, hole positioning, thread quality, surface smoothness and the condition of connecting regions. Components should also be checked for visible defects such as cracks, surface deformation, uneven printing, warping and separation between material layers, particularly when additive manufacturing techniques are used.

In addition to visual and dimensional examination, engineers should verify whether the selected materials and manufacturing procedures comply with the approved design requirements. Special attention must be given to components that carry mechanical loads or directly influence user safety. All connecting elements, including brackets, adapters, bearings, screws, electrical wires, sensors and control units, should be compared with the approved component list before assembly. Any part showing damage, incorrect dimensions or manufacturing defects should be separated and reported for further evaluation. Reworking or replacing defective components should only be carried out through an authorised and documented procedure. This inspection process helps prevent assembly errors and improves the reliability of the final product.

Traceability and Manufacturing Documentation

Maintaining proper manufacturing records is important for ensuring the quality and consistency of prosthetic devices. Each stage, beginning with the initial CAD design and continuing through fabrication, inspection and final assembly, should be supported by appropriate documentation. A digital record can contain information about the approved design version, manufacturing file, machine details, raw material identification, production settings, inspection observations and the configuration of the completed device.

Such documentation allows engineers and manufacturing personnel to identify the origin of individual components and understand how the final prosthesis was produced. If a defect or operational problem occurs during service, these records can help determine the possible cause and support suitable corrective action. They are also useful when replacing damaged components, reproducing a previously manufactured part or carrying out future design improvements.

Since prosthetic manufacturing may involve sensitive anatomical measurements and personal information, appropriate precautions must be taken when collecting, storing and sharing these records. Access should be restricted to authorised individuals, and the information should be handled according to the user's consent, applicable privacy regulations and institutional data-management procedures. A well-maintained documentation system therefore supports manufacturing quality, product accountability, maintenance planning and long-term device management.

Artificial Limb Assembly: Step-by-Step Method

Assembly must be performed by trained personnel using approved instructions and component-specific specifications. The following workflow is a general engineering sequence; the actual order and torque settings vary by device architecture and manufacturer.

Stage	Assembly activity	Verification point
1. Work preparation	Review prescription/design approval, bill of materials, tools and instructions.	Correct revision; components compatible; calibrated tools available.
2. Interface preparation	Inspect socket, liner, adapters and mating surfaces; clean as specified.	No cracks, burrs, contamination or dimensional mismatch.
3. Structural assembly	Fit pylon, brackets, joints, knee/ankle or wrist modules as applicable.	Alignment, seating, fastener engagement and specified torque.
4. Functional mechanism	Install hand, fingers, terminal device, foot or other end effector.	Free movement; no binding; safe range and mechanical stops.
5. Electrical integration	Mount controller, sensors, motors, battery and harnesses where applicable.	Polarity, insulation, connectors, strain relief and cable clearance.
6. Software setup	Load approved firmware and configure control parameters.	Correct version, calibration, fault response and safe default state.
7. Enclosure and finish	Fit covers, guards and cosmetic components; protect moving parts.	No exposed sharp edges, pinch hazards or blocked service access.
8. Bench verification	Conduct unloaded and controlled functional checks.	Repeatable operation, no abnormal noise, heat or loosening.

Upper-Limb Prosthetic Assembly

The assembly of an artificial arm requires careful integration of mechanical components, electronic circuits and movement-control mechanisms to achieve the intended functions. In electrically operated prosthetic arms, particularly myoelectric systems, the correct positioning of electrodes is important for detecting muscle-generated electrical signals. These electrodes must maintain proper contact with the user's skin through the socket arrangement to ensure consistent signal transmission. Any disturbance in electrode positioning or contact quality may affect the accuracy of movement control.

The electronic control unit, sensors and associated wiring should be installed in suitable protective enclosures to minimise damage caused by moisture, perspiration, vibration and accidental impact. The mechanical drive system also requires detailed inspection before operation. Components such as motors, gear arrangements, artificial tendons and connecting linkages should be examined for smooth movement, excessive clearance, mechanical resistance and unwanted displacement. The movement range of each joint must be restricted to its intended operating limits, and suitable protection should be incorporated to prevent damage during excessive loading.

After completing the mechanical and electrical integration, the artificial hand or terminal mechanism should undergo functional evaluation. Different gripping operations can be examined using objects of various shapes, sizes and weights. The testing process should assess grip consistency, movement response, object handling and repeatability. These evaluations help determine whether the prosthetic arm performs according to its intended design requirements.

Lower-Limb Prosthetic Assembly

The construction of an artificial leg requires particular attention to the positioning and connection of its major structural components. The socket, supporting pylon, knee mechanism and artificial foot must be assembled with appropriate alignment to provide stability and support during standing and walking. Even small alignment errors can influence load distribution, balance and movement patterns. Therefore, the relative positions of these components should be carefully examined during the initial assembly stage.

The alignment process generally begins with a workshop or bench assessment, where the assembled prosthesis is checked against the prescribed design and alignment requirements. Once the initial inspection is satisfactory, further adjustments are carried out under the supervision of a qualified prosthetist. The device is then evaluated during controlled standing and walking activities to examine its stability, movement and interaction with the user's body.

Any modifications required during this evaluation should be introduced gradually, with each change recorded for future reference. Particular care must be taken when modifying the position of the knee, foot or connecting elements, as these adjustments can influence the overall biomechanics of walking. Before allowing an individual to use the prosthesis, its structural strength, connection security and functional performance must be adequately verified. An experimental prototype or an assembly with unresolved mechanical defects should never be used for walking trials.

Artificial Intelligence and Intelligent Automation

AI can contribute across the prosthetic product lifecycle, from design support to manufacturing quality and adaptive control. Its value depends on representative data, transparent performance evaluation, safe fallback behaviour and clear human responsibility. In practice, AI should be introduced as a validated support function rather than as an autonomous decision-maker for clinical prescription.

AI / automation application	Potential contribution	Important limitation

Personalised geometry	Assist segmentation, shape comparison and socket design iteration.	Anatomical interpretation and fit approval require qualified review.
Predictive engineering	Surrogate models estimate stress or deformation across design variants.	Must be validated against FEA and physical tests.
Myoelectric pattern recognition	Classify muscle activation patterns for intended hand functions.	Sensitive to electrode shift, fatigue, sweat and user variability.
Gait and activity analysis	Analyse IMU, pressure and motion data to identify patterns.	Clinical context and sensor placement affect interpretation.
Robotic manufacturing	Automate trimming, drilling, finishing or repeatable assembly tasks.	Fixtures, guarding, calibration and process validation are essential.
Visual quality inspection	Detect surface defects, missing parts or assembly anomalies.	False acceptance and false rejection must be quantified.

Intelligent Control Architecture

The application of intelligent control systems has significantly expanded the possibilities for developing advanced prosthetic devices. In a myoelectric artificial arm, the movement of the prosthetic hand is controlled using electrical signals produced by the muscles of the remaining limb. These signals are collected through surface electromyography (sEMG) electrodes placed at appropriate locations on the skin. The captured signals are then passed through electronic circuits, where unwanted noise is removed and the useful information is extracted for further processing. After signal conditioning, the processed information is analysed using suitable machine-learning algorithms or mathematical models to identify the intended movement. Depending on the control strategy, the system may recognise commands such as opening the hand, closing the fingers, rotating the wrist or selecting a particular grip pattern. The control unit converts the recognised command into electrical instructions for the motor driver, which operates the corresponding actuator. Through this sequence, muscle activity is translated into mechanical movement of the artificial limb.

For dependable operation, the control system should continuously observe important operating conditions, including electrode signal quality, battery charge, motor current and unexpected changes in movement. If the detected signals become unreliable or an abnormal operating condition occurs, the controller should activate a predefined protective response. This may involve stopping the motor, restricting movement or reducing the actuator output. The appropriate response must be established through a detailed safety assessment based on the design and intended application of the prosthesis.

Agentic AI and Connected Prosthetic Systems

The introduction of agentic artificial intelligence provides opportunities to improve engineering activities associated with prosthetic design, manufacturing and maintenance. AI-based software agents can assist engineers by collecting technical information from approved databases, examining component specifications, comparing manufacturing requirements and identifying missing information in assembly records. They can also help prepare inspection schedules, organise production documents and generate maintenance notifications. In a manufacturing environment, such systems can support coordination between CAD models, component inventories, production records and quality inspection activities. For example, an AI agent could examine a bill of materials and identify a mismatch between the selected actuator and the approved design specification. It could also highlight incomplete inspection records before the assembly proceeds to the next production stage.

However, the use of autonomous software in prosthetic systems requires appropriate restrictions. Clinical settings, movement parameters and safety-related operating conditions should not be modified automatically without authorised professional approval. Similarly, untested software updates should not be transferred directly to a device intended for human use. Connected prosthetic devices may exchange information with computers, mobile applications or healthcare monitoring systems. Such connectivity introduces additional responsibilities concerning information security and privacy. Appropriate authentication, protected communication, controlled software updates and secure storage of personal information are necessary. Users should also have clear control over the collection, access and sharing of their prosthetic performance data.

Digital Twin Technology in Prosthetic Development

Digital twin technology provides a method of connecting a computer-based engineering model with its corresponding physical prosthetic device. The digital representation can include the geometry, material properties, component arrangement and operating characteristics of the actual assembly. Where suitable sensors are available, information such as movement, loading, temperature and operating cycles can also be incorporated into the digital model. During the design stage, engineers can use this approach to examine different configurations and study how modifications may influence the performance of the prosthesis. Once the physical device is manufactured, the digital model can be updated with its actual component details and configuration. This creates an opportunity to compare expected performance with information collected during operation.

Digital twin technology may also assist in identifying unusual changes in component behaviour, planning maintenance activities and evaluating possible design improvements. For instance, repeated changes in actuator current or abnormal

movement patterns may indicate that a mechanical component requires further inspection. The reliability of a digital twin depends on the accuracy of the original engineering model, the quality of sensor measurements and the methods used to update the simulation. Therefore, the model should clearly identify which information comes from direct measurements, which values are estimated through computational methods and which results are obtained through simulation. These distinctions are important when using digital twin technology for engineering decisions.

Testing, Quality Assurance and User Validation

The performance of an artificial limb cannot be established simply by completing its fabrication and assembly. A properly developed prosthetic device must undergo a series of engineering examinations and practical evaluations before it can be considered suitable for its intended application. These assessments help determine whether the manufactured product meets the original design requirements and whether it can perform the activities expected by the user. Two important stages in this process are design verification and product validation. Verification involves examining whether the manufactured prosthesis conforms to the specified dimensions, materials, assembly procedures and performance requirements. Validation focuses on determining whether the completed device actually fulfils the user's functional expectations under the intended conditions of use. A prosthetic prototype may demonstrate the required mechanical movement during a laboratory trial but still encounter difficulties during practical operation. Problems such as uncomfortable socket fitting, insufficient suspension, inaccurate movement, instability or complicated maintenance can affect its usefulness. For this reason, quality evaluation should include both controlled engineering tests and supervised assessments involving the user and relevant rehabilitation professionals.

Mechanical and Functional Evaluation

Mechanical testing is necessary to examine the strength, stability and operating behaviour of the prosthetic structure. Different tests can be selected according to the type of artificial limb and the conditions under which it is expected to function.

The following examinations are particularly relevant:

1. Dimensional accuracy assessment: The manufactured components should be measured to confirm that their dimensions, connecting holes, joint positions and assembly clearances correspond to the approved CAD design.
2. Static load evaluation: Selected components should be subjected to controlled mechanical loads to examine their ability to withstand the forces expected during operation without unacceptable deformation or structural damage.
3. Repeated loading assessment: Prosthetic structures may experience numerous loading cycles during everyday activities. Cyclic testing helps investigate material fatigue, joint deterioration and the possibility of failure after repeated use.
4. Joint movement examination: Artificial fingers, wrists, elbows, knees and ankle mechanisms should be evaluated to confirm that they operate within their intended movement ranges without unwanted contact or mechanical obstruction.
5. Fastener and connection inspection: Bolted joints, threaded connections and mechanical adapters should be examined for loosening, displacement or damage following appropriate test cycles.
6. Environmental performance assessment: Where relevant, the effects of temperature changes, moisture, dust and cleaning procedures should be investigated to understand their influence on component performance.

Electrical and Control System Evaluation

For powered prosthetic devices, the electronic and control sections require separate examination to ensure reliable operation and protection against electrical faults. These tests should be conducted using suitable instruments and controlled procedures.

Important evaluation activities include:

- Checking the battery, electrical polarity, protective circuits, insulation and condition of connecting terminals.
- Measuring the electrical current consumed by the motors and monitoring temperature changes during operation.
- Examining the accuracy of sensor readings and identifying signal disturbances, interruptions or inconsistent outputs.
- Evaluating the response of actuators to different control commands and checking whether the programmed movement limits function correctly.
- Testing emergency stopping arrangements and protective responses under simulated fault conditions.
- Confirming that the installed software version is authorised and that the system can recover safely from interrupted updates or unexpected shutdowns.

The results should be compared with the established design requirements. Any abnormal behaviour must be investigated and corrected before the device proceeds to further evaluation.

Socket Fitting, Usability and Rehabilitation Assessment

The interaction between the prosthesis and the user's body is one of the most important factors influencing the overall success of the device. Even a mechanically strong and electronically advanced prosthesis may become unsuitable if it causes discomfort or restricts normal activities. The socket should therefore be examined for proper fitting, stability, pressure distribution and skin response. The user should also be able to wear and remove the device without unnecessary difficulty. Particular attention should be given to areas where excessive pressure or friction may develop during movement.

Practical evaluation should be based on activities relevant to the particular prosthesis. For an artificial arm, these may include holding objects, releasing items, performing basic gripping operations and carrying out selected daily tasks. For an artificial leg, assessment may involve standing, maintaining balance, transferring between positions and walking under appropriate supervision. The user may require a period of training to become familiar with the operation and movement

characteristics of the new device. Feedback obtained during this stage should be recorded and considered when making further adjustments. Rehabilitation, periodic assessment and technical support are essential parts of successful prosthetic use.

Applicable Standards and Regulatory Requirements

The development and evaluation of prosthetic devices should follow relevant technical standards and applicable medical-device regulations. The World Health Organization's standards for prosthetics and orthotics provide guidance on improving the quality of prosthetic services, including product development, professional training and service delivery. For lower-limb prosthetic structures, ISO 10328 provides procedures for evaluating mechanical strength through specified static and cyclic loading conditions. Engineers should consult the current published edition and its applicable requirements before planning structural tests. The appropriate national regulatory framework must also be considered before a prosthetic product is introduced for clinical use or commercial distribution. Compliance with a technical standard does not automatically establish that a particular prosthesis is suitable for every individual. The final device must still be selected, fitted and evaluated according to the user's clinical condition and functional requirements.

Risk Assessment and Safety Management

Potential hazards should be identified during the design, manufacturing, assembly and operational stages of prosthetic development. Early identification of these problems allows engineers to introduce suitable protective measures before the device reaches the user.

Some important risks include:

- Structural damage or fracture resulting from excessive mechanical loading.
- Improper socket attachment or failure of the suspension arrangement.
- Uncontrolled movement caused by sensor errors or electronic malfunction.
- Excessive heating of batteries, motors or electrical components.
- Skin irritation, pressure-related discomfort or injury.
- Accidental trapping of fingers or other body parts within moving mechanisms.
- Software malfunction or unauthorised modification of control parameters.
- Exposure or misuse of personal information collected by connected devices.

Each identified hazard should be examined in terms of its possible consequences and likelihood of occurrence. Suitable preventive measures must then be introduced and their effectiveness evaluated through appropriate testing. Any remaining risks should be explained clearly to the user and relevant professionals.

Challenges, Implementation Roadmap and Future Scope

The development of advanced artificial limbs involves several technical, economic and practical difficulties. Although recent improvements in artificial intelligence, additive manufacturing, robotics and digital engineering have created new opportunities for prosthetic development, implementing these technologies in real-world applications requires careful planning. Engineers must consider not only the technical performance of the device but also its affordability, ease of use, durability and suitability for different individuals.

The major challenges associated with prosthetic development are discussed below.

Major Challenges in Artificial Limb Development

1. Individual Requirements and Design Customisation

Every prosthesis user has different physical characteristics, anatomical conditions and functional expectations. A design that works effectively for one individual may not provide the same level of comfort or performance for another. Developing customised sockets, joints and mechanical components while maintaining a repeatable manufacturing process remains an important engineering challenge.

2.Manufacturing Cost and Affordability

Advanced prosthetic systems may require specialised sensors, electronic controllers, motors, batteries and precision-manufactured components. The use of expensive materials and sophisticated manufacturing technologies can increase the overall product cost. Making these devices affordable and accessible, particularly in resource-limited regions, requires the development of economical designs, locally available materials and cost-effective manufacturing methods such as FDM-based 3D printing.

3. Durability Under Practical Operating Conditions

Artificial limbs are exposed to different mechanical and environmental conditions during everyday use. Repeated loading, accidental impacts, moisture, perspiration, dust and continuous movement can gradually affect the performance of structural and electronic components. Selecting suitable materials and conducting appropriate fatigue, strength and environmental tests are therefore essential for improving product life and operational reliability.

4. Consistency of Intelligent Control Systems

AI-controlled and myoelectric prostheses depend on biological signals to identify the user's intended movements. However, these signals may change due to muscle fatigue, electrode displacement, variations in skin contact and changes in the condition of the residual limb. Such variations can reduce control accuracy and create difficulties during operation. Developing adaptive control algorithms that can respond to these changes remains an important research area.

5. Compatibility Between Different Components

Prosthetic systems often combine mechanical parts, electronic devices and software developed by different manufacturers. Differences in dimensions, connecting arrangements, communication protocols and operating requirements can create

integration difficulties. Developing compatible interfaces and modular architectures can make component replacement, upgrading and maintenance easier.

6. Safety Evaluation and Regulatory Approval

The introduction of AI and advanced automation into prosthetic systems requires proper evaluation of their performance and safety. A successful simulation or laboratory demonstration alone cannot establish that a device is suitable for practical use. Mechanical testing, electrical evaluation, clinical assessment and compliance with applicable medical-device regulations are necessary before deployment.

7. Maintenance and Technical Support

The usefulness of a prosthesis depends not only on its initial performance but also on the availability of repair facilities, replacement components and trained technical personnel. Difficulties in obtaining spare parts or accessing professional support can reduce the effective service life of the device. Therefore, maintenance-friendly construction, user training and locally available technical assistance should be considered during the initial design stage.

Future Scope

Further developments in artificial intelligence, robotics, additive manufacturing and smart materials are expected to create new possibilities in prosthetic engineering. Future research can focus on lightweight structures, improved gripping mechanisms, adaptive movement control, customised socket development and intelligent monitoring systems.

The integration of 3D scanning with CAD modelling and Ultimaker-based FDM manufacturing can support the production of customised prosthetic components. Similarly, AI-assisted design optimisation and ANSYS-based structural simulations can help engineers investigate alternative geometries and improve material utilisation. These developments provide opportunities to produce prosthetic devices that are more economical, functional and suitable for individual requirements.

Suggested implementation roadmap

Phase	Activities	Expected output
Phase I – Needs and requirements	Consult users and clinicians; define use case, constraints and risks.	Approved user requirements and design inputs.
Phase II – Concept and digital design	Develop architecture, CAD, material choices and initial FEA.	Reviewed digital prototype and risk register.
Phase III – Prototype and assembly	Manufacture parts, integrate mechanisms/electronics and document build.	Traceable engineering prototype.
Phase IV – Verification	Conduct dimensional, mechanical, electrical and software tests.	Test report and corrective-action log.
Phase V – Supervised evaluation	Fit, train and assess with qualified clinical professionals and users.	Documented feedback and design revisions.
Phase VI – Lifecycle support	Monitor service issues, maintain records and plan updates.	Maintenance, upgrade and post-market feedback plan.

Future Research Directions

Continuous developments in engineering technology are creating new opportunities to improve the design, functionality and performance of artificial limbs. Future research should focus on developing prosthetic devices that are lightweight, comfortable, reliable and capable of responding effectively to the user's movements. One important area of investigation is the use of topology optimisation to reduce unnecessary material while maintaining the required structural strength. This approach can help engineers develop lighter prosthetic structures without compromising their mechanical performance. The development of customised socket designs using 3D scanning, CAD modelling and additive manufacturing is another promising research area. By considering individual anatomical characteristics, engineers can work towards improving socket fitting and reducing discomfort during prolonged use. Research into flexible materials, variable-stiffness mechanisms and compliant joints may also help produce prosthetic systems with more natural movement characteristics.

The integration of multiple sensors with intelligent control algorithms offers further possibilities for improving prosthetic operation. Combining muscle activity signals with information from pressure sensors, inertial measurement units and position sensors could provide a better understanding of the user's intended movements. Machine-learning techniques may then be used to improve grip selection, movement recognition and adaptive control. However, these systems must be evaluated across different users and operating conditions to ensure consistent performance. Another important direction is the development of affordable, modular prosthetic devices that can be assembled, repaired and upgraded without replacing the complete system. Standardised mechanical and electronic connections could simplify component integration and improve compatibility between different manufacturers. Future investigations should also explore explainable AI methods, secure handling of personal data and reliable control algorithms that perform effectively under changing operating conditions. Research activities should not focus exclusively on introducing new technologies. Equal importance must be given to user comfort, functional improvement, structural durability, ease of maintenance and manufacturing cost.

The ultimate objective should be to develop prosthetic solutions that provide meaningful improvements in everyday activities and remain accessible to a wider population.

Sustainability in Prosthetic Engineering

Environmental responsibility is becoming an important consideration in the development and manufacturing of modern prosthetic devices. The selection of materials, manufacturing methods and component configurations can influence the environmental impact of a prosthesis throughout its useful life. Therefore, sustainability should be considered from the initial design stage rather than only after the product has been manufactured.

One approach is to develop prosthetic structures that use materials efficiently while maintaining the necessary strength and durability. CAD-based optimisation and additive manufacturing can help reduce unnecessary material consumption by producing components with geometry suited to their intended functions. Suitable recyclable polymers and reusable materials may also be investigated, provided they satisfy the required mechanical and safety conditions. The construction of modular prosthetic systems offers another opportunity to reduce manufacturing waste. When individual components are designed for easy removal and replacement, a damaged motor, connector, joint or electronic unit can be repaired without discarding the complete assembly. Similarly, future improvements can be introduced through selective component upgrades rather than manufacturing an entirely new device. Local manufacturing facilities, including appropriately qualified 3D-printing centres, may help reduce transportation requirements and improve access to replacement components. Energy consumption during printing, material processing and post-processing should also be considered when selecting a manufacturing method. A complete sustainability assessment should examine every stage of the prosthetic product's life, including raw material selection, component production, transportation, fitting, daily operation, cleaning, maintenance and final disposal. Particular attention should be given to the actual service life of the device and the availability of repair facilities. A prosthesis cannot be considered sustainable simply because it uses less material or a recyclable polymer. It must also provide adequate functionality, safety, comfort and durability throughout its intended period of use. Therefore, environmentally responsible prosthetic engineering should combine efficient material utilisation, repairable construction, suitable manufacturing technologies and long-term user requirements.

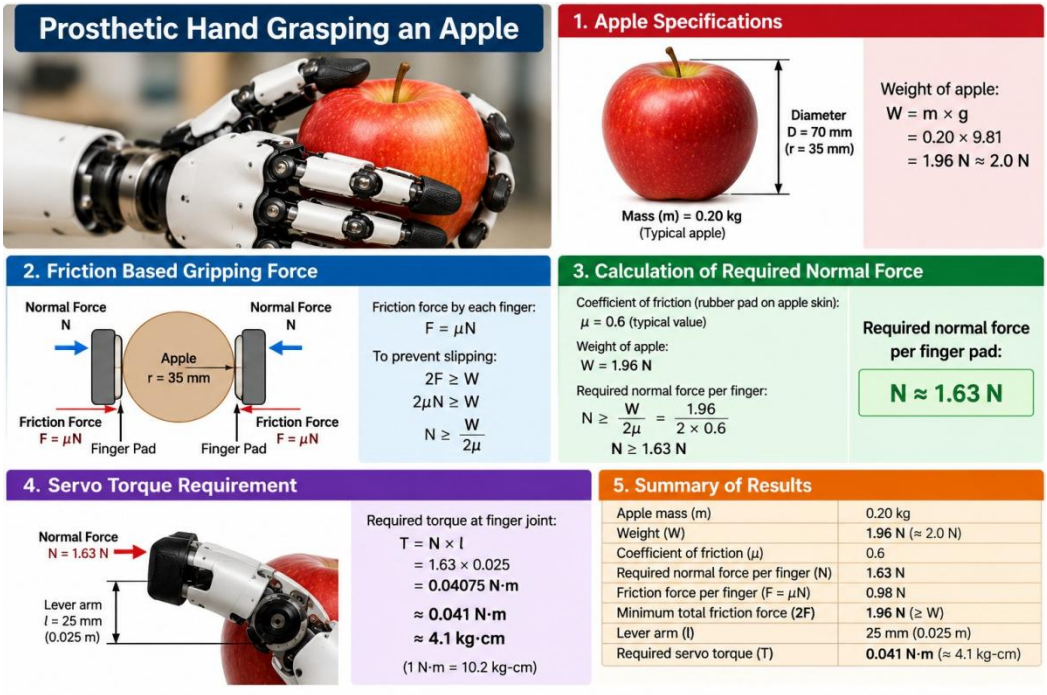


Fig.4.Prosthetic arm applications

CONCLUSION

Artificial limb development involves the combined efforts of engineering, medical science, and rehabilitation professionals. The successful design of a prosthetic device depends on several factors, including a comfortable connection between the device and the human body, sufficient structural strength, properly functioning mechanical components, and reliable electronic control systems. Every component must work together to provide the required functionality, safety, and ease of use. Although upper-limb and lower-limb prostheses follow similar design principles, they differ in their mechanical requirements, movement patterns, load-bearing capacity, and individual fitting needs.

Recent developments in artificial intelligence and intelligent automation have opened new possibilities for improving prosthetic design and manufacturing. These technologies can assist engineers in developing customised designs, optimising component geometry, improving manufacturing accuracy, and enhancing the performance of control systems. AI-based simulations and predictive models can also support design evaluation and maintenance planning. However, computer-generated results alone cannot confirm whether a prosthetic device is safe or suitable for an individual. Proper experimental testing, structural evaluation, risk assessment, and professional supervision are essential. The involvement of the user, prosthetist, rehabilitation specialist, and design engineer is therefore important at every stage of development. The development of an effective artificial limb should follow a systematic approach, beginning with an understanding of

the user's physical requirements and functional expectations. Based on these requirements, engineers can develop a customised and modular design that allows convenient assembly, adjustment, and maintenance. The selected components should then be manufactured under controlled conditions and assembled according to appropriate engineering procedures. Finally, the completed device must undergo mechanical testing, functional verification, and supervised fitting to assess its performance and usability. Combining these practices with modern AI tools and advanced manufacturing technologies can contribute to the development of prosthetic devices that are more reliable, accessible, comfortable, and responsive to individual needs.

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