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Review Article

Smart Prosthetics: A Systematic Review of 3D-Printed Myoelectric Limbs with Integrated Sensory Feedback

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Abstract

The advancement of prosthetic technology has undergone a significant transformation with the incorporation of 3D printing, myoelectric control, and integrated sensory feedback systems. This systematic study analyses the contemporary field of smart prosthetics, emphasizing 3D-printed upper-limb prosthesis augmented with myoelectric data acquisition and tactile feedback systems. The paper examines advancements in materials and fabrication methods, namely the application of biocompatible polymers and soft robotics, alongside control schemes that encompass signal processing and actuation. It also assesses sensor integration, such as touch and pressure sensors, and the consequent enhancements in clinical and functional outcomes, including dexterity, user comfort, and cost-effectiveness. Significant limitations, including power supply issues and user adaptability, are thoroughly examined, with recommendations for enhancing usability and accessibility presented. This analysis underscores the transdisciplinary advancements influencing next-generation prosthetics and stresses the necessity for scalable, user-centric solutions to improve limb replacement technologies.

Keywords: Intelligent prosthetics; Additive manufacturing; Myoelectric control; Sensory feedback; Biocompatible materials; Signal processing

Introduction

Limb loss resulting from accident, congenital anomalies, or disease profoundly affects an individual's quality of life, mobility, and autonomy [1]. In recent decades, the domain of prosthetics has experienced significant developments, especially with the incorporation of myoelectric control systems and additive manufacturing (3D printing) technology [2,3]. These developments have led to the emergence of a new generation of smart prosthetics, intelligent, adaptable devices that can not only replicate limb movement but also deliver sensory feedback, thereby restoring a measure of tactile perception to the user [4,5]. Myoelectric prostheses operate by sensing electrical impulses from the remaining muscles in the severed limb and converting them into controlled movements of an artificial limb [2]. This control mechanism provides more intuitive and natural movement than standard mechanical prosthetics; yet, it has previously been deficient in sensory feedback, which is essential for executing delicate or precise tasks [4]. Recent research has concentrated on incorporating sensory systems, such as pressure, temperature, and proprioceptive sensors, into prosthetic design to facilitate closed-loop communication between the device and the user's nervous system, thereby addressing this constraint [5]. The emergence of 3D printing has transformed prosthesis production by facilitating affordable, customized, and lightweight designs [3,6]. This technique facilitates swift prototyping and customized fitting, rendering advanced prosthetic options more attainable, particularly in resource-limited environments. The merger of 3D printing, myoelectric control, and sensory integration has facilitated the creation of advanced prosthetic limbs that are both functionally advanced and economically accessible, prioritizing user needs [3,6]. This systematic review seeks to rigorously evaluate the existing research and development in smart prostheses, emphasizing 3D-printed myoelectric limbs with embedded sensory feedback. The review examines design techniques, control algorithms, sensor technologies, user experiences, and clinical outcomes. The study synthesizes recent findings to identify gaps, challenges, and future directions essential for improving the functionality, usability, and accessibility of intelligent prosthetic systems.

Evolution of prosthetics

The history of prosthetics is a testament to human ingenuity in the face of physical adversity. Early prosthetic devices, dating as far back as ancient Egypt and Rome, were rudimentary and primarily cosmetic or functional substitutes for lost limbs, typically constructed from materials like wood, leather, and metal [1]. These devices lacked articulation and were largely non-functional, often serving more as symbolic replacements than true mobility aids. Significant advancements emerged in the post-World War eras, driven by the increased number of amputees and the demand for improved rehabilitation tools [1]. The mid-20th century witnessed the introduction of body-powered prostheses, which used harnesses and cables to transfer motion from the user's body to the prosthetic limb [1]. While functionally superior to their predecessors, these devices were often bulky, uncomfortable, and limited in their range of motion. The next major leap occurred with the advent of myoelectric prosthetics in the 1960s, pioneered by Soviet researchers [2].

These devices harnessed electrical signals generated by residual muscles in the amputated limb to control motorized prosthetic components. Myoelectric systems offered more intuitive control and eliminated the need for mechanical harnesses, marking a paradigm shift in prosthetic technology. Over time, advancements in signal processing and microcontroller technology further refined the accuracy, responsiveness, and versatility of these devices [2]. In the 21st century, the field has been revolutionized by the integration of biomechanics, robotics, and neuroscience, paving the way for smart prosthetics, devices that incorporate machine learning, wireless communication, and sensory feedback systems [4,5]. Moreover, the use of 3D printing has democratized prosthetic production by enabling low-cost, customizable, and lightweight solutions tailored to individual users [3]. Simultaneously, researchers have made strides in restoring sensory perception through neural interfaces and tactile feedback systems [4,5]. These advances aim to close the feedback loop, allowing users not only to control prosthetic limbs with greater precision but also to "feel" through them, thereby improving functionality, embodiment, and user satisfaction. Thus, the evolution of prosthetics reflects a shift from static mechanical devices to intelligent, adaptive systems that enhance both motor and sensory integration [1-5]. This progression continues to be propelled by interdisciplinary innovations in biomedical engineering, materials science, and artificial intelligence.

Role of 3D printing and embedded sensors

The amalgamation of 3D printing technology and embedded sensor systems has profoundly altered the design, functionality, and accessibility of contemporary prosthetic limbs [3,6,7]. These two technologies are essential to the development of smart prostheses, providing innovative answers to enduring issues related to cost, customization, usability, and sensory integration.

Three-Dimensional printing in prosthetic design

3D printing, or additive manufacturing, facilitates the swift production of intricate and tailored prosthetic parts through Computer-Aided Design (CAD) [3]. This technology has revolutionized prosthetics by facilitating the creation of lightweight, anatomically precise, and individualized devices at a significantly reduced cost compared to conventionally produced prosthetics [3]. In contrast to traditional techniques that necessitate specialized labor and costly molds, 3D printing enables local and decentralized manufacturing of prosthetic limbs, which is especially advantageous in resource-limited or post-disaster environments [6,8]. Additionally, it fosters user-centered design, facilitating iterative prototyping and real-time adjustments to enhance fit, comfort, and visual appeal [6]. The incorporation of biocompatible and resilient materials, including Polylactic Acid (PLA), Thermoplastic Polyurethane (TPU), and Acrylonitrile Butadiene Styrene (ABS), significantly improves the structural integrity of 3D-printed prosthetic devices, rendering them appropriate for prolonged utilization [3,9].

Integrated sensors and sensory feedback mechanisms

3D printing enhances the physical design and accessibility of prosthetics, while embedded sensors furnish the functional intelligence necessary for responsive and interactive control of prosthetics [7]. The sensors, including Electromyography (EMG), Force-Sensitive Resistors (FSRs), Inertial Measurement Units (IMUs), temperature sensors, and pressure sensors, facilitate the prosthetic limb's ability to discern the user's intentions and engage with the environment [7]. Myoelectric control systems employ surface EMG sensors to capture muscle impulses from the residual limb, enabling users to manipulate prosthetic movements in a more natural and intuitive way [2]. Simultaneously, pressure and tactile sensors included in the prosthetic hand or fingers can transmit feedback to the user via haptic actuators, vibrotactile systems, or neural interfaces, thus completing the sensorimotor loop [4-5]. This integration boosts both dexterity and precision in task execution, as well as embodiment, the psychological perception that the prosthetic limb is an integral part of the user's body [5].

This facilitates enhanced device acceptability and diminishes cognitive load during operation.

Collaborative advantages

The amalgamation of 3D printing with sensor integration establishes a versatile, scalable, and economical foundation for the advancement of smart prosthetics [3,7,10]. Sensors may be integrated directly during the printing process or affixed to modular components after production, facilitating seamless mechanical and electrical integration [10]. This convergence facilitates prosthetics that are both customized in design and responsive in function, adapting dynamically to human intent and environmental stimuli [3,7].

Materials and Fabrication

The advancement of intelligent prosthetics, specifically 3D-printed myoelectric limbs with embedded sensory feedback, depends significantly on progress in material science and digital manufacturing technology [3,11,12]. This breakthrough is fundamentally based on three essential components: soft robotics, printable electronics, and biocompatible polymers. These materials and fabrication techniques facilitate the creation of prostheses that are lightweight, adaptable, user-friendly, and functionally integrated with embedded sensors and actuators.

Compliant robotics

Soft robotics has incorporated compliant, deformable materials into prosthesis design, emulating the flexibility and dexterity of organic tissues [11]. In contrast to conventional rigid prosthetics, soft robotic actuators utilize elastomeric materials and pneumatic or hydraulic systems to facilitate fluid, multi-Degree-of-Freedom (DoF) movements [11]. These solutions augment comfort, mitigate injury risk, and enhance the natural relationship between the prosthetic limb and the user's residual limb or adjacent surroundings. Recent advancements include the 3D printing of silicone-based actuators and the integration of fluidic networks within soft prosthetic fingers, facilitating adaptive gripping and enhancing safety in human-prosthesis interactions [11]. Soft robotic systems enable the integration of sensor arrays for pressure and strain feedback, enhancing closed-loop control methods.

Printable electronics

Printable electronics facilitate the incorporation of flexible circuits, sensors, and conductive paths directly onto prosthetic elements [10]. These circuits are produced utilizing conductive inks, such as silver nanoparticle inks, graphene-based materials, or carbon nanotube composites, via methods including inkjet printing, aerosol jet printing, and screen printing [12]. This technique facilitates the seamless integration of EMG sensors, temperature and pressure sensors, strain gauges, and wireless communication modules onto the inner or exterior surfaces of the prosthetic shell [12-13]. Consequently, real-time data collecting and signal processing can transpire without the need for cumbersome, discrete hardware. The downsizing and adaptability of printable electronics improve the cosmetic and ergonomic attributes of the prosthesis, hence fostering user acceptability and extended wearability [12].

Biocompatible polymers

Biocompatibility is essential for all wearable medical devices [11,14]. Prosthetics that sustain skin contact or interact with neurological or muscle tissues must be constructed from non-toxic, hypoallergenic materials that do not induce discomfort or inflammation after prolonged use.

Frequently utilized biocompatible materials in 3D-printed prosthesis comprise:

Polylactic Acid (PLA): A biodegradable and dermally safe polymer generated from renewable materials [3,9].

a) Thermoplastic Polyurethane (TPU): Esteemed for its flexibility, durability, and comfort in dynamic joints and socket linings [9].

b) Polycaprolactone (PCL): A gradually disintegrating polymer frequently utilized in bespoke orthopedic and prosthetic applications [9].

c) Silicone elastomers are utilized for soft liners, finger pads, and flexible joints in prosthetics that incorporate soft robotic mechanics [9,11].

These materials are suitable for several additive manufacturing methods, including Fused Deposition Modelling (FDM), Stereolithography (SLA), and Selective Laser Sintering (SLS) [3,9]. Besides mechanical integrity and biocompatibility, numerous polymers provide post-processing methods for surface modification or sensor integration. The integration of soft robotics, printable electronics, and biocompatible polymers has advanced the domain of smart prosthetics, resulting in more adaptable, functional, and cost-effective solutions [3,9,11,12]. These material advancements not only diminish manufacturing complexity and expenses but also facilitate the seamless integration of sensing and actuation systems vital for responsive and intuitive prosthetic limbs. Table 1 presents the materials used in Smart Prosthetic Fabrication.

Table 1: Materials used in smart prosthetic fabrication [3,9,11,12].

Material	Component/Application	Properties	Advantages	Limitations
Carbon Fiber Composites	Structural frame, limb sockets	High strength-to-weight ratio, rigid	Lightweight, durable, energy-efficient	Expensive, brittle under certain loads
Titanium Alloys	Joints, connectors, load-bearing structures	Corrosion-resistant, strong, biocompatible	High mechanical strength, long lifespan	Costly, heavier than carbon fiber
Aluminum Alloys	Mechanical parts, frames	Lightweight, corrosion-resistant	Economical, easy to machine	Less durable than titanium

Silicone Rubber	Liners, cosmetic skins, interface pads	Flexible, skin-like texture, inert	Comfortable, biocompatible	Degrades over time, retains dirt
Thermoplastics (e.g., Polypropylene, Polyethylene)	Socket interfaces, covers	Moldable, lightweight	Easy to shape and adjust	Lower structural strength
Thermoset Resins (e.g., Epoxy)	Composite matrix, bonding agents	High stiffness and adhesion	Supports carbon fiber lamination	Brittle, non-recyclable
Smart Textiles	Embedded sensors, surface interfaces	Flexible, conductive fabrics	Enables wearable electronics	Limited durability, complex integration
Conductive Polymers	Sensor arrays, EMG interfaces	Electrically conductive, flexible	Can interface with biological signals	Still experimental in prosthetics
Hydrogels	Bio-sensor interfaces, pressure pads	Water-retaining, soft	Biocompatible, conformable	Fragile, moisture-dependent

Control Strategies

The efficacy of smart prosthetics is primarily contingent upon sophisticated control algorithms that decode user intent and convert it into accurate and lifelike prosthetic motion [2,15]. Myoelectric control, together with real-time data processing and actuation, constitutes the foundation of contemporary upper-limb prostheses. These solutions facilitate intuitive control, enhance motion precision, and allow for the possibility of closed-loop feedback systems [2,5,15].

Myoelectric signal acquisition

Myoelectric control utilizes surface Electromyography (sEMG) to identify the electrical activity produced by muscle contractions in the residual limb [2]. These signals are obtained using surface electrodes positioned across designated muscle groups, usually the flexor and extensor muscles in the forearm or upper arm [2]. Essential elements of myoelectric acquisition comprise:

a. Electrodes: Dry or moist surface electrodes non-invasively acquire EMG signals [2].

b. Amplifiers: Low-amplitude EMG signals are augmented to guarantee precision in detection [2].

c. Band-pass filters (often 10-500 Hz) are utilized to remove noise and motion distortions [2].

d. Analog-to-Digital Conversion: Signals are digitized for processing by internal microcontrollers or external processors [2]. The acquisition procedure is acutely dependent on electrode positioning, skin impedance, and individual muscle physiology, requiring calibration and frequently personalized adjustment of the prosthetic system [2,16].

Signal processing and actuation

Upon acquisition of the EMG signals, they undergo a sequence of computer processes for analysis and activation [2,15].

Signal processing pipeline: Preprocessing encompasses filtering, normalizing, and signal rectification [15].

a. Feature Extraction: Time-domain features, such as mean absolute value and waveform length, together with frequency-domain features, including median frequency and zero crossings, are calculated [15].

b. Classification Algorithms: Machine learning algorithms, including Support Vector Machines (SVM), Artificial Neural Networks (ANN), K-Nearest Neighbors (KNN), and Linear Discriminant Analysis (LDA), are utilized to categorize signal patterns into designated motions or movements [15].

c. Regression Models: In proportional control, regression models predict force or velocity of movement based on EMG amplitude [15].

Actuation mechanism: Subsequent to signal classification or regression, control commands are transmitted to actuators, typically DC motors, servo motors, or pneumatic actuators, integrated into the prosthetic device [10]. Actuation methods may include:

a) Position-oriented: The actuator adjusts the prosthetic joint to a specified angle [10].

b) Velocity-based: The actuator modulates joint velocity in accordance with the intensity of the EMG signal [10].

c) Force-based: The actuator provides grip force commensurate with muscle activation [10].

These actuators are generally synchronized through microcontrollers (e.g., Arduino, STM32, or Raspberry Pi) that oversee motor control, power management, and sensor integration [10].

Integration of sensory feedback (towards closed-loop control)

Advanced control strategies seek to provide bidirectional prosthetics through the use of sensory feedback mechanisms, including [4-5]:

i. Tactile sensors (force, pressure, or deformation) [7,13].

ii. Vibrotactile and electro tactile feedback mechanisms [4].

iii. Peripheral nerve stimulation or transcutaneous electrical nerve stimulation (TENS) [5].

This allows the prosthetic system to deliver instantaneous input about contact, grip strength, and object texture, hence enhancing fine motor control and embodiment [5]. Myoelectric control methodologies enhanced by advanced signal processing and actuation systems have transformed prosthesis technology. They provide amputees with enhanced control precision, natural movement dynamics, and, progressively, a level of sensory perception [2,5,15]. The integration of bio-signal acquisition, machine learning, and soft actuation represents a crucial advancement towards fully autonomous, user-adaptive, and intelligent prosthetic limbs. Table 2 shows the summary of control methods and performance while Figure 1 illustrates the Myoelectric Control Workflow.

Table 2: Summary of control methods and performance [2,10,15].

Control Method	Description	Control Accuracy	User Effort	Adaptability	Limitations
Body-Powered Control	Uses cables and harnesses driven by residual limb or shoulder movement	Low to moderate	High physical effort	Low	Limited dexterity and unnatural movement
Switch-Based Control	Uses mechanical or electronic switches to trigger movements	Low	Moderate	Low	Limited degrees of freedom, unintuitive
Myoelectric Control	Uses EMG signals from residual muscles to control motors	Moderate to high	Moderate	Moderate	Requires training, affected by muscle fatigue
Pattern Recognition (EMG)	Analyzes EMG signal patterns to identify complex movements	High	Moderate	High	Requires robust training dataset and calibration
Inertial Control (IMU-based)	Uses motion sensors to detect limb orientation or gestures	Moderate	Low	Moderate	Sensitive to drift and noise
Brain-Computer Interface (BCI)	Direct neural input (EEG or implanted electrodes) to control prosthesis	Very High (in lab settings)	Low to moderate	Very High	Invasive or bulky, expensive, limited commercial use

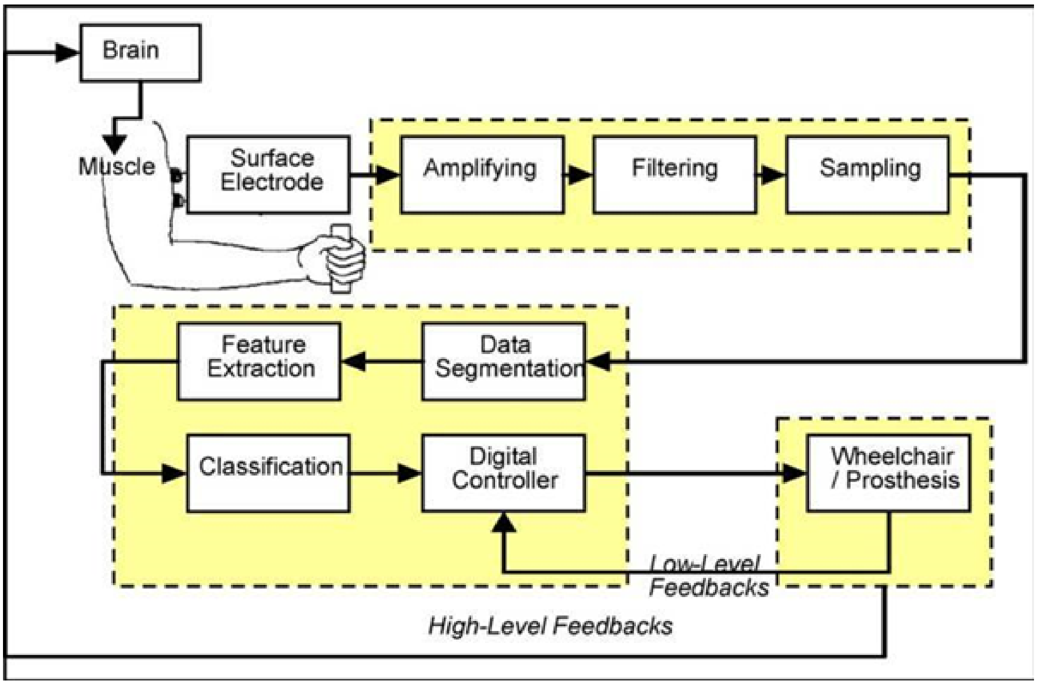

Figure 1: Myoelectric control workflow [17].

Sensor Integration

The incorporation of touch and pressure sensors with haptic feedback systems is crucial for converting passive prosthetic limbs into intelligent, user-responsive devices [4,7,13]. These components facilitate closed-loop control by enabling the prosthetic to detect interactions with the external world and transmit sensory information to the user, thereby improving precision, embodiment, and user confidence [4-5].

Tactile and pressure sensors in advanced prosthetics

Tactile and pressure sensors function as the principal sensory interfaces in intelligent prosthetic systems, facilitating the detection of physical interactions including grip force, object texture, slippage, and surface compliance [7,13]. These sensors are essential for mimicking normal hand function and responsiveness. Diverse sorts of touch sensors are utilized according to their operational principles. Piezoresistive sensors, which modify electrical resistance in response to pressure, are frequently utilized for their simplicity and cost-efficiency, especially in fingertip applications [13]. Capacitive sensors, recognized for their enhanced sensitivity, identify variations in capacitance resulting from surface contact or deformation [13]. Piezoelectric sensors produce voltage when subjected to mechanical stress and are especially adept at detecting dynamic touch and vibrations [13]. Furthermore, optical and magnetic sensors are employed for the detection of surface deformation and proximity. To facilitate seamless incorporation into prosthetic designs, these sensors are typically manufactured on flexible substrates by printed electronics, enabling adaptation to curved surfaces like fingertips, palms, and wrist joints [13]. The positioning of sensors is intentionally optimized throughout the prosthetic limb [7]. Fingertips facilitate precise tactile perception and force application; the palmar and phalangeal areas analyses load distribution; whilst the wrist and forearm regions aid in evaluating force vectors and adaptive grip modifications. The acquired sensory data is processed by embedded microcontrollers or onboard computing systems, where algorithms evaluate the inputs to produce suitable actuation responses or deliver real-time user feedback [7,15].

Haptic feedback systems

Haptic feedback is an essential element that finalizes the sensorimotor loop in smart prosthetics, allowing the prosthetic to convey sensory information to the user [4-5]. This functionality is crucial for reinstating tactile sensation and proprioception, enabling amputees to proficiently manage grip strength, discern object properties, and react to environmental stimuli with diminished reliance on visual cues [4]. Multiple haptic feedback modalities are frequently employed. Vibrotactile feedback employs vibrating motors positioned on the residual limb or other skin-contact areas to provide stimuli, with variations in vibration frequency or amplitude signifying grip intensity or contact location [4]. Electro tactile stimulation utilizes regulated electrical impulses transmitted via surface electrodes to stimulate underlying nerves; although technique provides excellent precision, user acclimation may be necessary to mitigate discomfort [4]. Mechan tactile feedback utilizes actuators to exert mechanical pressure or deformation on the skin, thereby emulating a more immediate tactile experience or force feedback [4]. Innovative techniques encompass temperature-based feedback, which conveys information via thermal fluctuations to signify item temperature or interaction context [4].

Feedback can be categorized into various strategies: event-centric feedback is triggered solely by specific occurrences, such as object contact or slippage; continuous feedback is delivered in accordance with real-time sensor inputs, such as grip strength; and location-specific feedback correlates sensor data to particular regions of the skin to improve spatial awareness [4]. Feedback is normally supplied to the residual limb, but alternate places such as the contralateral limb, chest, or back are also examined for more effective sensory mapping [4]. The incorporation of these haptic feedback systems provides several advantages, such as improved grip force management, enhanced item manipulation, heightened spatial and kinetic awareness, and alleviation of phantom limb pain [4-5]. Moreover, it fosters an enhanced sense of embodiment and psychological comfort for users. The integration of touch sensors and sophisticated haptic feedback systems signifies a pivotal transition from passive prosthetic devices to dynamic, responsive smart prosthetics, greatly improving their functionality and user acceptance [4,5,7,13]. Table 3 highlights the Types and Roles of Embedded Sensors.

Table 3: Types and roles of embedded sensors [2,7,13].

Sensor Type	Function	Application in Prosthetics	Benefits	Challenges
Electromyographic (EMG) Sensors	Detect electrical activity from muscles	Control prosthetic movement based on muscle signals	Enables intuitive movement	Signal noise, muscle fatigue
Force Sensors (e.g., FSRs)	Measure applied pressure or force	Grip control, weight sensing	Prevents over-gripping, enhances object handling	Calibration and durability issues
Inertial Measurement Units (IMUs)	Track motion using accelerometers and gyroscopes	Detect limb orientation and gait patterns	Enhances stability and mobility	Drift and accuracy over time
Temperature Sensors	Monitor thermal conditions	User comfort and device safety	Prevents overheating or skin irritation	Limited direct control function
Proximity Sensors	Detect nearby objects	Object approach warning, grip preparation	Increases environmental awareness	Sensitivity and range limitations
Tactile Sensors	Mimic sense of touch	Surface texture and object detection	Improves dexterity and user feedback	Complex signal processing
Strain Gauges	Measure deformation or bending	Joint angle detection in fingers/limbs	Fine movement tracking	Susceptible to mechanical wear

Clinical and Functional Outcomes

The efficacy of smart prosthetics, particularly those utilizing 3D printing, myoelectric control, and sensory input, is ultimately assessed by their clinical and functional results [4,6,14]. These outcomes influence the practical effects on users' quality of life, daily functioning, and acceptance of the prosthetic device. The principal domains evaluated encompass dexterity, comfort, and cost-effectiveness.

Agility

Dexterity denotes the prosthesis user's capacity to execute intricate and accurate hand and finger movements, essential for activities spanning from gross motor functions to fine manipulation [4,6]. The influence of myoelectric control and sensory feedback: Research consistently indicates that myoelectric prostheses equipped with sensory feedback systems enhance dexterity in comparison to body-powered or passive devices [4]. The closed-loop control enabled by tactile and haptic feedback permits users to adjust grip force, minimise item slippage, and execute intricate operations such as buttoning or typing [4-5]. 3D-Printed Prosthetics and Dexterity: Customizable 3D-printed designs provide optimum articulation of finger joints and tailored mechanical properties, hence enhancing functional hand movements [6]. Nonetheless, constraints in actuator strength and sensor resolution may occasionally diminish precision in challenging jobs [6]. Assessment Instruments: Standard clinical evaluations for dexterity are the Box and Block Test (BBT), Nine-Hole Peg Test (NHPT), and Southampton Hand Assessment Procedure (SHAP) [4].

Comfort

Comfort is a crucial determinant affecting prosthesis usage duration and user contentment, including socket fit, weight, material biocompatibility, and ergonomic design of the user interface [14]. Socket and Interface Design: Innovations in 3D scanning and printing permit custom sockets that precisely match the contours of the residual limb, hence minimizing pressure points and skin discomfort [14]. The utilization of soft biocompatible polymers and flexible liners improves comfort [9,14]. The lightweight characteristics of 3D-printed polymers, in contrast to conventional prosthetic materials, mitigate fatigue over extended usage [9]. Research indicates that sensory feedback systems enhance users' psychological comfort by augmenting limb embodiment and alleviating phantom limb pain [5].

Economic efficiency

Cost-effectiveness pertains to the financial accessibility of the prosthetic as well as the enduring value provided in terms of functionality and durability [3,6,8]. 3D Printing and Cost-Effectiveness: 3D printing markedly decreases production expenses by minimizing material waste, facilitating quick prototyping, and permitting local fabrication without the need for costly tooling or assembly lines [8]. This is especially significant in resource-limited environments [17]. Maintenance and Repair: Modular designs and the capacity to swiftly fabricate replacement components diminish downtime and repair expenses in comparison to conventional prosthetics [8]. Notwithstanding cost benefits, the requirement for sophisticated electronics, sensors, and actuators in smart prostheses may elevate total expenditures [10]. Nonetheless, continuous advancements in affordable sensors and open-source control systems seek to close this gap [6,8]. The clinical and practical results of smart prostheses demonstrate significant enhancements in dexterity and comfort due to advanced materials and sensing technologies, while cost-effectiveness is progressively being tackled through additive manufacturing [3,4,6,8,9,14]. Nonetheless, ongoing advancement is essential to reconcile intricate control and feedback systems with cost-effectiveness and enduring usability. Table 4 presents Functional Assessment of Smart Prosthetics.

Table 4: Functional assessment of smart prosthetics [4,5,10,14,15].

Functionality	Description	Assessment Criteria	Current Capability	Challenges
Sensory Feedback	Ability to provide real-time tactile or pressure sensations	Precision, latency, user perception	Limited, mostly experimental	Integration with nerves, signal interpretation
Myoelectric Control	Use of muscle signals to control prosthetic movement	Signal accuracy, responsiveness	Widely available, moderate performance	Noise in signal acquisition, muscle fatigue
Brain-Computer Interface (BCI)	Direct control via neural impulses from the brain	Signal fidelity, training time	Emerging, high potential	Invasiveness, complexity, cost
Adaptive Grip and Motion	Adjusts grip strength and movement based on object type and context	Reaction time, strength modulation	Moderate to high in advanced models	Delayed response in low-end devices
Energy Efficiency	Power consumption during operation	Battery life, energy per cycle	Varies (4-8 hours avg. for active use)	Heavy power draw from motors and sensors
Wireless Connectivity	Connection to smartphones, cloud, or clinician interfaces	Reliability, data transfer rate	Common in modern models	Security, interoperability
Machine Learning Integration	Learning user behavior over time to optimize performance	Learning curve, adaptability	Early-stage in consumer models	Requires continuous data and user feedback
Comfort and Fit	Ergonomics and skin compatibility	Pressure points, heat dissipation	Good with custom 3D designs	Long-term wear discomfort
Aesthetic Design	Visual appeal and realism	Customization, skin tone matching	Improving with 3D-printing	Costly for hyper-realistic models

Limitations and Future Directions

Smart prostheses signify a significant advancement in prosthetic technology, integrating 3D printing, myoelectric control, and sensory feedback, yet they encounter numerous technological, physiological, and practical constraints that hinder general adoption [8,16,18]. Primary areas of concern encompass power supply issues, user flexibility, and comprehensive integration into healthcare systems.

Challenges in power supply

A significant obstacle to the functionality and usability of smart prostheses is a dependable and efficient power source. Battery Life Constraints: The incorporation of sensors, actuators, microcontrollers, and wireless feedback systems markedly elevates power consumption. Most myoelectric prosthetics depend on lithium-ion batteries, which generally offer restricted operational duration (usually 6-12 hours) before requiring recharging. Bulky Battery Packs: Achieving longer battery life sometimes comes at the cost of greater bulk and weight, compromising comfort and prosthetic aesthetics. Energy Efficiency: Current actuators and sensor systems are not optimized for low-energy operation, and energy regeneration technologies (e.g., from limb motion) are currently under development. Prospective Trajectories: Advancement of lightweight, high-capacity energy storage solutions (e.g., graphene batteries, flexible supercapacitors). Integration of energy-harvesting systems (e.g., piezoelectric generators or thermoelectric materials). Utilization of low-power microcontrollers and signal processors to enhance energy efficiency [10].

User flexibility

Despite advanced technology, user adaptability continues to be a crucial limiting factor affecting the long-term success and acceptance of smart prosthetics [16,18]. Training and Learning Curve: Operating myoelectric limbs with integrated feedback necessitates neuromuscular training to interpret signals and haptic feedback [16]. Numerous users, particularly elderly individuals or those with extended limb loss, encounter challenges in mastering these systems [16]. Cognitive Load: The continuous influx of sensory information and control impulses may result in cognitive fatigue, especially with intricate multi-degree-of-freedom prosthetics [16]. Psychological Factors: Embodiment, perceived usefulness, and device aesthetics all influence user satisfaction [18]. Some users endure dissatisfaction or abandonment due to device complexity or social stigma [18]. Prospective Trajectories: Creation of adaptive machine learning algorithms that tailor control systems to the user's EMG patterns and preferences [15-16]. Improved user interface designs to facilitate feedback analysis [4,16]. Extended rehabilitation programs and virtual training settings to enhance adaption and confidence [16].

Supplementary challenges and prospects

Sensor Resilience and Longevity: Numerous implanted sensors deteriorate due to perspiration, particulate matter, or continuous mechanical strain [7,13]. Integration with Neural Interfaces: Although promising, direct interaction with peripheral nerves or cerebral signals remains predominantly experimental [5]. Affordability and Accessibility: Although smart prosthetics are more economical through 3D printing, they remain excessively costly in low-income environments due to component expenses and insufficient clinical infrastructure [3,6,8].

Future research opportunities: Standardization of manufacturing and evaluation methods [19]. Greater interdisciplinary collaboration among materials scientists, neuroscientists, and rehabilitation specialists [19-20]. Expansion of open-source hardware and software platforms to democratize innovation [6,8].

Final assessment

Although intelligent prosthetics are initiating a novel epoch of user-interactive, anatomically adaptive mechanical limbs, significant issues in power efficiency, user training, and technological resilience require resolution [10,16,18,19]. Addressing these disparities necessitates ongoing research, user-centric design, and scalable manufacturing technologies to completely actualize the promise of prosthetics that restore both functionality and feeling. Recent comprehensive reviews have systematically examined the manufacturing challenges associated with 3D-printed robotic prostheses [19]. These challenges encompass material limitations, precision requirements in additive manufacturing, integration of electronic components, and quality control protocols [19]. Addressing these technical barriers is essential for advancing the reliability, durability, and accessibility of next-generation prosthetic devices. Future innovations must focus on developing standardized manufacturing protocols, improving material properties for long-term biocompatibility, and establishing rigorous testing frameworks to ensure consistent performance across diverse manufacturing platforms [19]. Table 5 shows the Key Gaps and Innovation Opportunities while Figure 2 presents the Design Roadmap for Future Prosthetics.

Table 5: Functional assessment of smart prosthetics [4,5,10,14,15].

Key Gap	Description	Innovation Opportunity	Potential Impact
Limited Sensory Feedback	Most prosthetics lack natural tactile or proprioceptive feedback.	Development of neural-integrated or haptic feedback systems.	Improved user control, embodiment, and satisfaction.
High Cost & Low Accessibility	Advanced prosthetics remain expensive and unaffordable for many.	Low-cost 3D-printed prosthetics using biodegradable materials.	Wider accessibility, especially in low-income regions.
Inadequate Customization	Standard designs may not match individual anatomical and functional needs.	AI-driven, user-specific prosthetic modeling and fitting.	Enhanced comfort and function through personalization.

Short Battery Life	Devices with advanced features (e.g., myoelectric arms) have limited power autonomy.	Energy-efficient actuators and solar-powered systems.	Longer usage time, reduced charging frequency.
Limited Integration with Neural Systems	Most devices are not directly controlled by brain signals.	Brain-computer interface (BCI) integrated prosthetics.	More intuitive control and faster response time.
Stigma and Aesthetics	Bulky or non-humanlike designs cause social stigma.	Biologically inspired and aesthetic-focused designs.	Greater social acceptance and user confidence.
Maintenance and Durability	Frequent breakdowns due to wear and environmental exposure.	Use of smart materials and self-healing polymers.	Reduced maintenance, longer lifespan.

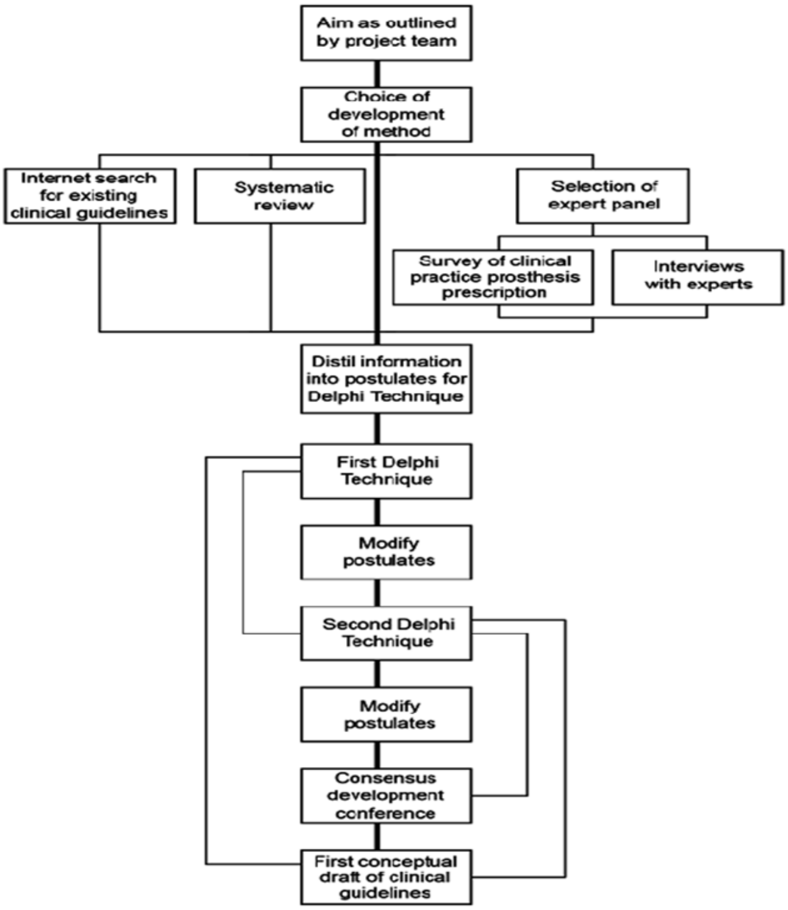

Figure 2: Design roadmap for future prosthetics [20].

Conclusion

Intelligent prosthetics are transforming the realm of assistive technology by integrating 3D printing, myoelectric control, and embedded sensory input into practical, user-centric artificial limbs. These innovations are augmenting the dexterity, comfort, and customization of upper-limb prostheses, providing users with more control and a heightened sensation of embodiment. 3D printing has transformed prosthetic design and production, facilitating rapid prototyping, reducing costs, and allowing for customization that meets the specific anatomical and functional requirements of everyone. Incorporating inbuilt touch and pressure sensors, smart limbs now provide haptic feedback, enabling users to execute delicate motor tasks with enhanced confidence and precision. Notwithstanding these advancements, the domain encounters significant restrictions, such as power supply constraints, sensor durability issues, and obstacles in user adaptability. Resolving these issues necessitates additional interdisciplinary research, especially in energy-efficient components, adaptive machine learning methods, and cost-effective open-source solutions. The integration of soft robotics, biocompatible materials, and intelligent control systems is advancing prosthetic technology towards a future in which artificial limbs serve as both functional replacements and responsive extensions of the human body. Future technologies must stress usability, clinical efficacy, and global accessibility to promote equitable and sustainable deployment.

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