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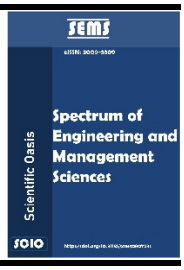


# A Comprehensive Review on Advances in Sensor Technologies for Prosthetic Palms

Ipsita Dhar[1], Bibhuti Bhusan Choudhury[1], Bidyadhar Sahoo[1], Sushil Kumar Sahoo[1,*]

[1] Department of Mechanical Engineering, Indira Gandhi Institute of Technology, Sarang (BPUT, Rourkela) Odisha, India

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**ABSTRACT**

Prosthetic palms owe their function and user experience to the great development in sensor technologies. The present work is a review of different types of sensor systems that have evolved and been integrated in the development control mechanisms, sensory feedback, and adaptability of prosthetic hands. These include force, pressure, tactile, position, and motion sensors involved in basic hand functions such as grip strength and tactile perception. Some recent developments like adaptive AI-driven prosthetics and neural interfacing are changing the levels of user interaction towards more intuitive and natural control haptic feedback also plays a role here. Issues related to biocompatibility have not been addressed here; costs and power consumption are merely considered trends that could lead toward self-healing materials or bio-hybrid systems. It has been highlighted in this review that looking at the present developments, interdisciplinary research is important for creating the coming generation of prosthetic palms with the desired user autonomy and quality of life.

## 1. Introduction

A Loss of a hand drastically affects an individual's daily life not only impairing physically but also emotionally and in social activities. Prosthetic hands have been long regarded as important implements in the rehabilitation journey towards achieving some level of independence and improved quality of life for amputees [1]. The first prosthetics were largely cosmetic or manually operated, thus offering insufficient functionality and no sensory feedback at all. But because a more natural and intuitive prosthesis has been requested, technological development has turned out to be rapid. Sensors located within prosthetic palms are essential to mimic the complex and dynamic sensory and motor function of the human hand, as they allow for a detailed and timely ability to sense force, pressure, touch, temperature, and motion. This allows prosthetic device users to better manage the finer aspects of the device and interact with their environment in a more natural way. Without integrated sensors, prosthetic hands are limited to basic open-close movements, which is a far cry from the dexterity and nuance of the biological hand [2].

* *Corresponding author.*
*E-mail address: sushilkumar00026@gmail.com*

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Therefore, the focus of this review paper is to provide an assessment of sensor technologies used within prosthetic palms. Ultimately; the following will be provided: the sensor types used, means of integration, how signals are processed, current challenges, and rationale for developments. It will also look at recent developments, and potential future direction. These aspects combined will provide researchers, clinicians, and engineers with an understanding of the evolving prosthetic sensor system and hopefully assist in motivating their ongoing consideration of the usefulness of potentially improved solutions in improving the lives of prosthetic limb users.

## 2. Basics of Prosthetic Palms

### *2.1 Structure and Functionality of a Typical Prosthetic Palm*

Most prosthetic palms are made to mimic the structure and function of a human hand in a simple way, with emphasis on goals such as grasping, holding, and releasing objects. Modern prosthetic palms generally consist of a lightweight skeleton structure made from materials like carbon fiber, titanium, or advanced polymers. Coverings may be cosmetic (silicone or rubber) or functional, aiding grip through textured surfaces. Internally, prosthetic palms are equipped with mechanical linkages, actuators (such as motors or tendons), and increasingly sophisticated sensor systems. Motors control the opening and closing of fingers, thumb opposition, and wrist movements, either through simple mechanical triggers or through more advanced bioelectric controls. The aim is to achieve multiple grip patterns—such as cylindrical, spherical, and precision grips—essential for daily tasks. Depending on the level of sophistication, prosthetic palms [3] may be classified as:

i. Passive prosthetics (cosmetic, limited movement);
ii. Body-powered prosthetics (controlled by cables and harnesses);
iii. Myoelectric prosthetics (controlled by electrical signals from muscles);
iv. Bionic hands (integrating multiple sensors and AI for autonomous adjustments).

### *2.2 Historical Evolution of Prosthetic Hands and Palms*

The history of prosthetic hands stretches back to ancient civilizations to modern era as shown in Table 1.

**Table 1**
Historical evolution of prosthetic hands

| Time period | Advancement |
|---|---|
| Ancient Civilizations | Use of simple wooden or metal hooks for basic functional restoration (Figure 1A) [4]. |
| 16th Century | Ambroise Paré developed early mechanical hands with locking mechanisms (Figure1B) [5]. |
| 19th Century | Introduction of articulated, body-powered prosthetics using shoulder harnesses (Figure 1C) [6]. |
| Mid-20th Century | Emergence of myoelectric prostheses controlled via muscle signals (Figure 1D) [7]. |
| Late 20th Century | Integration of microprocessors and basic tactile sensors for improved grip control (Figure 1E) [8]. |
| 21st Century | Highly advanced bionic hands developed with sensor tech, neural interfacing, and dexterity (Figure 1F) [9,10]. |

The historical trend shows in Figure 1 with a clear evolution from purely mechanical designs to intelligent, sensor-enabled prosthetics aiming to replicate natural hand movements and sensations.

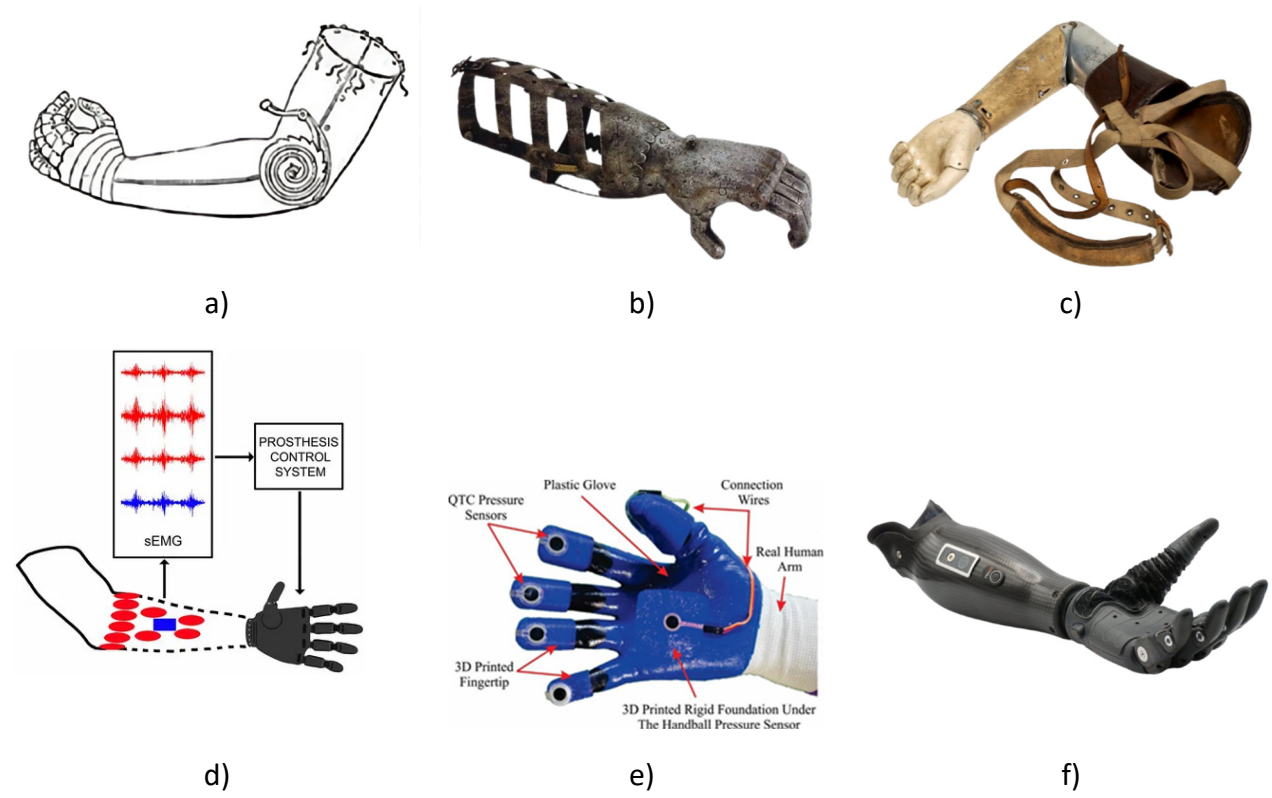


**Fig. 1.** Historical trend in prosthetic palms

*2.3 Role of Sensors in Improving Prosthetic Performance*

Prosthetic palms rely on a variety of advanced sensors to replicate the functionality of a human hand. These sensors help detect force, touch, position, temperature, and user intent, enabling more natural and responsive interactions [11]. Table 2 below summarizes the key types of sensors used in prosthetic palms, their working principles, and their specific applications.

## 3. Sensor Integration Techniques

*3.1 Flexible Electronics and Wearable Sensor Arrays*

Modern prosthetic palms require sensor systems that are not only sensitive and accurate but also adaptable to the dynamic, curved surfaces of the hand. Flexible electronics made from stretchable and bendable materials such as silicone, polyurethane, or conductive polymers are critical to achieving this goal [12]. Wearable sensor arrays are integrated directly onto the surface of prosthetic palms or embedded within artificial skin layers. These arrays consist of multiple sensors, enabling distributed sensing of pressure, temperature, and touch across the palm and fingers. Key advantages include:

i. Conformity to complex palm shapes;
ii. Lightweight, low-profile design;
iii. Ability to function under mechanical deformation like bending and twisting.

This flexibility allows for more natural interaction with the environment, enhancing both comfort and control for the user.

**Table 2**
Sensor principle and application

| Sensor type | Working principles | Applications | Visuals |
|---|---|---|---|
| Force and pressure sensors | -Piezoresistive Sensors: Change resistance under mechanical stress.<br>-Capacitive Sensors: Detect capacitance changes due to deformation. | -Control grip strength depending on object type.<br>-Prevent object slippage and damage by adjusting grip force dynamically. |  |
| Tactile sensors | -Optical Tactile Sensors: Detect pressure via light variation from surface contact.<br>-Piezoelectric Sensors: Generate electrical charge from stress. | -Mimic human skin sensitivity (touch, vibration, texture).<br>-Provide real-time environmental feedback using artificial skin integration. |  |
| Position and motion sensors | -Accelerometers: Measure linear acceleration.<br>-Gyroscopes: Measure angular velocity.<br>-IMUs: Combine accelerometer, gyroscope, and magnetometer. | -Enable precise tracking of finger movements and hand posture.<br>-Allow natural control during tasks like typing or small object handling. |  |
| Temperature sensors | -Detect heat flow between prosthetic and environment. | -Provide users with thermal feedback.<br>-Help identify hot/cold objects, enhancing realism and safety during interactions. |  |
| EMG and neural sensors | -Surface EMG Sensors: Detect muscle-generated electrical signals.<br>-Neural Sensors/BCIs: Interface with nervous system or brain for control. | -Allow intuitive control of prosthetic movements (e.g., open/close hand).<br>-BCIs enable thought-controlled actions, improving control speed and natural movement. |  |

### *3.2 Wireless Communication in Prosthetic Systems*

Traditional wired connections in prosthetic systems can be bulky, limiting motion and adding mechanical stress points. To overcome this, many advanced prosthetic palms now incorporate wireless communication technologies [13] such as:

i. *Bluetooth* – Enables low-power, high-speed communication between the prosthetic hand and external devices (e.g., smartphones, computers) for control customization, diagnostics, and firmware updates;
ii. *Near-Field Communication* – Provides ultra-low-power, short-range data transmission, ideal for quick pairing or energy-efficient updates. Wireless communication supports real-time monitoring, remote adjustments, and even tele-rehabilitation programs, greatly enhancing user convenience and system functionality.

### *3.3 Energy Harvesting and Battery Management*

Sensor-rich prosthetic palms require a reliable power source. However, traditional batteries add weight and require frequent charging [14]. To address this, researchers are exploring energy harvesting techniques and smarter battery management systems, including:

i. *Energy harvesting* – Capturing ambient energy from body motion (piezoelectric generators), heat (thermoelectric generators), or environmental light (small solar cells) to supplement battery power;
ii. *Battery management* – Advanced circuits monitor energy consumption, optimize charging cycles, and reduce energy wastage by putting non-essential systems into low-power modes during inactivity.

By improving energy efficiency and introducing self-charging capabilities, prosthetic palms can achieve longer operation times, reduce maintenance needs, and enhance overall user independence.

## 4. Signal Processing and Control Algorithms

### *4.1 Machine Learning Approaches for Sensor Data Interpretation*

The sensor data from prosthetic palms, especially multimodal sensors (e.g., force, touch, EMG), is complex and has required the use of sophisticated methods for interpreting the data [15]. The use of machine learning (ML) methods is becoming more common to process the sensor data automatically, interpret the sensor data, and improve the accuracy and responsiveness of prosthetic devices. Common supervised learning algorithms like Support Vector Machines (SVM) and Random Forest are used for tasks such as classifying muscle signals and detecting object interactions with the hand. Using supervised algorithms, the prosthetic palm is taught using big data, allowing it to learn and predict the intended movement of the user from the input signal collected by the sensor. Deep learning models such as convolutional neural networks (CNNs) have also been investigated to address the complexity of multi-modal sensor data (i.e. tactile, EMG, and motion sensor data), enabling the system to make more intuitive and natural adjustments in real time. Machine learning-based models allow prosthetics to:

i. Adapt to the user's behaviour over time;
ii. Enhance the precision of movement and control;
iii. Offer predictive maintenance by identifying abnormal sensor patterns.

### *4.2 Pattern Recognition for Gesture and Motion Control*

Prosthetic hands must be able to discriminate complex hand gestures and convert them into meaningful movements. The pattern recognition of identifiable gestures is critical in gesture and motion control, particularly when manipulating multiple degrees of freedom (for example, the individual fingers, wrist rotation, or types of grips) [16]. Pattern recognition systems to discern user intention from sensor data (for example, muscle activity, motion capture, and tactile feedback). Techniques used include:

i. *Template matching* – Comparing current sensor data with predefined templates of gestures.
ii. *Hidden Markov models* – Leveraging statistical models to predict sequential movements based on previous gestures.
iii. *Deep learning-based approaches* – Using neural networks to understand the context and nuances of user motions in more complex tasks.

By recognizing patterns of movement or specific gestures (e.g., grasping, pinching, or waving), these algorithms enable seamless control over prosthetic palms, allowing users to perform tasks like typing, holding delicate objects, or interacting with complex tools.

### *4.3 Real-Time Feedback Mechanisms*

One of the defining features of modern prosthetic palms is real-time feedback, which improves the user experience by providing tactile or sensory feedback during movement or interaction with objects. This feedback enables the prosthetic user to make quick adjustments and avoid accidents like crushing objects or losing grip [17]. Real-time feedback is typically provided through:

i. *Haptic feedback* – Using actuators (e.g., vibration motors or piezoelectric actuators) to simulate touch sensations, such as pressure or texture. This feedback is critical for tasks requiring precise grip control.
ii. *Visual feedback* – Displayed through external screens or mobile apps, where users can monitor force, temperature, or other sensor metrics in real time.
iii. *Auditory feedback* – Beeps, tones, or voice notifications may inform users of the prosthetic's condition or changes in force levels.

This feedback loop is crucial for the user to make immediate decisions during object manipulation, ensuring natural hand functions such as releasing an object when it is too hot or grasping it with the right amount of force.

## 5. Challenges in Sensor-Enabled Prosthetic Palms

Despite the significant advancements in sensor-enabled prosthetic palms, several challenges hinder their widespread adoption and long-term usability [18]. These challenges span technical, economic, and biological domains, affecting the performance, comfort, and accessibility of prosthetic devices. The Table 3 below outlines the key obstacles faced in the development and implementation of sensor-integrated prosthetic palms.

**Table 3**
Challenge area and key issues in sensor-integrated prosthetic palms

| Challenge area | Description | Key issues |
|---|---|---|
| Miniaturization and durability | - Sensors must be small to fit inside limited spaces of the palm and fingers.<br>- Smaller sensors can lose sensitivity and accuracy.<br>- Devices face wear and tear, moisture, dust, and impacts. | - Maintaining sensor performance in small sizes.<br>- Ensuring durability in varied environmental and mechanical conditions. |
| Cost and accessibility | - Advanced sensors and AI integration raise costs.<br>- High cost limits access for people in low-income regions.<br>- Inconsistent insurance coverage further complicates affordability. | - Making high-tech prosthetics affordable.<br>- Improving insurance support and manufacturing efficiency. |
| Biocompatibility and skin irritation | - Sensors and materials must be safe for prolonged skin contact.<br>- Risk of skin irritation, allergic reactions, or discomfort from unsuitable materials. | - Finding hypoallergenic, non-toxic, and skin-friendly materials.<br>- Designing for comfort over long-term use. |
| Power consumption and charging | - Sensors, actuators, and wireless features demand significant power.<br>- Limited battery life requires frequent charging.<br>- Lightweight, high-capacity batteries are needed. | - Balancing energy consumption and battery weight.<br>- Developing energy-efficient components and exploring motion-based energy harvesting (e.g., piezoelectric systems). |

## 6. Recent Developments and Case Studies

Recent advancements in prosthetic technology have led to the development of sensor-enabled, high-functioning artificial limbs that closely mimic natural human movement and sensory feedback. The following table highlights some of the most notable projects, their key features, real-world applications, and success stories. These examples demonstrate how innovation in prosthetics is transforming the lives of users by restoring functionality, enhancing comfort, and improving quality of life as shown in Table 4.

**Table 4**
Recent projects with key features and impacts

| Project | Description | Key features | Success/impact | Real-world application |
|---|---|---|---|---|
| DEKA "Luke Arm" [19] | Advanced bionic arm developed with U.S. Department of Defense support | - Independent finger movement<br>- Force feedback<br>- Proprioception using EMG signals | Successfully tested in trials; enabled users to grasp delicate objects and write | Allowed users to regain daily functions and independence |
| MIT Prosthetics Research [20] | Development of soft robotics and integrated sensors in prosthetics | - Soft, flexible materials<br>- Multimodal sensory feedback (touch, temperature, pressure) | Enhanced comfort and function for users; improved dexterity | Used in rehabilitation centers for tasks like playing instruments and assembling parts |
| Open Bionics "Hero Arm" [21] | 3D-printed, affordable bionic arm for children and adults | - Multiple grip patterns<br>- EMG-controlled finger movement<br>- Customizable cosmetic design | Demonstrated accessibility and effectiveness in both kids and adults | User showed improved confidence, social engagement, and activity performance |

## 7. Future Trends and Research Opportunities

The future of prosthetic palm technology is rapidly evolving with groundbreaking advancements in artificial intelligence, sensory feedback systems, material science, and neural integration. Table 5 outlines key emerging trends and research opportunities that aim to enhance the functionality, adaptability, and user experience of prosthetic palms. These innovations promise to bring prosthetic devices closer to the natural capabilities of the human hand, improving the quality of life for individuals with limb loss.

## 8. Conclusion

The evolution of prosthetic palm technology represents a convergence of engineering, medicine, and artificial intelligence transforming how individuals with limb loss interact with the world. As we move into the future, continued innovation and interdisciplinary collaboration will be critical in closing the gap between artificial and biological hands:

i. Recent advancements in AI, sensor integration, and material science have improved the functionality, adaptability, and realism of prosthetic palms;
ii. Haptic feedback and VR are revolutionizing rehabilitation and training, making it more immersive and effective;
iii. Challenges like cost, biocompatibility, and system integration remain, requiring collaborative problem-solving;

iv. The next generation of prosthetics aims for seamless brain control, smart materials, and personalized response systems;
v. Ultimately, prosthetic palms are becoming more than tools—they are becoming lifelike extensions of the human body.

**Table 5**
Emerging trends and research opportunities in prosthetic palm

| Trend | Core Concept | Technological Features | User Benefits | Research Opportunities |
|---|---|---|---|---|
| AI-Driven Adaptive Prosthetics | Use of AI/ML to personalize prosthetic function | - Sensor-based movement optimization<br>- Grip and finger position adjustment<br>- Activity-based learning | - Automatic adaptation to user habits<br>- Increased comfort & functionality<br>- Higher autonomy | - Behavior prediction models<br>- Long-term learning algorithms<br>- Real-time control systems |
| Integration of Haptics and VR Feedback | Combining touch simulation with immersive VR environments | - Tactile sensors & actuators<br>- Texture/pressure/temperature sensing<br>- VR-based skill training | - Feel of real objects<br>- Improved motor learning<br>- Remote rehabilitation | - Advanced VR rehab systems<br>- Haptic-embedded training simulators<br>- Telemedicine interfaces |
| Self-Healing Materials and Smart Skin | Materials that repair themselves and mimic human skin | - Self-repairing polymers<br>- Smart artificial skin with pressure/temperature sensors | - Enhanced durability<br>- Realistic touch sensations<br>- Reduced maintenance | - Development of bio-inspired materials<br>- Flexible, skin-like electronics<br>- Sensor integration in synthetic skin |
| Neural Interfacing and Bio-Hybrid Systems | Direct brain or muscle control of prosthetics | - Brain-computer interfaces (BCIs)<br>- Invasive/non-invasive neural links<br>- Feedback signal transmission | - Natural, intuitive control<br>- Bidirectional communication<br>- Seamless hand-like experience | - Neural decoding algorithms<br>- Bio-hybrid integration techniques<br>- Cortical and muscular signal mapping |

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## Conflict of interest
There is no conflict of interest to declare regarding the research and findings presented in this paper.

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