Recent Advancements, Trends and Future Prospects of Upper Limb Prosthesis through 3D Printing- A Systematic Review

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Abstract: New opportunities for personalised, functional, and affordable rehabilitation interventions have been made possible through the use of smart technologies in the design of prosthetic limbs. Prosthetic devices have had customisation and affordability revolutionised by 3D printing, but the integration of additive manufacturing with embedded sensors and adaptive control systems is still an emerging and exciting discipline. Conceptualization, development, and integration of embedded sensors for real-time evaluation, biomechanical feedback, and user-controlled algorithms are the subject of this review paper, which systematically explores the state-of-the-art of smart 3D-printed prosthetics. Important technologies augmenting prosthesis performance and user experience, including force and pressure sensors, electromyography (EMG) interfaces, inertial measurement units (IMUs), and soft robotics, are elaborated. For the creation of fully intelligent prosthetic systems, the article addresses major gaps that should be filled and identifies current developments and technical hurdles in the areas of biocompatibility, computational signaling, strength, and power management. The article concludes by pointing out that cross-disciplinary collaboration among materials science, biomedical engineering, robotics, and artificial intelligence is necessary to develop fully integrated, autonomous, and low-cost smart prostheses. Furthermore, the review highlights sustainability-driven advantages of 3D-printed prosthetics, including material efficiency, recyclability of thermoplastics, low-power sensing architectures, and environmentally responsible, low-cost manufacturing pathways.

Keywords: Upper limb prosthesis, 3D printing, Additive manufacturing, Myoelectric control, Electromyography (EMG), Sensor integration, Smart prosthetics.

1. INTRODUCTION

When an upper limb is amputated, it significantly impairs a person's capacity to carry out fine motor tasks, hold items, use gestures for interaction, and to keep psychological stability. Upper limb amputation results in a functional gap in manipulation and engagement with the environment, which is essential for carrying out fundamental activities of daily living (ADLs) and vocational duties, in contrast with second limb degeneration, which primarily impairs ambulation.

The prevalence of upper limb loss is steadily increasing worldwide, mostly as a result of genetic defects, cancer, and catastrophic traumas. Top limb prosthetic innovation has grown from simple passive devices to sophisticated myoelectric and neuroprosthetic limbs with simple manipulation and biofeedback in response to this expanding need (Roche *et al*., 2014). However, challenges persist in replicating the dexterity, sensory function, and user comfort intrinsic to the biological limb.

In this regard, additive manufacturing, or 3D printing, has become a game-changing tool for the development of prosthetics. It enables decentralised production, low-cost prototyping, and quick, patient-specific design, features that are especially useful in low-income and paediatric contexts (ten Kate *et al*., 2017). With promising functional results and great user satisfaction, researchers have demonstrated that 3D-printed prosthetic hands, like those created by the e-NABLE community, offer customisable solutions for a fraction of the cost of commercial equivalents (Zuniga *et al*., 2015).

The traumatic injuries, different diseases, and some multifarious as depicted in the Figure **1** were observed by us. Despite these advancements, a comprehensive review focused on the integration of 3D printing in upper limb prosthesis development- spanning design strategies, control systems, sensor technologies, psychosocial outcomes, and future prospects- remains lacking. Addressing this gap, the current review synthesizes findings across five key dimensions: (1) causes and epidemiology of upper limb amputation, (2) prosthesis classification and 3D-printed design techniques, (3) control algorithms and sensor

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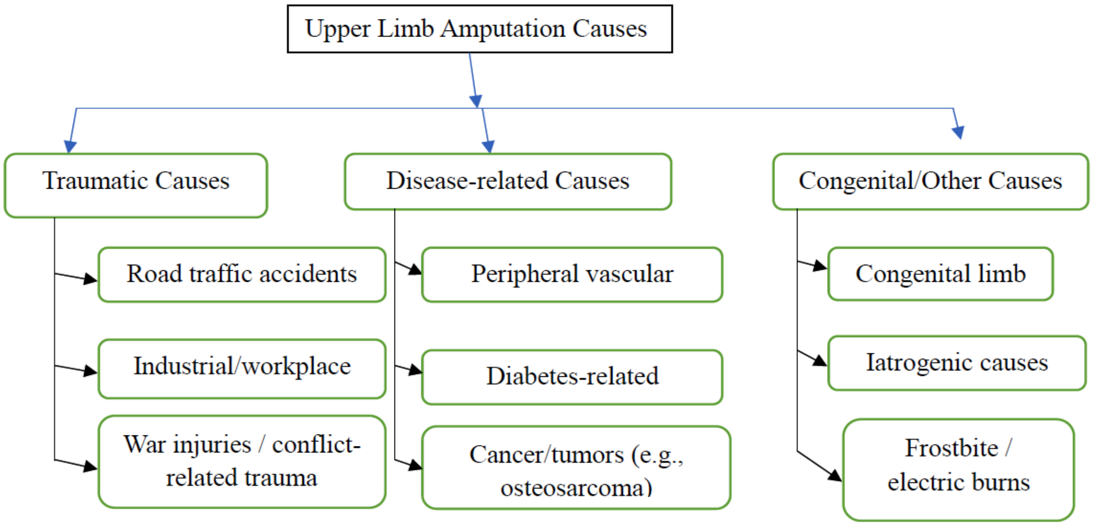

Figure 1: Common causes of upper limb amputations that happened in life routine matters have been illustrated.

integration, (4) psychosocial and functional impact on users, and (5) emerging trends, open-source platforms, and future research directions.

This review aims to guide researchers, developers, and clinical stakeholders in leveraging additive manufacturing to build next-generation prosthetic solutions that are affordable, customizable, and functionally restorative. Methodology of the review starts from Section-2 on lower limb amputation, causes of amputation, and country-wise surveys on lower limb amputation; Section-3 describes the categories of prostheses, design mechanisms, commercial developments, and 3D printing of the accessories for lower limb prosthesis; Section-4 presents brief information on control strategies, sensors, machine learning algorithms, and human gait cycle; section-V describes the summary of psycho-social impact of prosthetic users; Section-5 is about the design trends in patents. Section-6 highlights the challenges, discussions, and future prospects for lower limb prosthesis. Section-7 highlights the key contributions as concluded and suggested future work followed by acronyms used in these documents.

2. REVIEW UPPER LIMB PROTHESIS THROUGH 3-D PRINTING

2.1. Upper Limb Amputation

Upper limb amputations, though less common than lower limb amputations, have a disproportionately high impact on daily functioning, particularly due to the loss of dexterity and sensory feedback essential for activities of daily living (ten Kate *et al*., 2017). They can occur at various anatomical levels, including trans radial, trans humeral, and shoulder disarticulations.

Trauma remains the predominant cause globally, especially in younger adults and manual labor sectors, accounting for up to 80% of upper limb amputations in some regions (Limb amputation and limb deficiency). In low-resource and conflict-affected areas, war-related injuries and inadequate emergency care significantly increase traumatic upper limb amputations (Inspiratory muscle fatigue in trained cyclists).

Malignancies are other indications, particularly osteosarcoma, with surgical limb removal necessitating it at times in children and teenagers. Congenital limb deficiencies are another significant group, with challenges being faced because of growth-related prosthetic needs and psychosocial adjustment. In developed nations, trauma management advances have shifted some of the attention to post-amputation rehabilitation management, e.g., the incorporation of high-tech prosthetic systems (Resnik *et al*., 2012).

With the advent of 3D printing, upper limb prosthetic solutions are rapidly evolving to become more accessible, lightweight, and customized. This is particularly transformative in pediatric and low-income contexts, where conventional prosthetics are often unaffordable or unavailable (ten Kate *et al*., 2017). Recent innovations demonstrate the feasibility of printing functional prostheses at material costs below $500 (Bogue, 2020), drastically lowering economic barriers to upper limb rehabilitation.

2.1.1. Causes of Upper Limb Amputation

Trauma is the most prevalent cause of upper limb amputation, especially among young adults. Trauma-induced amputations are generally a result of machinery accidents, road traffic accidents, and high-energy injuries sustained during war. The aforementioned injuries generally involve complicated tissue injuries, i.e., bone, muscle, and neurovascular tissue, which complicates limb salvage. Jain & Robinson (2008) noted that war injuries, particularly anti-personnel mine and high-velocity projectile wounds, lead to extensive contamination and necessitate amputation in cases where surgical reconstruction is not feasible [8].

Congenital causes account for around 18% of upper limb amputations. These may result from amniotic band syndrome, genetic mutations, or vascular disruptions during fetal development. Such deficiencies vary from partial digit absence to complete transverse limb loss. The congenital nature allows early adaptation, but poses challenges in prosthetic fitting due to continued growth. Jain & Robinson (2008) provided a clinical summary of the common etiologies and psychosocial outcomes in congenital limb loss [8] .

While more frequent in lower limbs, upper limb amputations secondary to thromboembolism, arteritis, or atherosclerosis can take place. Buerger's disease and diabetic angiopathy may also be seen in young patients with digital gangrene. Jain & Robinson (2008) inform that vascular causes, while infrequent, are more likely in the aged with comorbid conditions [8].

Deep tissue necrosis with skin sparing is a frequent finding in high-voltage electrical injuries, and initial assessments are hence misleading. Industrial trauma or war can result in amputation through infection or preclude contracture by thermal burns. Wallace *et al*. (2015) present a comprehensive overview of electrical burn injury complications (Huang *et al*., 2015).

Alexander Miles & Edin stated that amputation of the upper limb was performed primarily for serious injuries such as gunshot wounds, malignant tumors with involvement of axilla and shoulder-joint, and far advanced disease of bone. It was once on account of a round-celled sarcoma which had involved the upper humerus, and again on account of recurrent scirrhous growth with severe pain and ulceration of the axilla [10].

Alshehri *et al*. presented that upper limb amputations were most commonly caused by trauma, including road traffic accidents and industrial injuries. Less frequent causes included tumors, vascular conditions, and infections. Trauma was especially prevalent in patients under 40 years old (Alshehri *et al*., 2022).

Mousavi *et al*. studied that the most common cause of upper limb amputation was trauma in 45.2%, which was largely caused by vehicle and motorcycle collisions. Vascular causes, including diabetes, arterial embolism, and chronic vascular disease, were the second most common cause (37.4%). Sarcomas and melanoma accounted for 4.9%, and congenital deformities and chronic infections accounted for 2.9% and 6.4% of the cases, respectively. The remaining unusual causes included frostbite, burns, and deformity of unspecified cause (Mousavi *et al*., 2012).

Resnik *et al*. stated that trauma was the leading cause of upper limb amputations, particularly from motorcycle and other vehicular accidents. Congenital deformities and tumors such as sarcomas and melanomas were also significant contributors. Chronic infections and rare causes like frostbite and burns were additionally mentioned. Vascular causes were minimal in upper limb cases, with diabetes and chronic vascular disease predominantly affecting the lower limbs (Resnik *et al*., 2019).

Geraghty & Jones stated that trauma was the primary cause of upper limb amputation among the patients studied, with all eight cases of painful neuromata resulting from traumatic incidents. No other causes such as vascular disease or tumors were reported in this group. The patients were predominantly young males in high-risk occupations. This supports the view that trauma is a major contributor to upper limb loss in active populations (Geraghty and Jones, 1996).

Kejla studied that upper limb amputations in the study were primarily caused by trauma, followed by vascular disease and tumors. Trauma was the most significant contributor, as reflected in the majority of cases reviewed. These causes were consistent with patterns observed in Denmark, where upper limb amputations represent only 3% of all amputations (Kejlaa, 1993).

Ostlie *et al*. determined that the primary cause of upper-limb amputation among participants was trauma, including occupational and traffic accidents, war injury, and other incidents. Other causes included cancer, infections, poor circulation, diabetes, and overdose. Trauma reported for 84.5% of the cases, making it the ruling cause in the Norwegian sample studied (Østlie *et al*., 2011).

Raiechle *et al*. stated that the causes of upper limb amputation were mainly trauma, including combat-related injuries among veterans. Other causes mentioned included ancestral limb deficiencies and diseases such as cancer. Trauma remained the most widespread case across participants (Raichle *et al*.).

The authors found that upper limb amputation in the majority of cases (83%) was caused by injury, with other causes including infection (8%), gangrene (8%), vascular issues (4%), and congenital reasons (1%). The study did not find significant alliance between the cause of amputation and the prevalence of different types of pain. However, it highlighted pre-amputation pain which was related with higher rates of back and neck pain post-amputation. The complex and multifactorial nature of upper limb loss and its associated chronic pain conditions were underscored by these findings (Hanley *et al*., 2016).

The author reported the most frequent cause of upper limb amputation in their study was trauma, accounting for 85% of cases, which aligns with previous findings in the literature. Additionally, tumors were reported as the cause in 9% of cases, followed by congenital malformations in 6%. This distribution emphasizes the main role of traumatic incidents in upper limb loss, especially in comparison to lower limb amputations, where vascular causes are more prevalent (Kooijman *et al*., 2000).

The author stated that upper limb amputations are primarily caused by traumatic injuries, which occur more frequently in males due to high-risk occupational and recreational activities. In contrast to lower limb amputations, often associated with vascular diseases or diabetes, upper limb loss is less commonly linked to such medical conditions. This difference intensifies the traumatic and sudden nature of most upper limb amputations, often resulting from accidents in industrial, military, or vehicular settings (Segura *et al*., 2024).

The author reported that trauma was the main cause of upper limb amputation, followed by diabetes, vascular obstruction, infections, tumors, and congenital anomalies. Trauma cases including blunt injuries, penetrating wounds, and burns. This pattern differs from developed countries where vascular disease is more common (Sarvestani and Azam, 2013).

The author stated that the primary causes of upper limb amputation were tumor-related conditions, especially sarcomas, followed by dysvascular diseases such as atherosclerosis, and then infections, trauma, and rare congenital anomalies. Tumors were the leading cause specifically for upper limb loss (Settakorn *et al*., 2005).

2.1.2. Country Wise Surveys for Causes of Upper Limb Amputation

Upper limb amputations, while less frequent than lower limb amputations, significantly disrupt daily life due to the intricate functions these limbs provide, such as dexterity and fine motor skills. The leading cause of upper limb loss globally is trauma, particularly prevalent among younger adults engaged in manual labor or high-risk activities, accounting for up to 80% of cases in certain regions. Other causes include congenital conditions, tumors, and vascular diseases. Country-wise surveys reveal stark disparities in amputation causes; for instance, traumatic injuries dominate in countries like Ghana and Ethiopia, while vascular diseases are more common in developed nations like Ireland. This summary underscores the need for tailored prosthetic solutions that address the unique challenges faced by upper limb amputees across different cultural and socioeconomic contexts, paving the way for innovative developments in prosthetic technology. Here, Table **1** represents information on lower limb amputations focusing the major causes of amputation. Second column refers to the survey year and Third column refers to the publication year of the survey.

2.1.3. Health Risks after Upper Limb Amputation

In Figure **2**, different levels of upper limb amputations are being seen by us. Health risks following upper limb amputation encompass both physical and psychological challenges that can significantly affect quality of life. Physically, amputees may experience complications such as phantom limb pain, which can lead to chronic discomfort and require ongoing management. Additionally, issues like infection, poor wound healing, and joint stiffness are common, necessitating careful postoperative care and rehabilitation. Psychologically, individuals may face emotional distress, anxiety, and depression due to the loss of functionality and changes in body image. These risks highlight the importance of comprehensive

Table 1: Country-wise Survey of Upper Limb Amputation

Country	Survey Period	Years	Number of Upper Limb Cases	Etiology (Causes)	Reference
Denmark	1900–1987	1987	66	Trauma (majority), Vascular disease, Tumors	[15]
USA	Not specified (mostly Vietnam-era veterans)	–	107	Combat injury (84.5%), Congenital, Disease (e.g., cancer, infection)	[17]
Thailand	2000–2004	2000	23	Tumors (especially sarcomas, 61%), Dysvascular disease, Infections	[22]
Iran	April 2002 – December 2011	2011	40	Trauma (majority), followed by Diabetes, Vascular obstruction, Infection, Tumors	[21]
Australia	6 months during 2017	2017	27 participants (after filtering incomplete responses)	Congenital (26.9%), Injury or trauma (19.2%), Cancer (19.2%), Sepsis/infection (30.8%), Complications from surgery (3.8%)	[23]
Ghana	June 2018 – September 2018	2018	50 individuals with upper limb amputation	Trauma (66%), Disease (24%), Congenital (10%)	[24]
India	2 years	2011-2013	60	Occupational trauma and congenital	[25]
Central Gujrat	2 years	2011-2013	37	Workplace trauma (manufacturing sector)	[26]
North India	4 years	2018-2022	37	Diabetic foot and Trauma	[27]
Pakistan	1-15 years	2008-2012	85	High voltage Electric Burns	[28]
South Korea	9 years	2004-2013	4201 ,535	Work upper am	[29]
Ireland	09 years	2020	172	Non-traumatic(vascular)	[30]
Cameroon	02Years	2020	172	Trauma	[31]
Ethiopia	March 2021 – May 2021	2021	97 participants with upper limb amputation	Trauma (65.9%), Disease (17.5%), Congenital (16.5%)	[32]
Nigeria	5 years	2021	92	Peripheral vascular diseases	[33]
South Africa	1 year	2021	152	Peripheral vascular diseases, Diabetes mellitus	[34]

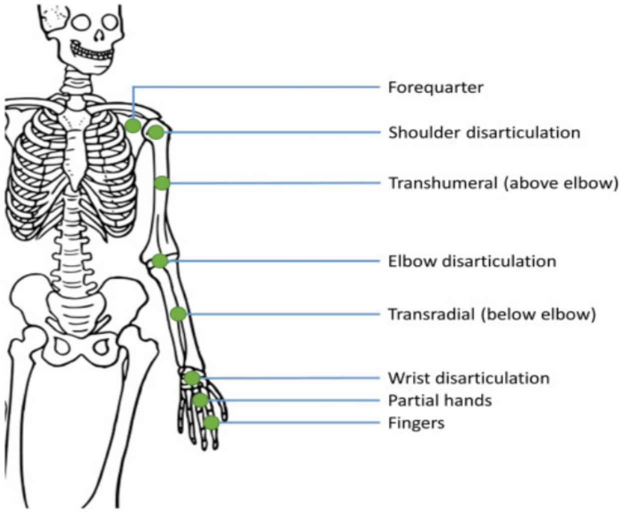

Figure 2: The different levels of upper-limb amputations [1].

rehabilitation programs that address both the physical and mental health needs of upper limb amputees to ensure a smoother transition and improved overall well-being.

Mitchell *et al.*, stated in his paper that after upper limb amputation, individuals reported moderate to high levels of physical and psychosocial disability. Despite access to advanced prosthetic technologies and comprehensive rehabilitation services, participants experienced diminished self-reported function and emotional well-being. The study found no significant long-term differences in functional outcomes between those treated with amputation and those who underwent limb salvage. Rates of depression (12.3%).

and PTSD (19.4%) were notable, and only 9.1% reported being pain-free, indicating a persistent burden of pain. Nevertheless, many individuals remained engaged in work, school, or vigorous recreational activities, suggesting adaptive capabilities despite the injuries. The findings emphasized that addressing PTSD, depression, chronic pain, and unhealthy habits could reduce the overall disability burden in this population (Mitchell *et al*., 2019).

Mattiassich *et al* explained that after upper limb amputation, most patients experienced significant limitations in daily activities, with 52% reporting chronic pain and many showing signs of psychological distress, including depression and anxiety. Despite prosthesis use, functional restoration remained limited, and satisfaction varied depending on the level and reason for amputation (Mattiassich *et al*., 2017).

Melcer *et al*., also stated that after upper limb amputation, patients showed a high prevalence of physical and psychological complications, especially in the first postinjury year. Over five years, although many complications declined, pain and psychological disorders (including PTSD) remained notably high. The authors also found that above-elbow amputees had significantly higher odds of issues like deep vein thrombosis, cervical pain, and mood disorders, while below-elbow amputees had fewer complications like osteomyelitis (Melcer *et al*., 2019).

2.2. Design and Development in Upper Limb Prostheses

The design and development of upper limb prostheses in this study focus on creating a low-power, high-torque robotic arm using control moment gyroscopes (CMGs). By utilizing CMGs, which generate torque through gyroscopic forces rather than traditional actuators, the prosthesis achieves efficient, agile movement with reduced power consumption. Natural motions like elbow and wrist flexion and forearm rotationare replicated by the three-degree-of-freedom arm and is controlled in real-time using electromyographic (EMG) signals from specific muscles. This innovative approach aims to increase prosthetic performance and user functionality for upper-limb amputees (Jarc *et al*.).

Radu *et al*. (2021) present a wide approach to the design and development of a customized upper limb prosthesis, emphasizing a mechatronic system driven by electromyographic (EMG) signals. The prosthesis incorporates micro-motors for complex finger, hand, and forearm motions, processed via an embedded control system integrating various sensors. The design relies on reverse engineering and 3D printing for anatomical accuracy, achieving precise kinematic functionality and user adaptability. This innovative prosthesis aims to be lightweight, cost-effective, and user-friendly, offering improved functionality and quality of life for individuals with upper limb amputations (Radu *et al*., 2021).

The authors presented the design and analysis of an underactuated anthropomorphic finger for upper limb prosthetics. They focused on creating a finger model that is capable of doing human-like motions

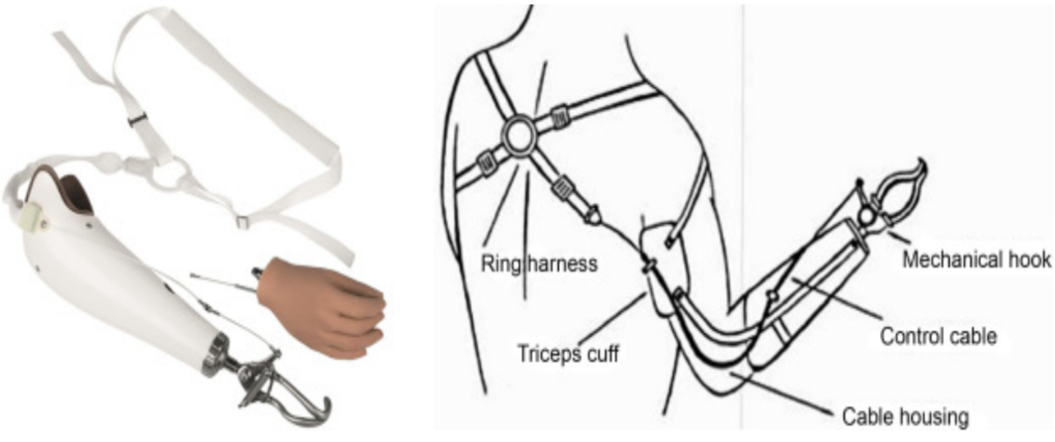

Figure 3: A body-powered arm hand system prosthesis (Roche et al., 2014).

using fewer actuators, thus improving efficiency and reducing complexity in prosthetic design (Omarkulov *et al*., 2015).

An innovative approach to the mass customization of prostheses using automated design and 3D printing was developed by Górski *et al*. They used 3D scanning of the patient's upper limb to create adaptive CAD models and developed a special algorithm to automate the 3D printing process, which resulted in low-cost, customized prosthetic devices (Górski *et al*., 2022).

This paper reviewed the mechanical designs and control algorithms for active upper-limb exoskeleton robots, which are used in rehabilitation and assistive robotics. The authors identified key requirements for these devices and categorized existing designs, discussing the challenges and solutions in developing exoskeleton robots for effective upper-limb rehabilitation [42].

The authors designed a prosthetic arm and hand using a bioengineering approach that requires only a single data channel to control multiple movements. The system uses muscle sensors to acquire signals, which are processed by an Arduino microcontroller to control arm and hand motions such as opening/closing and wrist supination/pronation (Saqib *et al*., 2018).

Yurova *et al*. designed an anthropomorphic robotic arm prosthesis with 21 degrees of freedom to closely replicate the function of a human arm. The system is designed for easy integration with various control systems like computers or EEG devices, providing an adaptable solution for research and prosthetic applications (Yurova *et al*., 2022).

Demofonti and colleagues developed a modular wrist module for upper limb prosthetics that features two degrees of freedom for active pronation/supination and passive elastic flexion/extension. The design improves the dexterity of the prosthetic hand, allowing for more natural and efficient movement during tasks such as grasping (Demofonti *et al*., 2023).

Lake's paper focused on the evolution of upper limb prosthetic socket design, emphasizing the importance of a well-fitting socket for prosthesis success. The study traces the history of socket designs, from early work by Hepp to modern advancements in transradial and transhumeral socket technologies, highlighting the critical role of material science and specialized prosthetic knowledge (Lake, 2008).

3. GENERAL CATEGORIES OF UPPER LIMB PROSTHESIS

3.1. Man-Machine Interface in Active Prostheses

In this type of artificial limb, the man-machine connection depends on the type of activation, as it is directly linked to the way the user's aim is captured. They are divided into body activation prostheses, button-controlled prostheses, myoelectric prostheses and hybrid prostheses.

Body Activation Prostheses

The user's communication with body-activated artificial limb, or body-powered, as it is also known, is

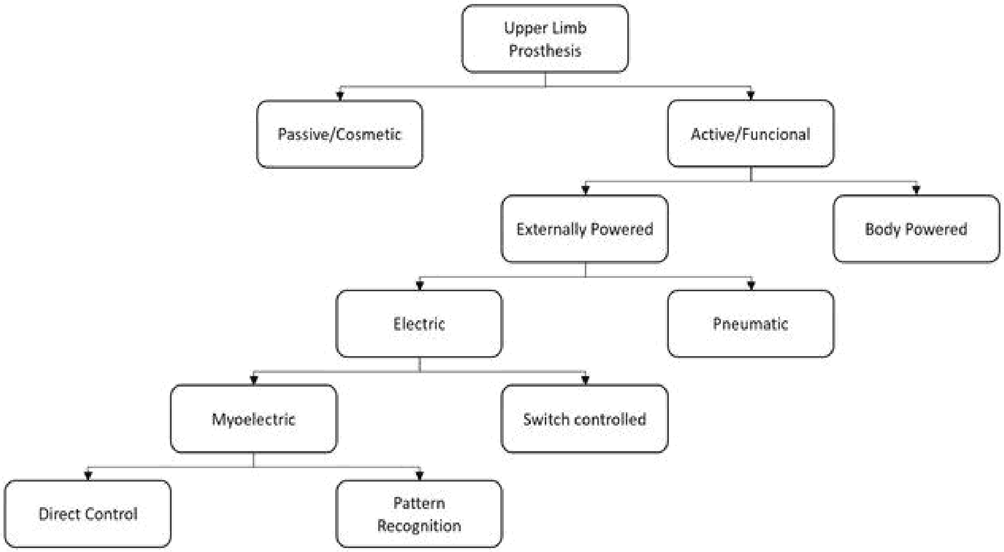

Figure 4: Upper limb prosthesis is classified as passive and active keeping in view the actuation power (Mereu et al., 2021).

done mechanically by means of cables attached to the patient's shoulder or torso. The prosthesis is designed so that certain movements that the user wishes to make with the remaining limb can be translated directly into it (Mereu *et al*., 2021).

Myoelectric Prostheses

The basis of this connection is the capture of electromyographic signals (EMGs) from electrical activities of the excitable cells of the muscles through electrodes on the skin (non-invasive method) or applied directly into the muscles (invasive method). Whenever the brain sends a signal to a muscle, this electrical activity increases [49]. The prosthesis has software responsible for serving these signals and using them to drive the motors of the various joints.

Hybrid Prostheses

It is called a hybrid as it links different user-obtained data collection techniques, such as myoelectric signals, electrical activities of the cerebral cortex, osseointegration, epimysial electrodes, and pattern recognition. The union of different techniques increases the user's ability to control the prosthesis, facilitating the training to use it, and making the control more spontaneous (McMullen *et al*., 2014). It is important to mention that osseointegrated prostheses (OIP) techniques have been developed and applied as an alternative to conventional socket-type prostheses (Gupta *et al*., 2018).

3.2. Commercial Development in Upper Limb Prosthesis

International sales of upper limb prosthetics have jumped up at a 4.3% CAGR between 2018 and 2022. Sales of upper limb prosthetics are estimated to grow at a 4.1% CAGR between 2023 and 2033. One of the main factors driving the growth of the upper limb prosthetics market is the surging geriatric population across the world (Trent *et al*., 2020).

Passive prosthetic, body-powered prosthetic, externally powered myoelectric prosthetic, hybrid prosthetic, and activity-specific prosthetic are the five general upper limb prosthetic groups. To increase a person's functional abilities, hybrid devices integrate body-powered and myoelectric components in one prosthetic.The majority of these designs are for transhumeral, shoulder-level, or forequarter amputees, and comprise body-powered prosthetic arms and myoelectric hands that may be manipulated simultaneously.Body-powered prosthetic devices are expected to account for a market share of around 30.9% in the global landscape. Furthermore, passive prosthetic devices and hybrid prosthetic devices together are set to account for 31.1% of the global market share in 2023. Due to deteriorating bones, older adults are more prone to orthopedic illnesses, which is another key factor driving global demand for upper limb prosthetics (Trent *et al*., 2020).

The rise in the number of road accidents is due to rapid modernization and increasing sales of high-performance vehicles. In addition, rash and drunk driving are contributing to an increase in the number of road accidents around the world. This is predicted to contribute to the upper limb prosthetics industry's improved growth.Even among amputees, there is a rising emphasis on physical fitness, leisure sports, and other physical activities such as aerobics and jogging, which has increased the demand for upper limb prosthetics for sports and recreation. These amputees can return to the sports and recreational activities that they enjoyed before their injuries with the help of upper limb prosthetic rehabilitation(Upper Limb Prosthetics Market Size, Trends, 2024) **.**

Prosthetic limbs and other prosthetics are predicted to expand in popularity as the prevalence of bone illnesses such as osteoporosis, osteosarcoma, osteonecrosis, and osteopenia rises.

- **Short Term (2022 to 2025):** The short-term goal for the upper limb prosthetics market is to constantly progress, with advances in technology and materials providing new opportunities to improve the functionality and usability of prosthetic limbs [54] .

- **Medium Term (2025 to 2028):** The popularity of upper limb prosthetics continues to grow. This growth can be associated with the emergence of prosthetics with incorporated pattern recognition for control, and post-targeted muscle distribution. The key developments in the market include the adoption of telehealth services for upper limb amputees for developmental, physical, and psychosocial processes.

- **Long Term (2028 to 2033):** Long-term goal for the upper limb prosthetics market is to develop prosthetic limbs that can be seamlessly integrated with the body. This could involve developing prosthetics that are controlled by the

Table 2: Upper Limb Prosthetics Market Report Coverage (Battraw et al., 2022)

Report Attribute	Details
Forecast Period	2020 - 2030
Market size value in 2021	USD 720.86 million
Revenue forecast in 2030	USD 1131.36 million
Growth rate	CAGR of approximately 4.97%
Base year for estimation	2021
Historical data	2017 – 2021
Unit	USD Million, CAGR (2021 - 2030)
Segmentation	By Device Type, By Component, By End-Use, and By Region
By Device Type	Hybrid Prosthetics, Body- Powered Prosthetics, Passive Prosthetics, Myoelectric Prosthetics
By Component	Terminal device, Prosthetic socket, Prosthetic wrist, Prosthetic shoulder, Prosthetic elbow.
By End-User	Prosthetic Clinics, Hospitals, Other End-Users
By Region	Asia Pacific, North America, Europe, LAMEA
Country Scope	United States of America, Germany, United Kingdom, Italy, France, Spain, Canada, China, Japan, India, Australia, South Korea, Mexico, Brazil, Argentina, Saudi Arabia, United Arab Emirates, South Africa
Company Usability Profiles	Coapt LLC, Össur hf, Motorica LLC, Ottobock SE and Co. KGaA, Protunix, Steeper, Inc., Fillauer LLC, Ortho Europe, Mobius Bionics LLC, Naked Prosthetics Endolite India Ltd., and Stryker Corporation.

user's nervous system, or even growing prosthetic limbs directly from the patient's cells.

Here, Table **2** represents Global Market Segmentation and Coverage of Upper Limb Prosthetics.

Global Upper Limb Prosthetics Market Competitive Landscape Analysis

Upper limb prosthetics is a competitive market with a few key competitors. These industry players concentrate on strategic collaborations, new product launches, and commercialisation to expand their business. Furthermore, these firms heavily spend on research, which helps them develop novel items and maximise their market share. The major competitors in global upper limb prosthetics market are:

- Coapt LLC
- Össur hf
- Mobius Bionics LLC
- Protunix
- Ortho Europe
- Ottobock SE and Co. KGaA
- Motorica LLC
- Steeper, Inc.
- Fillauer LLC
- Naked Prosthetics
- Endolite India Ltd.
- Stryker Corporation

Recent Developments

In May 2022, Ottobock SE & Co. KGaA demonstrated its Myo Plus TH upper limb prosthetic device at OTWorld in Leipzig. Ottobock believes introducing and demonstrating the Myo Plus TH upper limb prosthetic device will enable the company to deliver better possible treatment and achieve market readiness(Upper Limb Prosthetics Market Size, Trends, 2024) **.**In February 2022, Motorica LLC completed the first stage of its research on a person’s ability to sense bionic prosthetic hands by efficiently reducing patients’ phantom pain using electrostimulation. Motorica believes that the study will help them discover new treatment methods in phantom pain management.In July 2021, Stryker Corporation announced the launch of its Tornier Perform Humeral Stem as a part of its new portfolio, the Tornier Shoulder Arthroplasty

Portfolio. Stryker Corporation believes that the new product will assist the company in delivering on its mission to make healthcare better for both surgeons and patients.(Upper Limb Prosthetics Market Size, Trends, 2024)In July 2021, Össur hf announced the launch of its new Rebound Post-Op Elbow Brace. Össur believes that the brace's design will optimise the fitting experience for clinicians and improve the ease of use for patients recovering from injuries or surgical procedures.In July 2021, Coapt LLC announced the acquisition of Liberating Technologies, Inc. Coapt believes that the acquisition of Liberating Technologies will enable it to enhance its research and development capabilities and accelerate the development of new technologies in prosthetics (Paper *et al*., n.d.).

In Table **3**, various devices names are presented.

3.3. Residual Limb and 3d Printed Socket

The study by Tang *et al*. (2022) introduces an innovative approach to prosthetic socket design by using interface pressure data between the residual limb and socket to optimize fit and comfort. Through a custom adjustment function applied in a CAD environment and fabricated via selective laser sintering 3D printing, the optimized sockets significantly reduced pressure in sensitive areas-up to 85.6%-and improved walking performance and comfort for the user. This method shows promise in creating more personalized and evenly loaded prosthetic sockets compared to traditional methods (Tang *et al*., 2023).

Table 3: Various Devices that Key Market Leaders Develop(Upper Limb Prosthetics Market Size, Trends, 2024)

Product	Function	Key Player
Coapt Gen2 Controller Kit	Launches a new level of personal intuitive control, allowing the prosthesis to perform more effortlessly for patients with congenital limb difference or upper limb amputation.	Coapt LLC
Össur i-Limb Quantum	Enhances carry load, grip force, and speed boost to augment natural motion, strength, and functionality.	Össur hf
LUKE arm	Allows the user to control speed, flexion, grip, and extension.	Mobius Bionics
Motorica CYBI Hand	Makes the injured limb active, thereby strengthening the user's forearms.	Motorica LLC
GripLock Finger	Restore length, encourage bilateral hand use, and prevent metacarpal deviation.[54]	Naked Prosthetics

Figure 5: Various Devices of Upper limb prosthesis (Coapt Gen2 Controller Kit, Össur i-Limb Quantum, LUKE Arm) (Upper Limb Prosthetics Market Size, Trends, 2024).

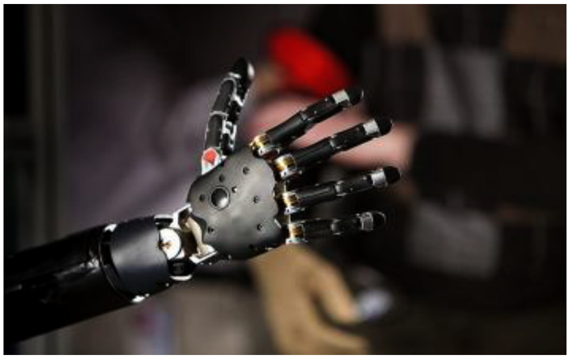

Figure 6: The Johns Hopkins Applied Physics Laboratory (JH APL) modular prosthetic limb (MPL) (Roche et al., 2014).

3.3.1. MATERIALS/METHODS FOR 3D PRINTED SOCKETS AND ACCESSORIES

Materials

The primary materialsis used in the fabrication of 3D printed prosthetic sockets including thermoplastics such as Polylactic Acid (PLA) and Thermoplastic Polyester (TPE). PLA is widely used due to its biodegradability and ease of use in 3D printing. It provides good strength and friction between layers, making it suitable for prosthetic sockets. TPE, while more flexible, offers better durability and comfort for patients. Both materials were selected for their properties, such as mechanical strength and ease of processing in fused deposition modeling (FDM) technology (Farah *et al*., 2023).

From a sustainability perspective, PLA is biodegradable and derived from renewable resources, making it environmentally favorable for prosthetic fabrication, while TPE offers durability and reusability that extend prosthesis lifespan and reduce material replacement. Compared to traditional laminated composites and metals, these thermoplastics enable recyclable and low-waste manufacturing.

Design Process

CAD software carries the design of the prosthetic sockets, with the process beginning with a 3D scan of the patient's residual limb. The scanned data is then processed to create a digital model of the socket, which is optimized for fit and comfort. The design parameters for the socket, such as thickness, diameter, and layer height, are adjusted based on patient-specific measurements (Górski *et al*., 2021).

3D Printing Process

Fused deposition modeling (FDM) technology is used to manufacture the prosthetic sockets. In FDM, the material is extruded layer by layer to build up the prosthetic structure. PLA and TPE filaments, available in 1.75 mm diameter, are fed into a 3D printer with a dual extruder setup. The typical printing process is involved selecting specific printing parameters such as nozzle temperature, bed temperature, and print speed. For PLA, the extrusion temperature ranges from 190°C to 220°C, while TPE requires a slightly higher temperature around 235°C (Cabrera *et al*., 2022).

The sockets are printed in a vertical orientation to enhance accuracy and ease of post-processing. The infill density, layer thickness, and print speed are performed to balance the structural integrity of the socket with its comfort and weight [63].

Post-Processing

After printing, basic post-processing methods are applied to develop the surface finish and improve the mechanical properties. These include the removal of su-pport structures, surface smoothing using sand-paper, and the application of resin coatings for reinforcement cause reinforcement materials like carbon fiber, carbon-Kevlar, and fiberglass used to enhance the mechanical strength of the printed sockets. The epoxy resin is used to ensure a durable, smooth surface [63].

Mechanical Testing

The mechanical properties of the printed prosthetic sockets are evaluated through both destructive and non-destructive testing. Tensile and compression tests are performed to assess strength and durability, while surface roughness is measured to ensure patient comfort. The results of these tests guide the optimization of the materials and design parameters to ensure the best fit and performance for the user (Lestari *et al*., 2024).

These steps together form a comprehensive approach to producing customized, functional, and cost-effective 3D printed prosthetic sockets. Further improvements in material technology and post-processing methods are expected to enhance the performance and applicability of 3D printed prosthetics in clinical settings.

Recommendation 1: Consideration of the static and dynamic pressure distribution within the residual limb and socket is essential for ensuring patient comfort, functionality, and well-being**.**

Recommendation 2: Total surface bearing sockets are recommended as they help decrease fitting times and enable higher activity levels, enhancing the overall usability of the prosthesis**.**

Recommendation 3: Compared to traditional foam-based interfaces, viscoelastic interface liners are recommended as they decrease dependency on walking aids, improve suspension and load distribution, reduce pain, and increase comfort for the user.

Recommendation 4: Among the modern suspension options, Vacuum Assisted Suspension (VAS) sockets are indicated to allow the least amount of pistoning within the socket, followed by suction suspension, and then pin-lock suspension.

3.3.2. Sensing Technologies For Socket

Various sensing systems have been described that play a vital role for sockets and their accessoriesfor upper limb prosthesis in this section. This table **4** focuses on the central role of sensing systems incorporated in the prosthetic sockets.

4. CONTROL, SENSORS, AND MACHINE LEARNING ALGORITHMS EMPLOYED IN UPPER LIMB PROSTHESIS

Controlling methods, techniques and strategies have been elaborated in this section focusing the nature of work, controlling strategy and main outcomes.

4.1. Controlling Strategies for Upper Limb Prosthesis

Table **4** presents a comparative review of various control strategies employed in upper limb prostheses, emphasizing the diversity of approaches in terms of functionality, input method, and user outcomes. The most widely appropriated method is myoelectric control, which utilizes surface electromyographic (sEMG) signals from the user's residual limb muscles to interpret motor purpose. While this approach is non-invasive and relatively effective, several studies noted limitations such as signal noise, muscle fatigue, and lack of sensory feedback, which affect precision and long-term usability.

Table4: Control Strategies for Lower Limb Prosthesis

File Name	Nature of Work	Control Strategy	Outcomes
[65]	Market Analysis of Limb Prosthetics	Myoelectric, Cable Operated	Market growth, technological advancements, reimbursement limitations
[66]	Canadian Cancer Statistics	N/A	Cancer statistics, mortality, survival data
[67]	Review of Pediatric Upper Limb Prostheses	Body-Powered, Myoelectric	Psychosocial and physical functioning assessment of prostheses
[68]	Development of Cycling Prosthesis for Upper Limb Amputees	Clamping, Sliding Mechanism for Cycling	Prosthesis prototype enables cycling, stability under controlled conditions
[69]	Functional Assessment of Current Upper Limb Prostheses	Myoelectric Control, Body-Powered Solutions	Performance analysis of prosthetics, functional tasks completion
[70]	Wearable sEMG Sensor for Upper Limb Prosthetics	sEMG Sensor	Low-cost solution for prosthesis control, wearable sensor
[52]	Review of Upper Limb Prosthetic Options and Design	Myoelectric, Body-Powered	Comprehensive review of current prosthetic design trends
[71]	Biomechanics of Control in Upper-Extremity Prostheses	Biomechanical control using mechanical devices amplifying remaining resources	Enhanced performance through biomechanical integration and device positioning
[72]	Control Strategy for Upper Limb Robotic Rehabilitation with a Dual Robot System	Cooperative control using 6-DOF model for safe robotic assistance during rehabilitation	Improved rehabilitation outcomes through coordinated robotic movement assistance
[73]	New Control Strategies for Neuroprosthetic Systems	Feedforward, feedback, and adaptive control strategies for neuroprostheses	Successful adaptation of control systems for customized neuroprosthesis operation
[74]	Control Strategies for Functional Upper Limb Prostheses	Electromyographic (EMG) control using machine learning approaches	Improved prosthesis function with machine learning-based control for multi-DOF limbs
[75]	Neural Machine Interfaces for Controlling Multifunctional Powered Upper-Limb Prostheses	Electromyographic (EMG) interfaces and peripheral nerve interfaces	Introduction of multi-site EMG control for more natural prosthetic control
[76]	Control Strategies and Performance Assessment of Upper-Limb TMR Prostheses	Myoelectric control strategies and performance assessment for Targeted Muscle Reinnervation (TMR)	Evaluated and improved performance of prostheses with TMR-based control strategies
[77]	Trajectory Control: An Effective Strategy for Controlling Multi-DOF Upper Limb Prosthetic Devices	Trajectory control using pre-defined motion paths for multi-DOF prosthetic devices	Demonstrated improved user experience through more intuitive control with reduced cognitive load

To improve control performance, more advanced strategies like pattern recognition and machine learning have been introduced. These allow for simultaneous and proportional control of multiple degrees of freedom (DoFs), enabling more natural and complex hand and wrist movements. Some systems also incorporate adaptive algorithms that adjust to the user's muscle patterns over time, improving robustness and personalization.

High-resolution input directly from nerves or brain signals are offered by neural interfaces such as Targeted Muscle Reinnervation (TMR) and electrocorticography (ECoG). These strategies aim to bridge the gap between cognitive intent and prosthetic action more directly, though they are still largely in the experimental phase due to their invasiveness and complexity.

Other studies included in the table focus on trajectory-based and finite-state machine controls. These simplify the user experience by limiting movement options to predefined paths or states, improving ease of use and reducing cognitive load, though at the cost of flexibility.

In summary, Table **4** highlights a spectrum of control methodologies, each with specific advantages and limitations. The choice of control strategy often depends on the user's level of amputation, available muscle sites, cognitive ability, and the desired balance between control complexity and functional versatility.

4.2. Role of Sensors and Instrumentation In Upper Limb Prosthesis

This section covers an effort done regarding the use of different sensors and their instrumentation characteristics achieved by different people. Accuracy, precision, threshold, etc. have been discussed. This section also determines the trends for the use of sensors in lower limb prostheses.

Emg Based Work For Upper Limb Prosthesis

Electromyographic Surface Signals (sEMG)

Weichao Guo *et al*. stated that surface electromyography (sEMG) has been widely used as a control method for upper-limb prostheses because it can capture muscle activation patterns during intended movement. The authors emphasize that while sEMG can achieve high offline classification accuracy (over 95% for certain wrist and hand motions), its online control performance often falls short, especially in real-time applications. They discuss limitations such as the scarcity of viable muscle sites in amputees and increased complexity when adding more EMG sensors. The paper proposes a hybrid control interface by combining sEMG with near-infrared spectroscopy (NIRS) to improve classification accuracy and reduce signal ambiguity, particularly for transradial amputees. sEMG is acknowledged as a vital but imperfect source of motor intent, prompting the need for multimodal approaches (Guo *et al*., 2017).

Jiaxin Ma *et al*. stated that surface electromyography (sEMG) is used to map muscular activities into prosthetic control movements based on the theory of muscle synergy. The authors implemented non-negative matrix factorization (NMF) to extract synergy patterns from sEMG signals and used them to control four different hand and wrist movements, open, close, pronate, and supinate. This method aimed to reduce the number of required sEMG channels and enable proportional, simultaneous control of multiple degrees of freedom (DOFs). They highlighted the advantage of sEMG in capturing subtle neuromuscular signals but also pointed out challenges like crosstalk and noisy outputs, which they addressed through a smoothing control algorithm to stabilize the prosthetic actions (Ma *et al*., 2015).

Marco Controzzi *et al*. stated that sEMG was central to the development of their dexterous prosthetic hand, the SSSA-MyHand. The authors integrated a myoelectric control system that uses sEMG signals from the residual limb muscles to provide intuitive and proportional control of the hand prosthesis. They emphasized that the use of sEMG allows users to command multiple grip patterns and perform complex hand gestures. The system employed conventional sEMG signal processing techniques to trigger mechanical actuators in real time, demonstrating reliable performance across different daily activities. The paper reflects confidence in sEMG's ability to serve as a robust control input, provided sufficient signal quality and muscle isolation can be maintained (Controzzi *et al*., 2017).

Andrei Ninu *et al*. stated that surface electromyography (sEMG) is the standard input method for myoelectric prostheses and is used to control grasping strength in real time. In their study, sEMG signals from the residual limb were processed to proportionally control the velocity and force of hand closure in an Otto Bock Sensor Hand prosthesis. The authors tested whether providing supplementary sensory feedback (visual or vibrotactile) could improve performance. They concluded that although sEMG allows for reasonably effective control, the absence of direct somatosensory feedback limits precision and user confidence. Nonetheless, sEMG remains a practical and non-invasive method for translating muscular intent into prosthetic movement (Ninu *et al*., 2014).

Matthew Schiefer *et al*. stated that while myoelectric prostheses are commonly controlled using sEMG signals from the residual limb, a major limitation is the lack of natural tactile feedback. They observed that individuals using sEMG-controlled prostheses rely heavily on visual or auditory cues due to the absence of true sensation. Their study explored how adding artificial sensory feedback through peripheral nerve stimulation could complement sEMG-based control. Although sEMG is essential for activating prosthetic motion, the authors stressed its inability to provide the user with tactile or proprioceptive sensation, which affects task performance and the sense of embodiment (Schiefer *et al*., 2015).

Stanisa Raspopovic *et al*. stated that sEMG signals were used to decode users' motor intentions in a bidirectional hand prosthesis system. They integrated sEMG acquisition with real-time neural feedback delivery by stimulating the median and ulnar nerves through intrafascicular electrodes. The aim was to achieve natural control over prosthetic grasping by closing the sensorimotor loop. sEMG played a critical role in enabling real-time decoding of different grasp types, which triggered proportional nerve stimulation. However, they noted a challenge when using sEMG in targeted muscle reinnervation (TMR) scenarios, where both control and feedback share the same anatomical site, leading to potential sensory gating conflicts (Raspopovic *et al*.).

William D. Memberg *et al*. stated that sEMG was part of a broader neuroprosthetic system designed to restore function in individuals with high-level tetraplegia. Although the primary method of stimulation involved implanted electrodes, the system included sEMG channels to capture voluntary muscle contractions from available upper body muscles, such as the trapezius and neck muscles. These sEMG inputs were used to trigger specific hand and arm movements through a functional electrical stimulation (FES) system. The paper demonstrates how sEMG can be effectively integrated into complex assistive systems when deeper or more invasive signals are either unavailable or need to be supplemented (Memberg *et al*., 2014).

Lauren H. Smith *et al*. statedthat their study used intramuscular EMG rather than traditional surface EMG, but they highlighted the shortcomings of sEMG as a motivating factor. They noted that surface EMG is limited by signal crosstalk and cannot reliably isolate signals from deep muscles, which restricts the ability to control multiple degrees of freedom (DOFs) simultaneously. By contrast, intramuscular EMG provided clearer, less contaminated signals, enabling better simultaneous and proportional control of wrist and hand motions. Thus, while sEMG has been foundational in prosthetic control, its limitations prompted exploration of more precise alternatives (Smith *et al*., 2014).

Aaron J. Young *et al*. stated that surface EMG remains a conventional method for controlling myoelectric prostheses, typically using amplitude thresholds from antagonistic muscle pairs. However, they argued that this approach is inadequate for simultaneous multi-DOF control due to crosstalk and the limited number of independent muscle signals available. Their study contrasted conventional sEMG control with pattern recognition-based systems and showed that when users were allowed to train simultaneous movement classes, performance improved. Nonetheless, they acknowledged that sEMG is a flexible and non-invasive interface that continues to play a significant role in prosthesis control strategies (Young *et al*., 2014).

Ortiz-Catalan, Håkansson, and Brånemark statedthat surface electromyography (sEMG), referred to as myoelectric signals (MES) in their paper, is a primary input modality for predicting hand and wrist movements in prosthetic control. The authors emphasized that the remaining muscles in an amputee's stump can produce reliable sEMG signals that reflect intended motion. They utilized eight pairs of Ag/AgCl electrodes placed around the forearm to capture these signals in a bipolar configuration. sEMG was used exclusively-without additional sensors like force transducers or motion capture systems-to drive an artificial neural network classifier. The classifier aimed to predict up to three degrees of freedom (DoFs) in simultaneous movements. This approach allowed the system to decode combinations of movements such as wrist rotation and hand opening at the same time, using only surface sEMG features extracted from

200 ms time windows. The paper also acknowledged challenges like false positives during mixed motion classification, and introduced variable threshold outputs in the ANN to address these issues in real-time prosthesis control [87].

Dalley, Varol, and Goldfarb stated that surface electromyographic (sEMG) signals are the basis for their novel finite-state machine (FSM) approach to control multigrasp prosthetic hands. Their method interprets sEMG from two bipolar electrodes placed on antagonistic forearm muscles, typically the flexor and extensor groups, and uses these signals to detect user intent through threshold crossing events. By mapping sEMG amplitude transitions to discrete prosthetic states (such as open hand, grasp, or pinch), the FSM can execute transitions between multiple grasp types using only simple sEMG input. The authors argue that sEMG provides a low-cost, widely available method for detecting muscular intention, even with only two channels. However, they also noted that conventional amplitude-based sEMG control is limited in supporting proportional or simultaneous control, which is why they designed their FSM to maximize functionality within the limitations of sEMG-based switching (Dalley *et al.*, 2012).

Gijsberts, Bohra, Sierra González, and Caputo stated that sEMG signals are widely used for intuitive control of prostheses, but their performance can degrade over time due to electrode shift, muscle fatigue, or changes in skin condition. In their study, they tackled the problem of domain shift in sEMG signals, which can negatively affect classification accuracy. Using a large dataset of sEMG signals recorded from 12 subjects over several days, they demonstrated that real-time prosthetic control using sEMG can benefit significantly from adaptive learning algorithms. sEMG signals were collected from 10 channels around the forearm, processed with a variety of feature extraction techniques, and fed into a machine learning framework to classify hand gestures. Their work enhances the value of sEMG as a high-resolution yet non-invasive control input, while also highlighting its sensitivity to signal variability and the need for robust algorithms to maintain performance over time (Vidovic *et al.*, 2016).

Implanted Electromyographic (iEMG)

Cipriani *et al*. stated that executed EMG (iEMG) signals were used to achieve reliable and automatic control in their bidirectional prosthetic hand system. iEMG was acquired from intramuscular electrodes, enabling high-fidelity, stable signals with minimal crosstalk. This allowed users to execute proportional commands for multiple grasp types while receiving sensory feedback through neural stimulation. The use of iEMG ensured robust control unaffected by external disturbances or electrode shifts, focusing its advantage over surface EMG for long-term, real-life prosthesis use (Cipriani *et al*., 2014).

Pasquina *et al*. stated that iEMG offers superior stability and signal quality for controlling advanced prosthetics in comparison to surface EMG. Their study evaluated long-term usability of implanted electrodes and found iEMG to be more resilient to artifacts caused by limb movement and electrode displacement. iEMG signals enabled consistent multi-function control and better classification accuracy across multiple sessions, making them ideal for daily prosthetic applications, especially when high reliability is critical (Pasquina *et al*., 2015).

Mastinu *et al*. stated that iEMG signals obtained via osseointegrated implants were central to their system for intuitive prosthetic control. The implanted electrodes recorded muscle activity from within the residual limb, offering high-resolution, low-noise signals. This setup supported real-time pattern recognition for natural limb movement and was integrated into a wearable controller that allowed robust, long-term, closed-loop prosthesis operation. Their work emphasized iEMG's clinical viability for stable and seamless neuroprosthetic interfaces (Mastinu *et al*., 2017).

ECoG

Matthew S. Fifer *et al*. stated that electrocorticography (ECoG) provides high-resolution neural recordings suitable for decoding intended finger movements in individuals with paralysis. Their study showed that high-frequency ECoG signals, particularly in the gamma band, could accurately classify attempted movements using real-time classifiers. They emphasized ECoG’s stability, signal quality, and suitability for long-term brain-computer interface (BCI) applications (Fifer *et al*., 2014).

4.3 Psycho-Social Impact of Lower Limb Prosthetic Users

Upper limb prosthetic users often face significant psycho-social challenges that go beyond physical disability. The loss of a limb can lead to diminished self-esteem, body image issues, and emotional distress such as anxiety, depression, or social withdrawal. Prosthesis use can restore a sense of normalcy, independence, and functional identity, positively influencing psychological well-being. However, limitations in prosthetic functionality, discomfort, and stigma may hinder social integration and user satisfaction. Peer support, counseling, and user-centered prosthetic design are essential for enhancing emotional resilience and improving overall quality of life.

4.3.1. Qol, Satisfaction and Psycho-Social Adjustment

Quality of Life (QoL)

In a study of 30 myoelectric prosthesis users, QoL measured by SF-36 Özcan *et al*. (2022) showed that older age correlated with greater physical role limitations. Psychosocial adjustment,as measured by TAPES-R,was moderately associated with daily prosthesis wear time.

Adaptation to upper-limb prosthesis was high in general and social adjustment, but poorer in adjustment to limitations. Overall QoL not directly measured but inferred from these TAPES outcomes (Šosterič *et al*., 2020).

Egyptian study, Abdel-Shebl & Mohammed (2018**)** stated that Among adults with prosthetic limbs (upper and lower), over half had poor physical and psychological QoL. Prosthesis type and user knowledge significantly affected QoL (Agamy *et al*., 2018).

Systematic reviews showed that QoL is negatively impacted across emotional, physical, and social domains; body image and satisfaction strongly predict higher QoL (Agamy *et al*., 2018).

Satisfaction with Prosthesis

Šosterič *et al*. (2020) statesthat average overall satisfaction scored around 7/10. Aesthetic satisfaction exceeded functional satisfaction. Users with longer experience and women reported higher satisfaction

Özcan *et al*. (2022) presented that **s**atisfaction assessed via TAPES-R, though detailed subscale scores not specified; psychosocial adjustment correlated with higher satisfaction indirectly (Šosterič *et al*., 2020).

Psychosocial Adjustment

Özcan *et al*. (2022) presented that TAPES-R psychosocial adjustment had a moderate positive correlation with daily prosthesis wear time (r = 0.425, p = 0.019). Šosterič *et al*. (2020) protraited in his studies thatgeneral and social adjustment scores were high among long-term users; adjustment to limitations was lower. Long duration with prosthesis predicted better psychosocial adaptation. Desmond & Gallagher (review on lower-limb, but applicable) stated that time since amputation, social support, satisfaction with prosthesis, and lower pain levels are associated with better psychosocial adjustment; depression and anxiety decline after two years post-amputation

5. DESIGN TRENDS IN PATENTS FOR UPPER LIMB PROSTHESIS

There are several notable patents in the field of upper-limb prosthetics that focus on improving the functionality, comfort, and usability of prosthetic devices. One such patent, **WO2020081914A1**, presents a hybrid-drive modular upper-limb prosthesis that combines body-powered and electronically-driven actuation. This design allows for modular components that can be swapped, depending on the user's needs, and includes 3D printing technology to make prostheses more affordable and customizable. The prosthesis includes modular links that control different degrees of freedom in the prosthetic arm, enhancing the user's ability to perform various tasks with ease [97].

Another important patent, **US6361570B1**, highlights providing an Endo skeletal upper-limb prosthesis with pivoting wrist, elbow, and shoulder joints. A worm gear and motor system controls these joints which enables smooth and precise articulation of the prosthetic limbs. This technology ensures the prosthesis is lightweight, durable, and capable of providing natural movement for the usermaking it easier to perform complex motions like grasping or reaching.

The patent **US8414658B2** label the issue of fitness and comfort by offering an anatomically arranged adjustable prosthetic device. The design incorporates adjustable cuffs and forearm sections, which allows the users with below-elbow amputations to have a customizable fit. This feature improves both the comfort and functionality of the device, making it easier for users to wear their prosthetic limbs for extended periods.

Another significant patent, **US11779473**, presents a powered prosthetic flexion device. This device provides powered wrist or elbow flexion, which assists users in orienting and positioning grasped objects. This functionality not only improves the user's ability to manipulate objects but also contributes to the overall ease of use and effectiveness of the prosthetic limb [98].

In addition, the patent **US10610385** introduces a multi-modal myoelectric control system that uses myoelectric signals to switch between different operating modes. This allows for intuitive and adaptive control of prosthetic functions, improving the user experience by providing more responsive and customizable control options.

Moreover, CN111568614A details a modular multi-degree-of-freedom prosthetic limb, which allows for complex movements across various joints, such as the shoulder, elbow, and wrist. The modular design makes the prosthetic flexible and adaptable to the user's unique needs, improving overall functionality and comfort.

Finally, **US20100082116A1** discusses an adjustable prosthetic device for below-elbow amputees. The design focuses on providing a more personalized and secure fit by incorporating adjustable components. This ensures that users experience greater comfort while using the prosthetic, contributing to better overall satisfaction and higher wear time.

These patents reflect ongoing efforts to enhance the design and functionality of upper-limb prostheses, improving both the physical and emotional well-being of users by offering greater comfort, adaptability, and control.

6. CHALLENGES AND FUTURE PROSPECTS

Promising developments in the eld of upper limb prostheses allowed the experts to be optimistic about the future. This section shows the future challenges and prospects in the area of lower limb prosthesis for the stakeholders like researchers, producers, organizations, pharmaceutics, surveyors and trend analyzers, etc.

6.1. CHALLENGES IN UPPER LIMB PROSTHESIS

Upper-limb prostheses face significant challenges in terms of functionality, control, and user satisfaction. Despite advancements in prosthetic technology, issues such as limited dexterity, discomfort from poor fit, and high abandonment rates persist due to factors like inadequate control over multiple degrees of freedom, lack of sensory feedback, and difficulty in adapting to the devices

Table 5: Challenges In Upper Limb Prosthesis

Challenges	Description
Lack of Dexterity and Control	Despite advances in prosthetic technologies, most prostheses still struggle with providing natural and coordinated control of multiple joints. Many devices do not allow for simultaneous control of multiple degrees of freedom, which affects usability.[99]
Functional Limitations	Many prostheses are limited in terms of function, providing only basic movements such as hand open/close, elbow flexion/extension, or forearm pronation/supination. This can hinder their effectiveness in real-world tasks. [99]
Comfort and fit	Ill-fitting prosthetics can cause discomfort, pressure on the residual limb, and dermatologic issues such as contact dermatitis. There is also a risk of excessive sweating and pain from poorly designed sockets.
Durability	Prosthetic devices often face durability issues, particularly with materials such as dielectric elastomers, which suffer from poor durability, susceptibility to contaminants, and high energy consumption. [100]
Sensory Feedback	The lack of tactile or sensory feedback from prosthetic devices remains a significant challenge. Users struggle to perform tasks that require force sensing or delicate movements.
High Cost	The high cost of advanced prosthetic systems (ranging from $20,000 to $100,000) limits their accessibility, especially for individuals in lower income brackets.[101]
Training and Adaptation	The learning curve for users, especially with myoelectric and pattern recognition-based devices, is steep. Users need to learn how to use muscle contractions effectively, which can be tiring and unintuitive.
Reliability and Control Mechanisms	Some prosthetics are not reliable under dynamic real-world conditions. Issues such as noise in signals, variability in muscle contraction force, and subject mobility can reduce control accuracy.
Power Consumption and Energy Needs	Many advanced prosthetics, especially those with actuators and myoelectric systems, require significant power, which can make them bulky, reduce battery life, and increase the weight of the device.

6.2. Discussions and Future Prospects for Upper Limb Prosthesis

The development of upper limb prostheses has witnessed remarkable strides, primarily driven by the convergence of 3D printing, biosensors, advanced control algorithms, and user-centric designs. These innovations have allowed for significant improvements in comfort, functionality, and accessibility, especially in resource-constrained environments. However, numerous challenges persist that require interdisciplinary focus and innovation.

Integration of Smart Technologies

Future prosthetic systems are expected to become more intelligent, adaptive, and user-aware. The use of embedded sensors such as EMG, IMUs, and pressure sensors, combined with machine learning algorithms, is paving the way for prosthetics that can adapt in real time to the user's movement intentions. A key frontier lies in developing robust signal interpretation mechanisms that can differentiate between nuanced gestures while minimizing noise and fatigue-related inaccuracies.

Toward Bi-directional Control and Sensory Feedback:

Current systems still fall short in replicating the sensory loop that allows humans to perceive touch, pressure, or temperature. The next generation of upper limb prostheses must integrate somatosensory feedback via haptic technologies or neural stimulation. Emerging approaches using implanted electrodes or non-invasive stimulation (e.g., vibrotactile feedback) hold promise in restoring partial sensation and improving task precision and embodiment.

Custom Socket and Residual Limb Interface:

One of the greatest contributors to prosthetic rejection is discomfort at the socket-residual limb interface. Future designs will likely incorporate pressure-distribution optimization using AI-enhanced CAD tools and 3D scanning. Materials such as TPE and viscoelastic liners, paired with adaptive socket mechanisms like Vacuum-Assisted Suspension (VAS), will enhance comfort, reduce skin breakdown, and improve suspension.

Energy Efficiency and Miniaturization

The high-power demands of multi-DOF systems hinder daily usage due to limited battery life and bulky form factors. Research into low-energy actuators, such as dielectric elastomer actuators or bioinspired soft robotics, will help develop lighter and more energy-efficient limbs. Wireless charging and solar-integrated solutions may also extend usage periods without compromising form.

Affordable Mass Customization

3D printing has drastically reduced the cost barrier, enabling open-source, modular, and pediatric-specific prosthetic solutions under $500. Going forward, widespread deployment in low-income regions will require regulatory frameworks, quality assurance, and scalable manufacturing ecosystems. Integration of AI into design automation, especially for growing children, will be instrumental.

Neural Interfaces and Brain-Machine Integration

Long-term prospects include direct cortical control via ECoG or BCI (brain-computer interface), enabling high-speed, intuitive control. Although still largely experimental, these systems aim to restore complete motor function, especially for high-level amputations. The integration of neuroplastic training tools and wearable EEG-based interfaces will further close the gap between thought and action.

Psychosocial and Rehabilitation Outcomes

Functional capability alone does not guarantee quality of life. Future prosthesis designs should account for aesthetics, ease of learning, and user empowerment. Peer-led training, virtual rehabilitation environments, and gamified learning tools can improve user satisfaction and reduce abandonment rates. Also, longitudinal studies are needed to assess how prosthetic adoption affects mental health, social reintegration, and occupational return.

Policy, Accessibility, and Reimbursement Models

Sustainable adoption of prosthetic innovations requires policy-level support. Public-private partnerships, government-backed reimbursement schemes, and local manufacturing incentives can dramatically expand access. AI-powered tele-rehabilitation and prosthetic fitting tools can further bridge the urban-rural care gap.

In summary, the future of upper limb prosthetics lies at the intersection of intelligent control systems, biofeedback integration, personalized fit, and affordability. While technical barriers remain in areas such as signal stability, power management, and sensory restoration, the collaborative progress of biomedical engineering, materials science, AI, and social policy can revolutionize the quality of life for millions of amputees. It is only through this interdisciplinary and inclusive lens that the vision of truly smart, accessible, and human-centered prosthetics can be realized.

7. CONCLUSION AND FUTURE WORK

The integration of 3D printing with advanced sensing, control, and design techniques marks a transformative step in the development of upper limb prosthetics. This review has systematically explored the multidimensional progress in prosthetic research, from the epidemiology and etiology of upper limb amputation to the innovative strides made in socket design, control strategies, sensor integration, and material customization. By enabling cost-effective, anatomically accurate, and patient-specific solutions, additive manufacturing has not only lowered economic barriers but also introduced a new era of accessible prosthetic technology, particularly in resource-limited and pediatric contexts.

Despite these promising developments, key challenges remain unresolved. Functional limitations in dexterity, lack of natural sensory feedback, high power consumption, discomfort at the socket interface, and affordability continue to hinder wide-scale adoption and long-term satisfaction. Additionally, the steep learning curve associated with controlling myoelectric or pattern recognition-based systems further restricts usability for many patients.

Future work must emphasize the convergence of interdisciplinary fields, robotics, materials science, machine learning, and neuroscience, to build prosthetic limbs that are not only functionally capable but also intuitive, energy-efficient, and emotionally supportive. Key directions include:

- **Development of bidirectional prostheses** that combine sEMG/iEMG control with real-time neural or haptic feedback for more natural motor-sensory integration.

- **Advancements in socket design** using AI-assisted modeling, adaptive materials, and pressure-distribution mapping to improve user comfort and reduce abandonment rates.

- **Power-efficient actuation systems**, such as soft robotics and gyroscopic drives, that offer low-energy operation with high torque-to-weight ratios.

- **Wider deployment of open-source platforms** and localized 3D-printing solutions to ensure global accessibility, especially in low-resource settings.

- **Clinical validation and user-centric trials** to evaluate long-term outcomes, psychosocial adjustment, and quality-of-life improvements from next-generation prosthetics.

In conclusion, the future of upper limb prosthetics is poised to shift from assistive devices to intelligent, integrated systems that restore autonomy and dignity to users. Continued collaboration among engineers, clinicians, policymakers, and users will be vital in translating technological advancements into meaningful, scalable, and sustainable prosthetic care.

Future research should emphasize sustainable prosthetic design through recyclable materials, modular components for repair and reuse, and energy-aware control systems aligned with circular economy principles.

Ethical Statement

According to the authors, this study was carried out in compliance with ethical standards and directives. The study did not include any sensitive personal information, animals, or human subjects. No external datasets with privacy concerns were used; all data were created or gathered specifically for this study. The writers made sure that all contributors and cited works received the proper credit and that the research, analysis, and reporting were done in an open and truthful manner.

The results of this study were not impacted by outside funding sources, and there are no conflicts of interest to disclose. The authors are committed to promoting the accessibility and usability of the outcomes of this work for the benefit of individuals with hearing and speech impairments, aligning with the goal of social inclusion.

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CONFLICT OF INTEREST

No conflicts of interest are disclosed by the writers. The investigation was carried out independently, and its design, implementation, and reporting were unaffected by any financial, professional, or personal ties. The writers' objective research efforts are reflected in the findings and conclusions in this study.

CONSENT TO PARTICIPATE

All participants involved in this study provided informed consent prior to their inclusion. The objectives, procedures, potential risks, and benefits of the study were clearly explained to each participant, and participation was entirely voluntary. Participants were assured that their data would be kept confidential and used solely for research purposes.

CONSENT TO PUBLISH

The authors affirm that all participants have provided their consent for the publication of anonymized data and findings derived from this study. No identifying information of participants is disclosed in this manuscript.

AUTHORS CONTRIBUTION

Hrittik Muralconceptualized the study; conducted the literature search and screening; performed data extraction, analysis, and interpretation; drafted andImtiaz Ahmed Choudhury, Md. Ragib Abid, Sajal Chandra Banik revised the manuscript; and approved the final version for submission.

Hrittik Mural is the corresponding author and handled all reviews and corrections.

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