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Review Article

A Methodical Approach for Comprehensive Analysis of Prosthetic Hand Designs

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***Abstract** - This paper presents a methodical approach to comprehensively analysing prosthetic hand designs over the past 20 years. The survey begins by examining prosthetic arm designs, highlighting the shift from basic mechanical structures to more sophisticated myoelectric systems, which were seen in around 55% of the systems, neuroprosthetic systems, which were preferred by 18% of researchers and other systems like EMG, Eye controlled systems and such which constitute 27%. Design approaches for improving the properties of the arm, such as the weight and utility of prosthetic arms, are discussed along with the integration of sensory feedback mechanisms. Functional aspects of prosthetic arms are explored in depth, including gripper and control capabilities. The survey covers the types of amputations, broadly Upper Limb Prostheses. Details regarding the design used for a prosthetic arm, the actuators used in the industry, the control for the arm, materials used and torque analysis for each type of amputation are studied thoroughly. It provides a methodical approach and direction for further improvement in the design and addressing identified challenges. The paper comprehensively reviews occupational activities made possible with the use of well-designed assistive aids. Propelling the field forward and addressing its challenges are the key themes of this article, which examines promising emerging technologies and research efforts.*

***Keywords** - Myoelectric systems, Neuroprosthetic systems, Prosthetic arm, Robotic hand design, Torque analysis.*

1. Introduction

In the past two decades, the field of prosthesis has seen a significant development toward a more functional and comfortable solution to amputation. This survey paper discusses a meticulous study of 135 papers published over the last 20 years in reputable journals, discussing the various methods of arms control, materials used, torque analysis, and such things for the system. The loss of a limb profoundly affects a person's self-dependency and way of life, making the development of effective prosthetic solutions a crucial endeavor [1]. Researchers, engineers, and clinicians have dedicated their efforts to creating innovative designs that mimic the intricate movements and dexterity of a natural arm [2]. Due to the latest innovations in material science, robotics, and neuroscience, prosthetic arm designs have evolved significantly to address the unique needs of individuals with upper limb loss [3]. The advancement of prosthetic arm technology has significantly improved the quality of life for individuals with upper-limb amputations. Over the past decade, myoelectric prosthetic arms have emerged as a promising alternative due to their ability to interpret electrical signals from residual muscles, providing users with intuitive control. However, despite considerable progress, challenges such as high costs, limited dexterity, and reliability issues persist. This paper reviews myoelectric prosthetic arm designs developed between 2011 and 2025, analyzing key advancements, limitations, and future research directions.

This literature survey explores a wide range of topics related to prosthetic arm designs, functionality, and utility. It delves into the advancements in actuators in industry, control methods, etc., which play a critical role in ensuring comfort and optimal control. The integration of advanced sensor technologies and machine learning algorithms is also examined, highlighting how these innovations have revolutionized prosthetic arms' intuitive control and responsiveness [4]. This survey discusses the types of amputation and how these make an impact on the design of a prosthetic arm. This study finally aims to come up with a state-of-the-art system for prosthetic arms and suggest methods for improvement in existing systems. The novelty of this study is the combination of the analysis of the amputee's needs with the study of existing solutions. This work is based on the literature review of innovations in prosthetic development as well as actual need analysis of the amputee persons. The study aims to gain a comprehensive understanding of the needs and obstacles encountered by individuals with limb loss and analyze the existing prosthetic aids. The criteria for selecting amputee subjects under study and the literature papers are elaborated on below. To analyze the needs of amputee people, a consent form and structured questionnaire were prepared to collect data from 121 adult participants aged between 21 and 50 years. Participants were provided information regarding the survey's objectives, their rights, and the confidentiality measures in place. They were informed of their option to withdraw at any stage. Confidentiality was ensured, and their responses were used solely for research purposes. Their active involvement greatly contributed to acquiring valuable insights for future advancements in mobility solutions. It's important to emphasize that the information presented in this study is solely based on the voluntary input of the participants, with strict adherence to ethical standards throughout the survey process. The evolution of prosthetic arm development over the last two decades is reviewed by studying 135 research papers. The selection criteria included relevance to prosthetic arm development, design innovation, and user experience improvements. The papers were selected to provide a comprehensive perspective on the state of the field. Valuable insights, future research opportunities, and beneficial information for researchers, engineers, and clinicians in the realms of rehabilitation and assistive technologies are also highlighted by the study.

2. Motivation

The World Health Organization estimates that 35–40 million people worldwide have a requirement for prosthetic or orthotic services. Around 100 million people need these aids to support damaged limbs. In 2017, 57.7 million people were living with limb amputation due to traumatic causes. In 2022, the global prosthetics and orthotics market was valued at USD 6.6 billion. The expected growth rate is 4.3% from 2023 to 2030. Figure 1 shows the trends in which expenses on prostheses throughout the years have increased. With advancements in technology and materials, prosthetic arm options have expanded dramatically, making it crucial to gather insights into their diverse features [5]. Firstly, such a survey can help us understand the preferences and priorities of amputees regarding aesthetics, utility, and ease of use. It would provide valuable information on the importance of customization and the role of aesthetics in boosting users' self-esteem and quality of life. Secondly, examining functionality is vital for improving prosthetic arm designs. In pursuit of a comprehensive understanding of the experiences and challenges faced by individuals who rely on prosthetic devices, a questionnaire was circulated within the vicinity of local hospitals. By gathering firsthand accounts and insights from this diverse group of individuals, the questionnaire aimed to shed light on the intricate and often underexplored dimensions of living with prosthetic devices.

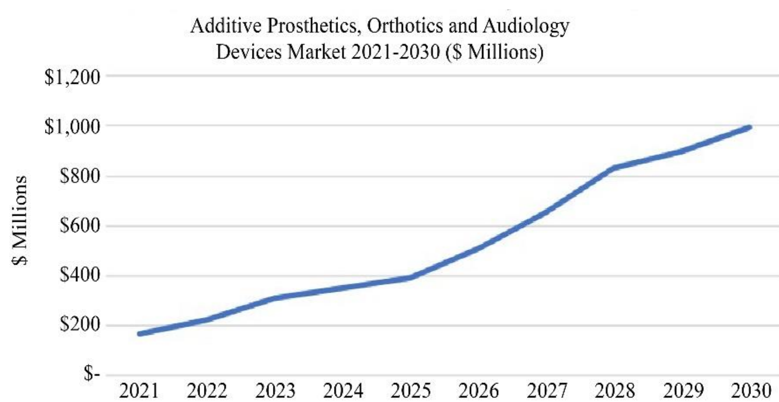

Fig. 1 Trends of expenses on prosthesis

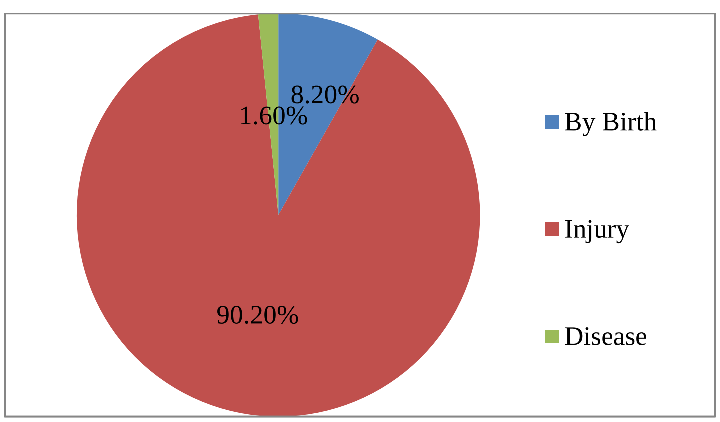

Fig. 2 Cause of disability

This research forms a crucial cornerstone in addressing the needs and aspirations of this community, contributing to a broader discourse on enhancing the quality of life and accessibility for those who rely on such assistive technologies. The results of this questionnaire are cited in the form of comparative and derivative analyses throughout the paper.

Assessing utility is essential to determine if prosthetic arms meet users' daily needs and expectations. Insights into the challenges faced in different contexts, such as work, hobbies, and daily activities, can drive innovations that enhance the overall utility of these devices. The leading causes of limb amputation, according to the questionnaire circulated, were road accidents, workplace injuries, medical amputation, electric shock and birth defects. Injury or accident is the cause of amputation in 90.2% of cases, as shown in Figure 2.

3. Technology Evolution

3.1. Types of Amputations

It is important to study different types of amputations as they greatly affect the development and design of a prosthetic. This helps understand the specific needs and challenges for different degrees of amputation and helps the designers and manufacturers create customized designs for different uses with unique use cases [6]. A survey on prosthetic arm designs, functionality, and utility is imperative to address individuals with limb loss's evolving needs and aspirations. One of the studies provides an overview of the distribution of upper and lower limb amputations, emphasizing the prevalence of upper limb amputations [7]. and the distribution of arm amputations in the United States among different age groups.

It distinguished individuals aged 21 to 64 years and those under 21 years who have experienced arm amputations, offering insights into the age-related patterns of arm amputations represented by Figure 3 [8]. Studying different types of amputations highlights specific physical and psychological challenges faced by amputees with upper limb amputations [9].

This further helps the researchers and clinicians pinpoint the pain points for each individual user and develop technologies for prosthetics accordingly [10]. This adds to the precision of the prosthetics and the utility and usability of the prosthetic.

Table 1 states the types of amputations discussed in this survey paper and their explanation [11]. The distribution of upper limb amputations by type within the group of upper limb amputees in the United States is shown in Figure 4.

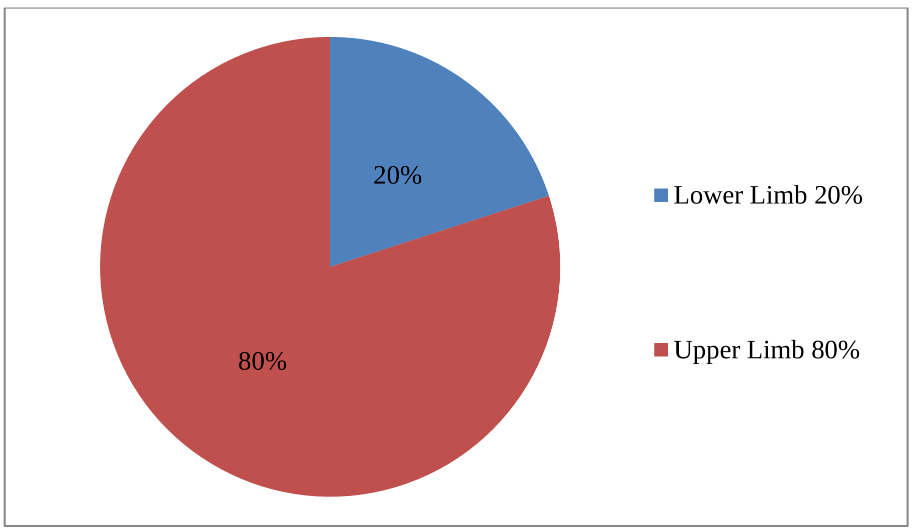

Fig. 3. Distribution of upper and lower limb

Table 1. Amputations in arm

Amputation	Description
Transradial amputation	Removal of the lower arm (forearm, wrist, hand)
Transhumeral amputation	Removal of the humerus bone (may include shoulder joint)
Shoulder disarticulation	Removal of the whole arm and shoulder joint while maintaining the integrity of the clavicle
Forequarter amputation	Removal of the collarbone, shoulder blade, and whole arm.
Wrist disarticulation	The forearm is preserved while the hand and wrist bones are removed.
Partial hand amputation	Removal of part of the hand, such as fingers, which may include a portion of the arm

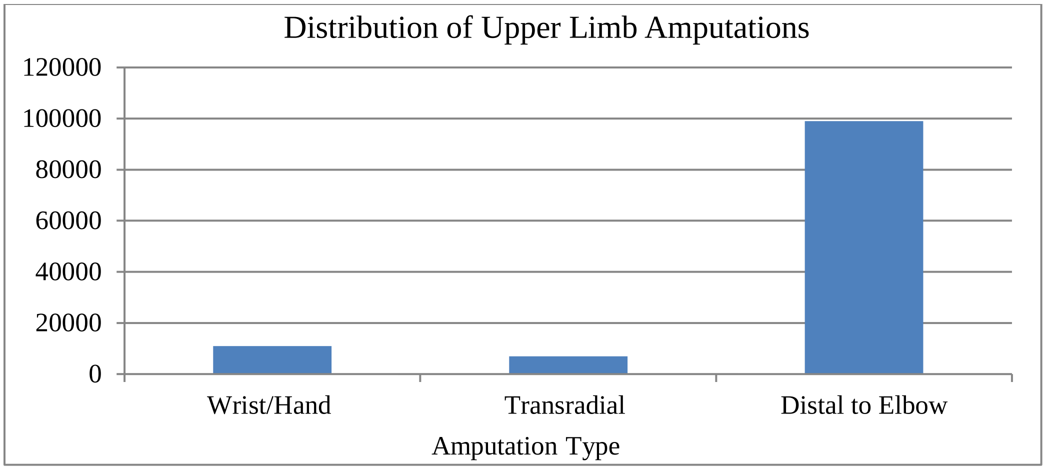

Fig. 4 Distribution of upper limb amputations

3.1.1. Transradial Amputation

In trans-radial amputation, the cut is made just below the hinge joint that joins the humerus bone to the ulna bones. The upper arm contains the humerus bone, whereas the lower arm contains the ulna. In this case, it is the radius bone and the ulna bones are the ones that end up being cut [12]. The muscles that are ultimately removed depend on the circumstances of each case, although in transradial amputations, the pronator teres and flexor carpi radialis muscles of the forearm are frequently affected [13]. The muscles from the upper arm, however, such as the biceps and triceps, are typically left intact. In the case of transradial amputation, the amount of control that the amputee has over the residual limb depends on several factors, including the degree of muscle damage, the level of amputation and the individual's unique circumstances [14]. The control the amputee retains over the residual limb is affected by where the cut is made on the forearm [15].

A distal transradial amputation refers to a cut made below the elbow joint; this leaves the forearm muscles intact. Distal transradial amputee has greater control over the residual limb as compared to proximal transradial amputation. Figure 5 depicts types of upper limb amputation and the percent of occurrence of the particular type of amputation according to the questionnaire circulated. In the case of transradial amputation, a body-powered control scheme using a cable system connected to the user using a harness worn around the shoulder [16]. The prosthetic arm's opening and closing and the wrist joint's movement may all be controlled by the user with the help of their shoulder or remaining upper arm muscles. It provides good mechanical precision and an advantage for high-force tasks. Such as lifting heavy objects or gripping tools [17]. However, it can induce fatigue in the user after extended periods of use. Muscles use electric signals induced by the brain to control movement and feedback information. These are usually referred to as EMG signals. In myoelectric control, these electric impulses can be collected using electrodes attached to residual limbs, and the user can control the prosthetic using their own muscle signals [18].

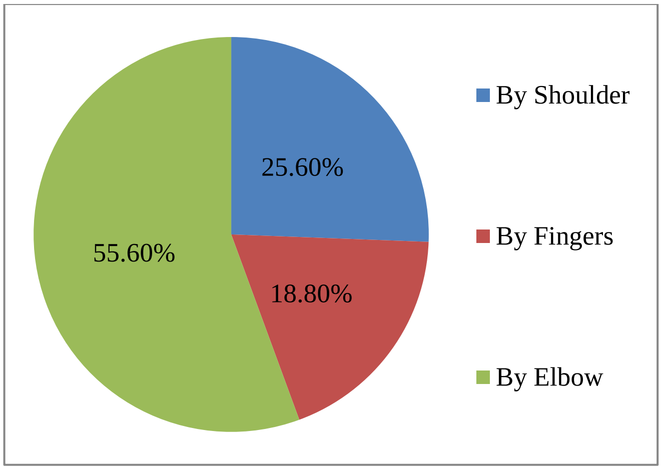

Fig. 5 Division of upper limb prosthesis

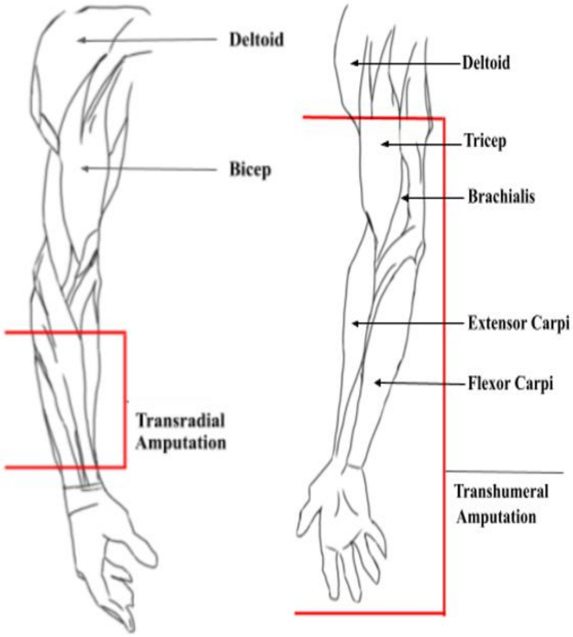

Fig. 6 Trans radial and transhumeral amputation

Typically, two to four electrodes are placed on the residual limb’s skin. On the skin of the residual limb, two to four electrodes are often positioned [19]. One possible layout for the electrodes places them over the forearm's residual flexor and extensor muscles or over the upper arm's bicep or triceps. However, This control method requires functional and intact residual muscles and may require training in prosthetic movements. In the hybrid control system, it entails using a combination of body-powered control and myoelectric control. This control system entails narrowing down the functions that the prosthetic needs to complete and then deciding the appropriate control scheme for each one of the functions in the event of a transradial amputation. Usually, a myoelectric control system is used in conjunction with a mechanical control system. The electrodes positioned over the skin of the residual limb pick up and process the electrical impulses produced by the muscles.

However, factors such as perspiration, electrical noise, and muscle exhaustion can interfere with myoelectric signals. A hybrid control system is implemented to overcome these limitations [20]. An example of a hybrid control system could be a mechanical switch for a particular function of the prosthetic, such as grasping using the hand, and a myoelectric control scheme for wrist movements, as it requires a number of controlling factors [21]. Switch control refers to a control scheme that uses switches and buttons to activate specific tasks on the prosthetic. The main advantage that switch control systems have over the other control systems is that they are simpler to implement and are usually less expensive than the other control systems. The user also needs a lesser amount of training and physical therapy to control these systems. Switch control is usually combined with some other control scheme, such as the myoelectric scheme. Different types of controls are used in switch control; one is a push button switch, which requires the user to push a lever or switch with an on-and-off state to activate a specific task or state of the prosthetic. A similar control type is a touchpad switch. These touchpads use a resistive sensor or a capacitive pad to detect the user’s touch and activate the switch.

3.1.2. TransHumeral Amputation

Transhumeral amputation involves the surgical removal of the bone above the hinge joint in the upper arm, specifically the humerus bone. The forearm muscles and ulna bones are generally left intact, though specific cases may vary, and certain muscles are compromised depending on individual circumstances [22]. In the majority of cases, the flexor and extensor muscles are intact. It gives the amputee control over vital muscles such as the pronator teres, flexor and extensor carpi radialis, and others. When critical muscle groups are preserved, the individuals undergoing transhumeral amputation retain a significant level of control and functionality in their residual arm [23]. Individuals can use control systems with the harnessing that enables them to regain a sense of independence and functionality. The amount of control that the amputee retains over the residual limb is influenced by the extent of muscle damage and the level of amputation. The location of the cut is a major factor when it comes to the amount of control that the amputee retains. A distal transhumeral amputation refers to the cut being made closer to the elbow joint. This allows for a greater portion of the upper arm muscles to remain intact compared to a proximal transhumeral amputation [24].

Body-powered control can be employed in cases of transhumeral amputation. This approach utilizes a cable system connected to a shoulder harness, integrating with the intact biceps and triceps of the amputee. With this setup, individuals gain the ability to govern the movements of the prosthetic elbow joint, effectively opening and closing it using the strength and coordination of these preserved muscles. The body-powered control scheme serves as a robust solution, particularly well-suited for tasks that require substantial force and power [25]. Users can confidently undertake high-force activities by engaging the biceps and triceps, empowering them to effortlessly lift objects and accomplish demanding physical tasks. The inherent limitations in controlling the intact muscles can affect the motor control required for precise movements.

3.1.3. Shoulder Disarticulation

Shoulder disarticulation indicates the surgical removal of the entire arm at the shoulder joint. This control system remains a valuable tool that provides individuals with the means to accomplish a wide range of functional activities. Figure 6 depicts the muscles affected in the case of transhumeral amputation. The myoelectric control scheme can be implemented by leveraging the intact bicep and tricep muscles. This approach involves the placement of electrodes over these preserved muscles, allowing for the detection and capture of myoelectric signals generated during muscle contractions.

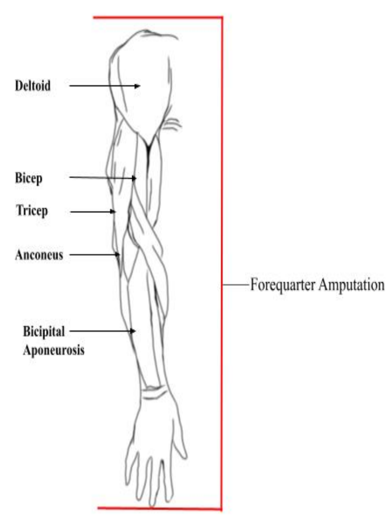

Fig. 7 Shoulder and forearm disarticulation

Subsequently, these signals are processed to assist in enabling the amputee to control their prosthetic limb [26]. The myoelectric signals obtained from the intact bicep and tricep muscles serve as a direct link between the individual's intentions and the prosthetic limb's movements. These captured signals undergo processing, enabling them to be translated into natural commands that dictate the precise movements of the prosthetic arm [27]. In this case, the amputee faces the absence of any residual limb/, significantly impacting the available control schemes and their ability to navigate and manipulate their prosthetic arm. The absence of residual muscles and limbs limits the amputee's natural control and movement possibilities.

Unlike other forms of amputation, where intact muscles can be utilized for control, shoulder disarticulation requires alternative approaches to restore functionality. By strategically attaching cables to the torso, the amputee can effectively channel their remaining physical capabilities into controlling the prosthetic arm. The intricate interplay between the torso and the prosthetic limb allows for the opening and closing of the prosthetic hand, akin to the natural movement of a human hand. [28,29] Figure 7 shows the position from which the arm is cut in shoulder disarticulation. It is important to note this when comparing the difference between this and the forearm.

As the muscles directly related to the amputated limb are not available for myoelectric control, chest muscles or upper back muscles can still be used to control the prosthetic. Electrodes are strategically placed over these remaining muscle groups, diligently capturing the myoelectric signals generated during muscle contractions [30]. These signals, akin to the body's natural language, are then processed and interpreted to translate the amputee's intentions into tangible movements of the prosthetic limb. Due to the limited availability of residual muscles, alternative control methods need to be explored. These alternative control methods encompass the strategic placement of switches or buttons in inaccessible areas. By combining these control systems, individuals can attain higher precision and fine-tuned control over their prosthetic devices [31]. Such innovative approaches are crucial in ensuring that individuals with shoulder disarticulation can regain functional independence and enhance their quality of life.

3.1.4. Forequarter Amputation

In cases of forequarter amputation, a surgical procedure is performed at the shoulder joint, resulting in the complete removal of the scapula and clavicle. This extensive amputation leads to the loss of the entire limb along with all the associated muscles. Consequently, no residual muscles remain for control purposes [32]. The muscles responsible for arm movement, such as the deltoid, pectoralis major, and other upper limb muscles, are completely excised during the procedure, thereby further limiting control options. The level of control that individuals with a forequarter amputation possess over their residual arm is severely restricted as a result of the absence of muscles in the amputated region. Consequently, this translates into an extremely limited control capacity for prosthetic devices. The absence of muscular functionality in the amputated area poses a substantial challenge in developing effective control mechanisms. Figure 7 shows the forequarter amputation. Body-powered control can still be implemented for Forequarter amputation. Harnessing the movements from other parts of the body is shifted using a control mechanism. For instance, a harness can be worn around the remaining shoulder or torso region, enabling control over the movement of the prosthetic device through torso rotation of shoulder elevation [33].

These movements can drive functions of the prosthetic hand and of the elbow. This control system relies on a cable system integrated into the prosthetic arm. These devices are designed to provide additional support to the residual shoulder, thereby enabling the amputee to perform specific movements with enhanced precision. The functional capabilities of the amputee can be optimized, and control of their prosthetic can be carried out by incorporating assistive devices into the rehabilitation process. Assistive devices serve as tools in promoting successful adaptation and rehabilitation for individuals with forequarter amputation. They provide improved stability, control, and range of motion for the residual shoulder. Using a prosthetic device, the individual's functional abilities and overall quality of life are enhanced.

3.1.5. Wrist Articulation

Wrist disarticulation is the surgical removal of the hand and wrist bones while keeping the forearm and associated muscles intact. The biceps and triceps muscles remain unaffected. By preserving the forearm and its muscular structure, individuals undergoing wrist disarticulation retain a considerable degree of functional capacity [34]. The intact flexor and extensor muscles enable control and manipulation of the wrist joint, enabling essential movements and dexterity. Furthermore, the preserved biceps and triceps contribute to the overall strength and functionality of the residual limb. Even with the loss of the hand and wrist muscles, individuals still maintain a certain level of control over their residual limbs. They can perform essential movements such as flexion and extension, enabling reaching, lifting, and pushing activities. The upper arm muscles contribute significantly to these functional capabilities.

However, it is of notable importance that the absence of hand and wrist muscles results in the loss of finer motor functions typically associated with these areas. Delicate manipulations and intricate movements requiring precise control are no longer possible without the presence of these specific muscles. The intact forearm muscles offer a remarkable opportunity for leveraging body-powered control in the context of wrist disarticulation.

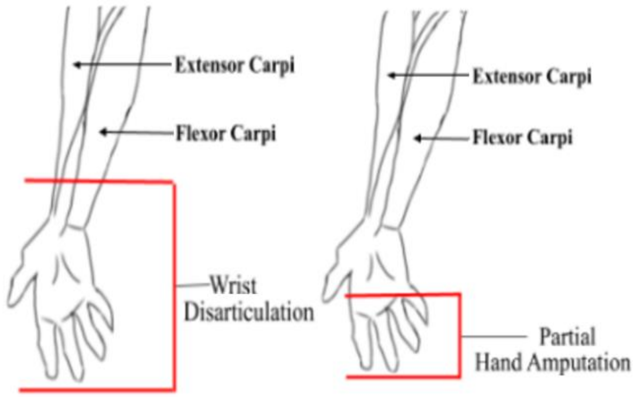

Fig. 8 Wrist disarticulation and partial hand amputation

A sophisticated cable system is seamlessly integrated into the prosthetic design, intricately connected to a purpose-built harness worn by the amputee. This innovative setup allows for a seamless fusion of human and artificial elements [35,36]**.** By consciously engaging and manipulating the intact forearm muscles, the individual exerts their influence on the intricate network of cables within the prosthetic. These intentional actions elicit specific movements, enabling users to navigate a world of tasks and challenges with admirable finesse and strength. The body-powered control scheme stands as a testament to the tremendous capabilities of the forearm muscles, particularly in tasks requiring mechanical advantage and force [37]**.**

Holding objects or performing an activity is carried out with the power within the muscles. The intact forearm muscles implement myoelectric control in the context of wrist disarticulation. Muscle contractions generated by the carpi radialis, extensor carpi radialis, and other muscles responsible for wrist movements, individuals can effectively harness their own electrical signals to govern the movements of their prosthetic arm [38,39]. These myoelectric signals are canalyzed and interpreted using signal processing techniques, enabling a more natural and intuitive control scheme. This approach facilitates the ability to finely modulate their prosthetic arm. Thus, intricate motor control closely emulates natural movements. Figure 8 shows the muscles involved in the wrist disarticulation.

3.1.6. Partial hand Amputation

Partial hand amputation involves surgical amputation of one or more digits. Each finger includes several muscles. The flexor digitorum superficialis, flexor digitorum profundus for flexion extensor digitorum, and extensor indicis for extension, to name a few. The specific muscles affected by the amputation vary depending on the location and extent of the finger loss. The degree of muscle damage directly influences the level of control individuals retain over their residual hand. Finger amputation significantly impacts the fine motor functions typically associated with the lost digits, such as precision gripping, dexterous manipulation, and tactile feedback [40]**.** Various prosthetic control schemes can be considered to address the control challenges faced by individuals with finger amputation.

Figure 8 depicts that only the fingers are incapacitated in case of partial prosthesis. Hybrid control systems combine both body-powered and myoelectric control approaches. This integration allows individuals to leverage the advantages of both systems to achieve a more versatile and intuitive control experience. For instance, body-powered control can be used for gross prosthetic hand movements, while myoelectric control can provide finer control for individual finger movements, presenting fuzzy sliding modes. Body-powered prosthetics for finger amputation employ cables that connect to the remaining hand or wrist. Mechanisms within the prosthetic are activated using muscle strength to replicate finger movements.

Using the contraction of the remaining hand muscles, the cable system can enable gripping or releasing actions in the prosthetic fingers [41]. Surface electrodes placed on the skin surface of the residual forearm muscles are a crucial part of myoelectric control. The electrical signals detected and translated by electrodes are generated by the remaining muscles into specific prosthetic movements. The prosthetic fingers' opening, closing, and other gestures can be controlled. Switches or buttons placed within the prosthetic or external are activated. Residual hand movements, the movement of another body part, or external devices can activate these switches. The switches can trigger specific functions or movements of the prosthetic fingers, providing a simpler and more accessible control option [42].

3.2. Design

3.2.1. Socket

The socket is an interface between the residual arm and the prosthetic device. This is custom-made to fit the needs of every particular individual. Each socket is fabricated according to the unique design of each case's different residual limbs and muscles. It is meant to provide a secure and comfortable fit, considering the weight distribution and forces exerted on the limb. While designing the socket, it is important to consider factors such as shape, size, and condition of the residual limb to ensure a proper fit and minimize discomfort or skin issues [43].

3.2.2. Components

The prosthetic arm comprises components that facilitate the movement and functionality of the user to carry out regular tasks. The components include joints, hinges, cables, and connectors, among others. The specific needs and activities dictate the selection of components for the prosthetic arm. For example, a prosthetic arm meant to be utilized in a sports-oriented environment dictates that the prosthetic be lightweight and durable. So, materials such as aluminum and titanium are used.

3.2.3. Alignment

Positioning the prosthetic with respect to the user's body is called the alignment of the same. It is important to achieve proper alignment to facilitate optimal biomechanics, balance, and functionality. Factors such as the user's anatomical alignment, gait pattern, and individual preferences are considered. It is important that the prosthetic promotes a natural gait, minimizes stress on the body, and provides stability during various activities [44,45].

3.2.4. Prosthetic Covers

Prosthetic covers are cosmetic additions to the prosthetic arm. They are optional. Prosthetic covers are placed over the prosthetic limb to provide a natural appearance to the limb and protect the internal component of the prosthetic arm. Materials such as silicone or foam are used to manufacture prosthetic covers. Factors such as the amputee's skin tone, texture, and size dictate the manufacturing of prosthetic covers.

3.2.5. Interface and Suspension

Interface is the part of the prosthetic arm that comes into direct contact with the residual arm of the amputee. The interface provides a secure fit, distributes pressure, and minimizes friction. Interfaces like cushions, liners, or sockets with custom gel or silicone padding are widely used. Suspension systems secure the prosthetic limb to the amputee's residual limb [46]. The suspension also prevents the movement or rotation of the prosthetic during the operation. E.g. straps, suction, or vacuum-availed suspension.

3.2.6. Weight and Proportions

The prosthetic arm needs to be as lightweight as possible, as reducing the weight leads to a reduction in fatigue and strain on the user's body. This leads to more comfortable and efficient movement by the user. The prosthetic arm needs to be carefully manufactured, considering the user's limb length, thickness, and joint placement [47].

3.3. Actuators Used in the Industry

Actuators provide the necessary force and controlled movement to replicate the functions of a natural limb. Various studies and advancements have been made in the field of actuators for prosthetic arms in recent years. The most popularly used actuators are discussed in detail in this section.

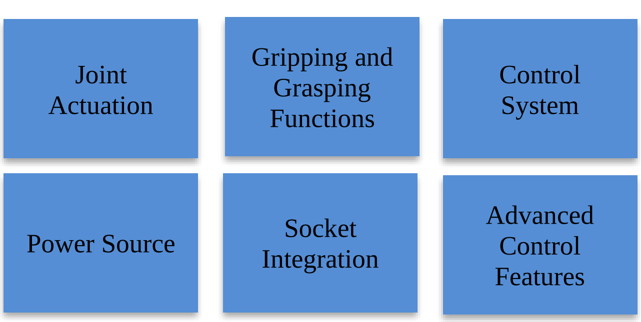

Fig. 9 Functionalities of motors in prosthetic arm

As shown in Figure 9, motors, in general, can be used for a myriad of things, including joint actuation, gripping and grasping, in a motor control system, for power supply, socket integration, and to implement advanced control features.

3.3.1. Electric Motors

Electric motors, including DC motors and stepper motors, are used in prosthetic arm applications. DC motors offer high torque and precise control, making them suitable for tasks requiring fine motor skills. Stepper motors, on the other hand, provide incremental movements, enabling accurate positioning of the prosthetic limb. Optimized motor size, weight, and power consumption enhance prosthetic arms' overall performance and usability [48,49].

Joint actuation using electric motors in prosthetic arms involves using motors to generate movement and torque at the various joints of the arm. The specific motor configuration and control system can vary depending on the design of the prosthetic arm and the desired range of motion. Joint actuation using electric motors in prosthetic arms aims to replicate natural human movement and provide users with functional and intuitive control over their prosthetic limbs. Different types of electric motors can be used for joint actuation, such as DC motors, stepper motors, or brushless motors. The choice of motor depends on factors such as torque requirements, speed, precision, power consumption, and control complexity. In many cases, electric motors are coupled with gear systems to provide the desired torque and reduce the speed at the joint. Gears can increase the torque output while decreasing the rotational speed of the motor, allowing for smoother and more controlled joint movement [50].

The system consists of sensors, microprocessors, and software algorithms that interpret control signals and translate them into motor commands. It produces electrical stimulation by defining the voltage, current, and timing of the motor. It develops desired joint movement. Systems incorporate feedback mechanisms for improved control [51,52]. The position sensors, force sensors, or encoders measure the joint position, torque, or applied force. The feedback information adjusts motor commands in real-time, improving joint movements' accuracy and responsiveness. This enables prosthetic arms to achieve a wide range of motion at the joints, allowing users to perform various daily activities and tasks. The motors can be controlled to provide flexion and extension movements, rotational movements, or a combination of both, depending on the targeted joint and function.

Joint actuation can be controlled using various input methods. These can include myoelectric control, where signals from the user's residual limb muscles are used to command the motor movement. Other control inputs may include switches, buttons, or external sensors that detect the user's intentions or gestures. Gripping and grasping functions in prosthetic arms are important for making it easy for the users to interact with objects and perform daily activities [53]. Electric motors play a significant role in achieving these functions. Motors control movements like opening and closing of palm or fingers. These aim to replicate the human hand's dexterity, strength, and versatility. Prosthetic hands typically have a mechanical structure that mimics the natural human hand. Electric motors are integrated into this mechanism to generate the required force and movement for gripping and releasing objects [54,55]. These are also used to actuate the individual fingers of the prosthetic hand. The number of motors employed depends on the complexity of the hand design and the desired range of finger movements. Each motor is responsible for controlling the movement of a specific finger, allowing for independent finger control. Prosthetic hands with electric motors can be programmed to execute different grasp patterns. Power grasp, precision grasp, and pinch grasp are some grasping patterns.

A firm grip on the object indicates a power grasp. A delicate precision grasp is the finger arrangement for holding the key, pinch for holding paper, and tripod for holding the pen, which are some examples of patterns. Motors need to be controlled to achieve the desired finger position. The force required to hold the object varies. Feedback sensors ensure the proper force is exerted to hold the object. Some advanced prosthetic hands use force and pressure sensors [56]. These sensors are embedded in the fingertips or palm of the prosthetic hand. While grasping, the sensors generate feedback. This allows for a more delicate and precise grip. Motor commands are adjusted in real time, ensuring a secure hold without damaging objects [57]. The control system includes sensors, microcontrollers and software algorithms that interpret the user’s control inputs. The motors are moved based on these inputs.

The control system discussed in joint actuation and gripping has some components that act together to interpret control signals and command the electric motors for the movements to occur. The motor control system's main objective is to translate the user's control inputs, sensor feedback, and algorithmic processing into precise and coordinated movements of the electric motors. These components are sensors, microprocessors, control algorithms, motor command generator voltage and current control system, real-time feedback mechanism, power management, integration and communication. The motor control system incorporates sensors to gather information about the user's intentions and the current state of the prosthetic arm, which then, in turn, can include myoelectric sensors that detect electrical signals generated by the user's residual limb muscles, force sensors that measure applied forces, position sensors that determine joint angles, or other types of sensors that provide feedback about the arm's position and environment [58,59]. The sensor data is processed by microprocessors and control algorithms within the motor control system. This control ensures that the motors operate within their specified limits and deliver the required power for joint actuation or gripping and grasping actions [60,61]. Electric motors in prosthetic arms require a power source. This power is usually provided by rechargeable batteries or external power supplies [62,63]. The motors receive the necessary electrical energy to drive the mechanical movements of the arm. Many prosthetic arms utilize rechargeable batteries as a portable and convenient power source [64]. These batteries (usually Lithium-ion or Lithium-polymer) have a high energy density, allowing for longer periods of operation between charges. They can be integrated into the prosthetic itself or housed in a separate battery pack that can be easily recharged as needed. Attachment and Disassembly. In some cases, the prosthetic may rely on an external power source instead of or in addition to the rechargeable battery. These power supplies can include AC/DC adapters or power banks.

External power supplies provide a continuous power source and can be useful for extended periods of use or situations where immediate access to charging is available. Prosthetic arms incorporate power management systems to regulate and distribute power effectively [65]. Efficient motor control algorithms, low-power components, and smart power management strategies help minimize energy consumption while maintaining adequate functionality [66,67]. The socket design, motor placement, and transmission mechanisms should be carefully tailored to the individual user's needs and specific requirements [68]. The socket is typically created through a casting or scanning process, ensuring precise fit and intimate contact with the residual limb. The socket is designed to securely hold the prosthetic arm in place while distributing forces and minimizing discomfort. When integrating electric motors into the socket design, careful consideration is given to their placement. The motors should be strategically positioned to align with the prosthetic arm's intended joint movements and function [69]. Proper placement ensures that the motor's output is efficiently transmitted to the mechanical components responsible for joint actuation or gripping and grasping actions.

This alignment allows for natural and anatomically appropriate movement. The range of motion of the motors should be carefully coordinated with the user's limb movement to achieve harmonious and functional interaction. Proper motor placement and design considerations should account for factors such as socket shape, padding, suspension mechanisms, and weight distribution to maintain optimal socket function [70,71,72]. Mechanical components, including gears, linkages, cables and pulley systems, are responsible for joint actuation. Wiring and control components are integrated into socket design. Care must be taken to maintain the integrity and functionality of the wiring while considering factors such as durability, flexibility, and ease of maintenance [73]. Incorporated in certain contemporary prosthetic arms with electric motors are advanced control features, including proportional control, pattern recognition, and myoelectric control, further increasing functionality and ease of use [74]. Complex algorithms, electric motors, sensors, and control systems are all seamlessly coordinated within the prosthetic arm design to integrate its features. Signal processing techniques are also essential for this integration to work effectively [75,76]. Proportional control allows users to modulate the movement and force of the prosthetic arm based on their intended actions. Using proportional control, the electric motors can respond to the user's input signals continuously and proportionally. This feature enables finer control over the prosthetic arm's speed, position, and force, allowing for more precise and delicate movements [77]. Pattern recognition technology in prosthetic arms utilizes machine learning algorithms to analyze the user's muscle signals or other control inputs [78]. By recognizing specific patterns associated with different movements or actions, the prosthetic arm can predict the user's intended motion and adjust the electric motor commands accordingly. This feature enhances the user's ability to perform complex and coordinated movements, such as grasping and manipulating objects.

Myoelectric control is a widely used method in which the prosthetic arm is controlled based on the electrical signals generated by the user's residual limb muscles. Surface electrodes placed on the skin detect these muscle signals, which are then translated into motor commands [79]. Myoelectric control allows intuitive prosthetic arm control, as users can activate specific movements by contracting or relaxing specific muscles. Electric motors respond to these signals, enabling coordinated and precise movements of the prosthetic arm. Some advanced prosthetic arms offer mode-switching capabilities, allowing users to switch between different control modes for different tasks or activities [80]. For example, a user can switch between a fine motor control mode for precise movements and a power mode for tasks requiring a stronger grip. Additionally, gesture control can be implemented, where specific gestures or movements of the user's residual limb are recognized and mapped to corresponding prosthetic arm movements.

3.3.2. Pneumatic Actuators

Generating force and motion with compressed air or gas, pneumatic actuators offer several benefits, including an efficient weight design and an easy-to-navigate system with an optimized power-to-weight ratio. Known as McKibben muscles, pneumatic muscles have also been used to copy human muscle contraction and expansion in prosthetic arms. Meanwhile, several studies on using pneumatic actuators for prosthetic arms have aimed at augmenting force output and reaction time, which can foster strength while completing tasks [81,82]. Pneumatic actuators, particularly in the form of McKibben's muscles, have been utilized in prosthetic arms to replicate human muscle contraction and expansion. These actuators offer several advantages that can contribute to the overall performance and functionality of the prosthetic arm, and they are lightweight compared to other actuation systems, such as electric motors. Joints at the wrist, elbow, fingers, etc., can be controlled using valves, sensors and microcontrollers for precise and coordinated movement. The motors can be connected to cylinders that simulate natural elbow flexion and extension [83]. Pneumatic motors can be integrated into prosthetic hand and finger mechanisms for grasping and manipulation. Motors control the hand's opening and closing and the individual fingers' movement. The limitations of pneumatic motors include the need for a compressed air or gas source, the potential for system leaks, and the need for a control system to regulate airflow and pressure. These challenges must be considered when designing and implementing prosthetic pneumatic actuators to ensure their reliability and effectiveness.

3.3.3. Hydraulic Actuators

Hydraulic actuators generate force and movement using pressurized fluid. Their high power density makes them suitable for heavy-lifting applications. Hydraulic actuators are mechanical devices that utilize the power of pressurized fluid to generate force and movement. They consist of a fluid-filled chamber or cylinder, a piston, and a control valve. When fluid, typically oil, is pumped into the chamber under pressure, it causes the piston to move, resulting in a mechanical output. One of the significant advantages of hydraulic actuators is their high power density. The force and torque generated by these actuators are substantial relative to their size and weight. This makes them particularly suitable for heavy lifting or high-force applications, such as construction equipment, industrial machinery, and aerospace systems. While hydraulic actuators are less common in prosthetic arms than other actuator types, such as electric motors or pneumatic actuators, they have been explored for their potential benefits in advanced prosthetic designs.

Prosthetic arms equipped with hydraulic actuators can provide enhanced strength and grip force, allowing users to perform tasks that require a higher level of force, such as lifting heavy objects or exerting pressure [84, 85]. The use of hydraulic actuators in prosthetics offers several advantages. Firstly, they provide a high force-to-weight ratio, meaning they can generate significant force without adding excessive weight to the prosthetic limb. Secondly, hydraulic actuators can offer a smoother and more precise movement control compared to some other actuator types. A level of control can improve the user's ability to perform delicate tasks that require precise movements and coordination.

However, there are some challenges associated with hydraulic actuators in prosthetic applications. One of the main concerns is the need for a power source and the associated components required for fluid storage, pumping, and control. This can add complexity to the prosthetic system and may require additional space and weight. Additionally, hydraulic actuators require a reliable sealing system to prevent fluid leaks [86,87,88]. The seals must be robust enough to withstand the pressures and forces exerted during operation, ensuring the longevity and durability of the prosthetic device.

3.3.4. Shape Memory Alloys (SMA)

Shape memory alloys, such as Nitinol, exhibit the ability to change shape in response to temperature changes. These alloys can be used as actuators in prosthetic arms to create natural-looking movements. Researchers have investigated using SMAs to develop lightweight, compact actuators that offer improved flexibility and responsiveness. One possible use of SMA in prosthetic arms is in the fingers or hand joints. SMA wires can be integrated into joints to mimic the flexing and extending movements of natural fingers. When an electrical current is applied to the SMA wires, they heat up and return to their original shape, allowing the fingers to move and grasp objects. Another application of SMA in prosthetic arms is to provide a more secure grip. By incorporating SMA springs or wires into the hand or fingers, the prosthetic arm can adjust its grip strength based on the object being held. [89,90] While SMA technology holds promise for prosthetic arms, there are still challenges to overcome. These include the miniaturization of SMA components to fit within the limited space of a prosthetic limb, developing reliable and efficient control systems, and ensuring long-term durability and functionality. Overall, the use of SMA in prosthetic arms has the potential to enhance functionality and improve the user experience by enabling more natural movements and better control.

3.3.5. Electroactive Polymer (EAP)

In response to an electric field, materials that can alter their shape or size are referred to as electroactive polymers. Their ability to create large deformations and their weightlessness has caught the attention of researchers considering using them in prosthetic arm actuators. EAP actuators offer the advantage of quieter operation and improved aesthetics, as they can be integrated into the prosthetic limb structure. EAPs can replicate the movement of human muscles when stimulated with an electric current. Integrating EAP actuators into a prosthetic arm's joints and fingers makes it possible to achieve more natural and intuitive movement [91,92]. EAPs can also be employed to provide sensory feedback to the user. Integrating sensors into the prosthetic arm and connecting them to the EAP materials allows the user to receive feedback on touch, pressure, temperature, and other sensory information. This feedback allows for better control and interaction with the environment. EAP-based prosthetic arms have the potential to be more energy-efficient compared to traditional prosthetics [93]. EAP materials can store and release electrical energy, allowing for more efficient use of power and potentially reducing the weight and size of the power source. EAP materials are highly flexible and can be shaped into various forms. This property enables the creation of prosthetic arms that can be custom-designed to fit the individual's unique limb shape and size. While EAP technology holds great promise for prosthetic arms, it's important to note that it is an area of ongoing research[94]. Significant advancements are needed to overcome technical challenges and improve the reliability, durability, and affordability of EAP-based prosthetics [95]. However, with continued progress in this field, EAPs have the potential to revolutionize the functionality and, hence, the usability of prosthetic arms. This offers users a more natural and integrated experience.Fig.10 depicts that electric motors are the most used actuators in the prosthetic arm, closely followed by pneumatic and hydraulic motors. SMA and EAP are developing technologies being studied at the moment and are thus the least used. These conclusions were derived after looking into all the research papers. Ongoing research aims to improve the strength, control, and efficiency of these actuators to enhance the overall functionality and user experience of prosthetic arms.

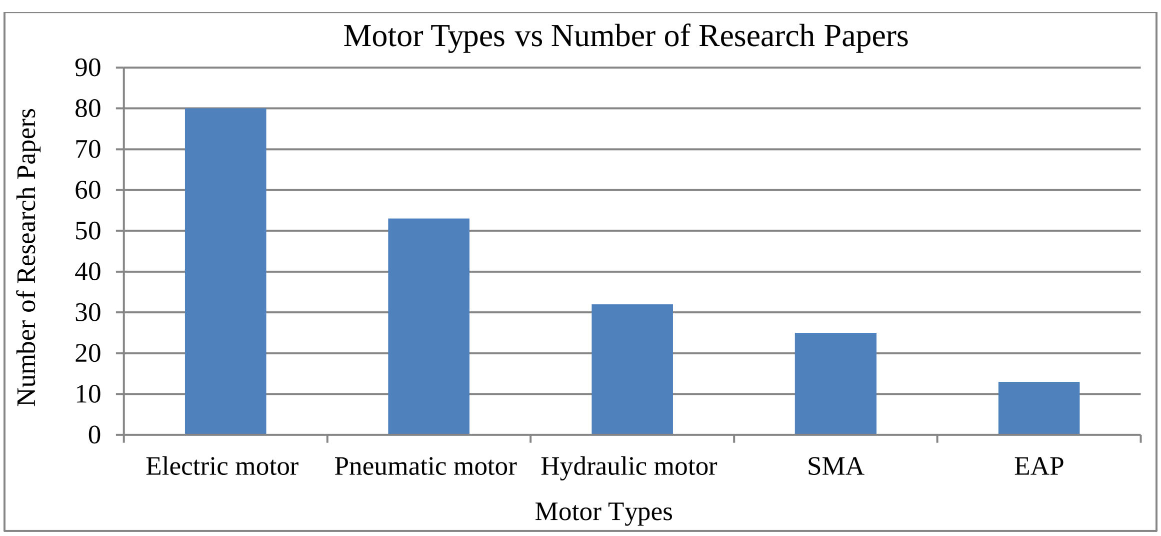

Fig. 10 Frequency of usage of each motor

3.4. Pressure Control and Design

Pressure control in prosthetic arms is a dynamic process that relies on precise calculations and adjustments to accommodate the nature and size of the objects being manipulated. The application of pressure on an object depends on various factors, including the object's weight, shape, and fragility. Here, we delve into some statistics and mathematics related to pressure control in prosthetic arms. When gripping an object, the prosthetic arm needs to exert an appropriate amount of pressure to secure it without causing damage. This requires an understanding of the force applied to the object due to gravity. The force of gravity on an object can be calculated using Newton's second law of motion, as shown in equation (1).

$$F = m * g \tag{1}$$

where F represents the force in Newtons,
m is the mass of the object in kilograms,
g is the acceleration due to gravity (approximately 9.81 m/s^2 on Earth).

To calculate the pressure required to lift an object without dropping it, the prosthetic arm's sensors and control system need to continuously monitor the object's weight and adjust the grip force accordingly. For example, when picking up a 1-kilogram object, the prosthetic arm should exert a force of approximately 9.81 newtons to counteract gravity. Pressure control becomes even more critical when dealing with fragile objects. The prosthetic arm must apply minimal pressure to prevent breakage. The Young's modulus of the object's material plays a crucial role in determining how much pressure can be safely applied. Young's modulus (E) represents the stiffness of a material and is measured in pascals (Pa). The formula for stress (σ) in a material is given by equation (2).

$$\sigma = F / A \tag{2}$$

where
F = Force applied
A = Cross-sectional area of contact
σ = Stress

If a prosthetic arm picks up a glass with Young's modulus of 7.2 x 10^10 Pa, and the cross-sectional contact area is 10 cm^2 (0.001 m^2), the maximum force that can be applied without breaking the glass can be calculated. Let's say the glass weighs 0.2 kilograms (200 grams). First, calculate the force due to gravity: $F = 0.2$ kg * 9.81 $m/s^2 \approx 1.96$ newtons. Then, calculate the maximum stress the glass can withstand: $\sigma = F / A = 1.96$ N / 0.001 m^2 = 1960 Pa (or 1.96 kPa). The prosthetic arm's pressure control system must ensure that the applied pressure remains below this threshold to avoid damaging the glass. Moreover, the shape of the object also affects pressure control. Irregularly shaped objects may require the prosthetic arm to adjust its grip to distribute pressure evenly. This requires sophisticated algorithms that consider the object's geometry. For example, when grasping a cylindrical object, the pressure applied should be greater at the contact points and lower on the sides to maintain a secure grip without damaging the object. Pressure control is not solely about static calculations but also involves dynamic adjustments. When lifting or manipulating an object, the prosthetic arm's control system must continually adapt the pressure to maintain a stable hold. The rate of change in pressure (dP) can be calculated using calculus, where dP/dt represents the change in pressure over time (t). This dynamic control ensures that the prosthetic arm can respond to sudden changes in the object's position or the user's intentions. In summary, pressure control in prosthetic arms relies on a combination of statistics and mathematics to calculate and adjust the pressure applied to objects. This includes calculating the force of gravity, considering Young's modulus for fragile objects, accounting for object shape, and dynamically adjusting pressure during manipulation. These calculations are essential to provide users with safe and effective means of interacting with objects of varying sizes, shapes, and materials, ultimately enhancing their quality of life and independence. As technology continues to advance, these calculations and adjustments will become even more precise and responsive, further bridging the gap between human and prosthetic capabilities.

3.5. Control Systems for Prosthetic Arms

A prosthetic arm can be controlled in a wide range of ways. The selection for the control method varies due to the level of precision and control required for the amputee's physical function and so on. [96,97] The methods are Body-powered control, Myoelectric control, Brain-Computer Interface (BCI) control, EMG-driven control and Speech and Eye controlled control. The most used methods among these are Body-powered, Myoelectric and BCI control methods.

Figure 11 shows what control systems are used by the people who have volunteered for the questionnaire that was circulated. The Brain Computer Interface (BCI) control method uses electrical signals generated from the sensors placed on the brain. The amputee can then control the prosthetic arm by thinking about moving it; this is called motor imagery. Electrical signals from the brain are amplified and used to control the prosthetic arm. BCI prosthetic arms are the most precise control method, but they are also the most expensive and require surgery to implant the electrodes. The body-powered control method uses cables or harnesses to connect the prosthetic arm to the body. The amputee can then move the prosthetic arm by moving their body, such as their shoulder or chest. [98] Body-powered prosthetic arms are the oldest type of prosthetic arm. They are controlled by cables or harnesses that are attached to the body. [99] The amputee can move the prosthetic arm by moving their body, such as their shoulder or chest, as shown in Fig.12.

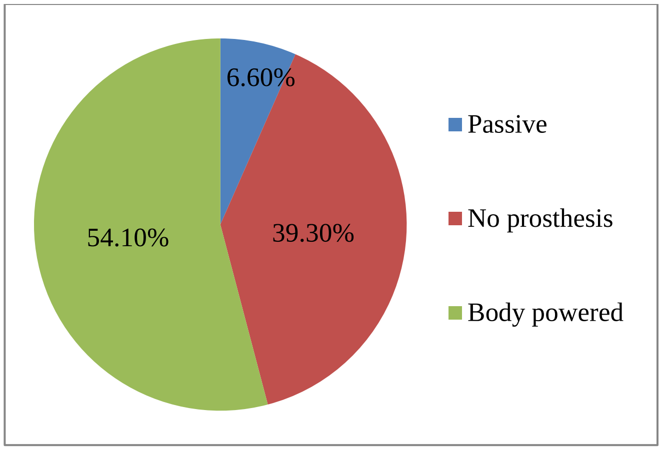

Fig. 11 Control Systems in existing systems

Body-powered prosthetic arms are relatively simple and affordable, but they can be difficult to control with precision. The myoelectric control method uses electrodes placed on the skin. It detects electrical signals from the muscles in the residual limb. The amputee can then control the prosthetic arm by contracting their muscles. Electrical signals from the residual limb control the prosthetic arm [100]. Electrodes are placed on the skin over the muscles, and the electrical signals from the muscles are amplified and used to control the prosthetic arm. Myoelectric prosthetic arms are more precise than body-powered prosthetic arms, but they can be difficult to learn how to use. Figure 13 shows the process followed by arms using the myoelectric control method. Table 2 shows how the systems used in prosthetic arms have developed over the years.

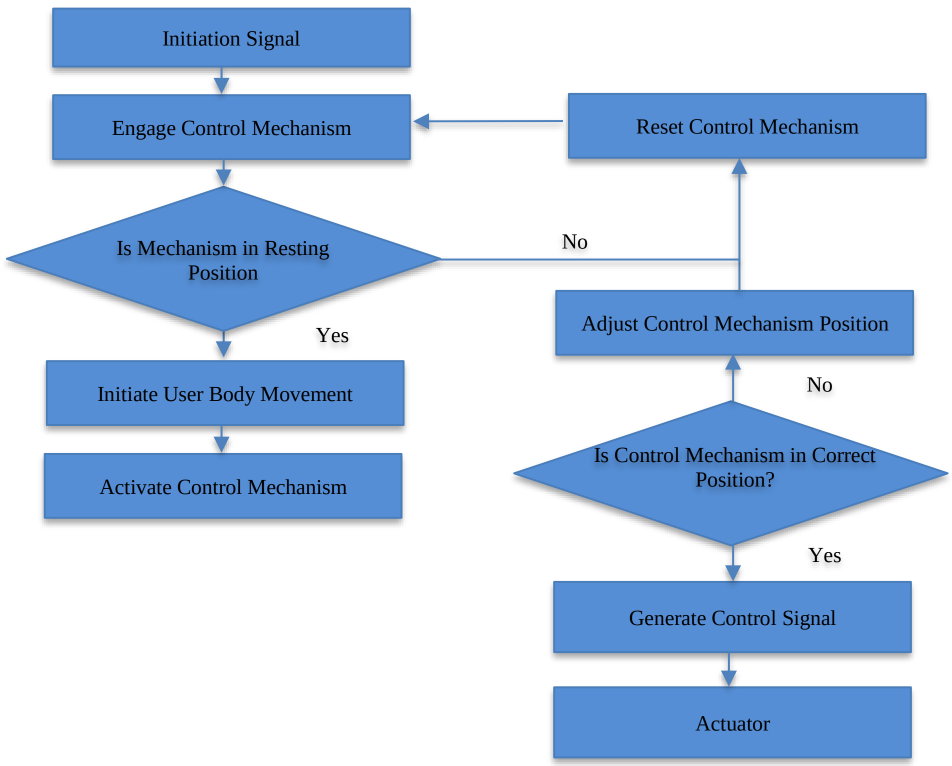

Fig. 12 Flowchart for a control system with body powered control method

Table 2. Timeline of prosthesis developments

Year	Key Developments
2005	Introduction of myoelectric upper limb prosthetics with ABS material.
2007	Myoelectric upper limb prosthetics with limited customization.
2011	Myoelectric upper limb prosthetic technology continues to evolve.
2014	Introduction of brain-computer interface (BCI) upper limb prosthetics. Limited customization and user adaptability. Ongoing development of myoelectric prosthetics.
2015	Myoelectric upper limb prosthetics with Ecoflex material were introduced.
2016	Body-powered upper limb prosthetics with various materials.
2017	Myoelectric upper limb prosthetics with ABS, aluminum, and steel materials were introduced. Challenges related to limited testing and durability.
2018	Introduction of silicone-based upper limb prosthetic with high weight. Myoelectric upper limb prosthetics with ABS material and detection delay. Limited motion in myoelectric prosthetics.
2019	Introduction of PLA and NA-based upper limb prosthetics with limitations. Brain-computer interface (BCI)

	prosthetics with limited user adaptability.
2020	Myoelectric and NA-based upper limb prosthetics were introduced. Body-powered upper limb prosthetic with PLA material. Challenges related to limited degrees of freedom (DoF) and specialized training.
2021	Myoelectric upper limb prosthetic with ABS material and complex setup. Brain-computer interface (BCI) prosthetic with ABS material and complex setup.
2022	Myoelectric and BCI upper limb prosthetics have various limitations. Challenges include limited object recognition, customization, and user adaptability.
2023	Myoelectric upper limb prosthetic with ABS and PLA materials. Challenges related to limited sensors and customization.

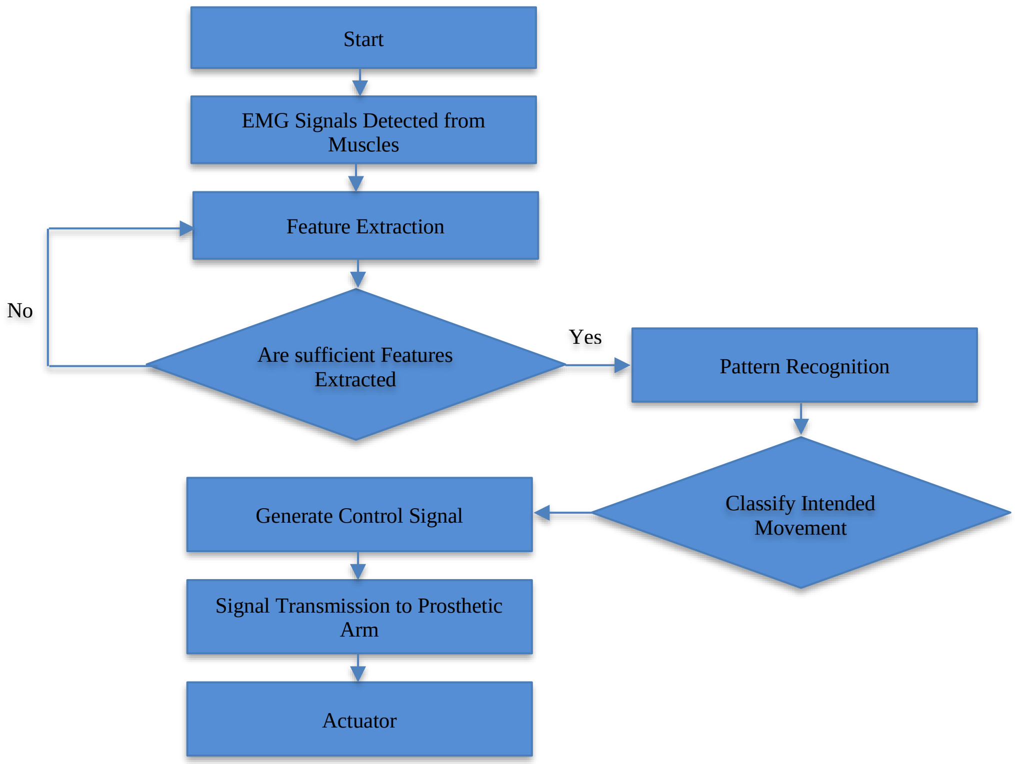

Fig. 13 Flowchart for a control system with myoelectric control method

The EMG-driven control method uses electrodes placed on the skin to detect activation generated by the electrical signals from the muscles in the residual limb [101]. The electrical signals from the muscles are then used to control the prosthetic arm. This method is similar to myoelectric control, but it is more precise and can be used to control more complex movements. Speech-controlled control method uses a microphone to detect the amputee's speech. The amputee can control the prosthetic arm by spoken commands. This method is still in development, but it has the potential to be a more natural and intuitive way to control a prosthetic arm. An eye-controlled control method uses an eye tracker to detect the amputee's eye movements [102]. The amputee can then control the prosthetic arm by fixating the eye glaze at different targets. This method is still in development, but it has the potential to be a more convenient and efficient way to control a prosthetic arm. Each method of control has its own advantages and disadvantages. Body-powered control is the simplest and most affordable method, but it can be difficult to precisely control the prosthetic arm. Myoelectric control is more precise than body-powered control, but it can be difficult to learn how to use it [103]. BCI control is the most precise control method but is also the most expensive and requires surgery to implant the electrodes.

3.6. Material Used in the Manufacturing of Prosthetic Arms

Prosthetic arms and artificial limbs, which are made to restore the functionality of a missing or non-functioning human arm, can be made using various materials. This section briefly goes through it. Various materials have been proposed across a span of 20 years. Metals such as aluminum, titanium, and stainless steel are mainly used in the structural components of prosthetic arms owing to their strength, durability, and lightweight properties. These metals provide the necessary support while allowing for ease of movement. Plastics, including thermoplastics and composites, offer flexibility and the ability to create complex shapes and contours that mimic the natural form of the human arm [104]. They are lightweight and easily customizable to fit individual requirements. Carbon fiber, a lightweight and high-strength material, is often utilized in advanced prosthetic arm designs. Its rigidity and durability make it suitable for both strength and flexibility applications. Soft materials such as silicone and rubber are employed in creating prosthetic arms' outer covering or glove-like components [105,106]. These materials provide flexibility, comfort, and a natural appearance. They also enhance grip and can incorporate tactile sensors for improved interaction with the environment. Composite materials, such as fibre-reinforced composites, offer a balanced combination of strength, lightness, and flexibility.

Embedding fibers such as carbon fiber in a resin matrix and composite materials enable the construction of prosthetic arms with improved performance and aesthetics. The choice of materials depends on factors such as functional requirements, weight limitations, cost considerations, and the desired level of realism and comfort for the user [107]. Continued advancements in material science and engineering expand the possibilities for creating prosthetic arms that closely resemble and function like natural human limbs [108,109]. The goal of achieving a realistic experience with the prosthesis led to incorporating a temperature feedback system in the smart bionic hand. Users can perceive the temperature of objects held by the bionic hand missing; to accomplish this, an Amlx90614 infrared thermometer is utilized, which can measure the temperature of an object by capturing the thermal radiation emitted from a specific region without requiring physical contact. On the other hand, various papers explore soft materials in the construction of the glove component of a prosthetic arm. The soft material is designed with a protrusion that helps prevent the material from shifting, thereby creating a more prominent protrusion [110]. This larger protrusion adapts the shape of the object that is being gripped, enhancing the user's ability to interact with various items. The study also involves a comparison of different materials, as shown in Table 3, that are suitable for manufacturing a robotic arm. FDM, Fused Deposition Modelling, is an additive manufacturing process that uses a thermoplastic filament as the printing material [111,112]. This filament, when heated and extruded through a nozzle, moves in a controlled manner to create layers that then solidify and build the desired object. FDM is majorly used for prototyping because of its affordability and ease of use. [113,114] Another material that is quite popular is a biodegradable thermoplastic called PLA Polylactic Acid, which is made from renewable resources like sugarcane or maize starch. It is one of the most often used materials in 3D printing because of its low cost and widespread availability. PLA is known for its low warping and odorless printing characteristics, making it suitable for various applications, including prototypes, toys, and household items [115,116]. ABS, which is Acrylonitrile Butadiene Styrene, is a durable thermoplastic that offers good strength, impact resistance, and high heat resistance. It is commonly used in 3D printing for functional parts and prototypes that require toughness and durability, making it a good choice for prosthetic arms. ABS has a higher printing temperature compared to PLA and can produce stronger and more robust objects. Nylon, on the other hand, is a synthetic polymer known for its excellent mechanical properties, including its high strength, flexibility, and durability [117]. It is mostly used in 3D printing for applications that require toughness and wear resistance. Nylon material can be conveniently used to produce functional parts, prototypes, and components that must withstand demanding conditions [118]. Another similar method is SLA (Stereolithography), which is available for a specific printing method [119]. These materials usually offer a balance between cost and ease of use.

Table 3. Comparative analysis of material properties

Quantity measured	FDM			SLA			SLS
	PLA	**ABS**	**Nylon**	**Stnrd**	**Tough**	**Durble**	**Nylon**
Tensile Strength (MPa) (X-Y axis)	37.0	29.3	49.3	43.8	55.7	31.8	46
Tensile Strength (MPa) (Z axis)	8.2	6.5	28.9	43.8	55.7	31.8	39
Elongation (%)	7	18	30	12	6.2	49	59
Price ($/kg)	19-75	14-60	73	70-100	70-100	70-100	15-150
Environmental Vulnerabilities	-	UV		UV	UV	-	
Density of material(kg/m^3)	1250-1430	1020-1180	-	1100-1200	1100-1300	1100-1200	950-1,200

It is a 3D printing process that uses liquid resin as the printing material. It selectively cures and solidifies the resin layer by layer by exposing the resin to a UV laser, which creates the final object. SLA is known for its high level of detail and accuracy, making it suitable for producing intricate and complex designs.

Standard typically refers to the default or basic options and acceptable performance regarding filament materials. Compared to standard filaments, these materials are designed to withstand higher stress levels, impact, and deformation. Contrarily, durable materials are those that, despite adverse circumstances, can keep their mechanical characteristics and performance over a lengthy period of time.

For applications that demand long-term stability and durability, durable materials are frequently chosen [120]. A powdered substance is used as the printing medium in the SLS

(Selective Laser Sintering) additive manufacturing method. The required object is created via layer-by-layer selective laser fusion of the powdered material. SLS can operate with a wide range of substances, including ceramics, metals, and polymers, making it renowned for its adaptability. It is mostly used for functional prototypes and production runs because it has good mechanical qualities. SLS Nylon offers several advantages in 3D printing [121,122].

It has high strength and durability, making it suitable for producing functional parts and prototypes that need to withstand mechanical stress and impact. It also has good chemical resistance and can withstand exposure to various chemicals without degrading. Figure 14 compares and analyzes materials according to tensile strengths.

3.7. Torque Analysis

When designing prosthetic arms, torque-a measure of rotating force-is essential. It is crucial for holding and moving objects while also regulating the arm's motion. The amount of torque needed for a prosthetic arm to operate at its best depends on the number of variables, including the weight of the arm and object being moved and the level of precision needed for that particular motion. To ensure that they can carry out tasks as well as a normal arm, prosthetic arms need accurate torque control [129]. However, the prosthetic system will move at a slow speed when lifting, so acceleration will be neglected in the calculation. In order to keep the objects from going out of hand, the static friction force must be equal to the object's weight. Figure 15 charts the torque requirements for each type of amputation.

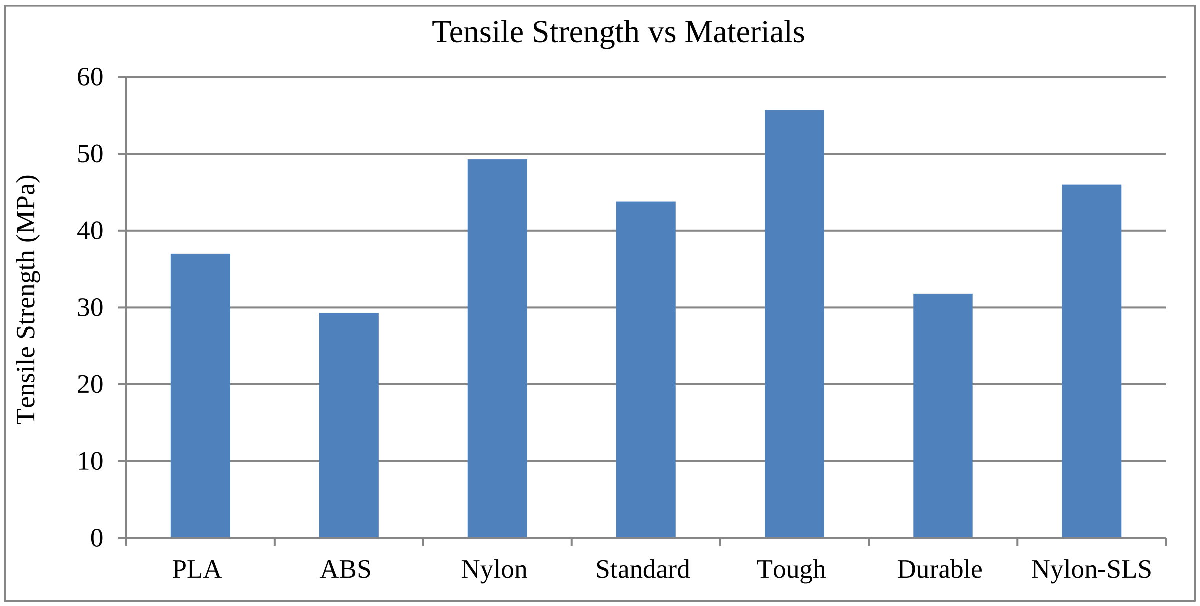

Fig. 14 Materials tensile strength

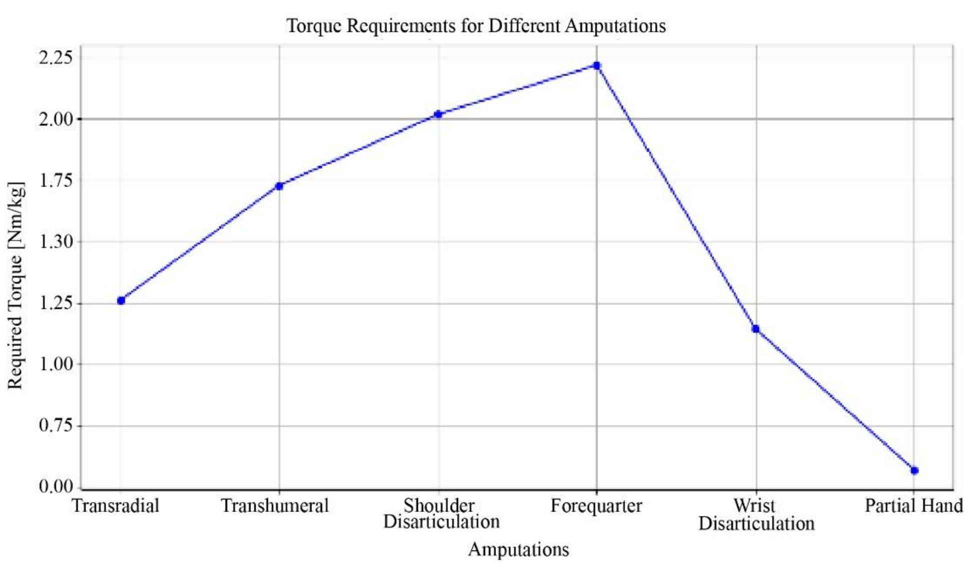

Fig. 15 Torque for different amputations

3.7.1. Types of Torque Sensors

When a load is applied, a strain gauge detects changes in electrical resistance to calculate torque. It is a widely used and reasonably priced torque sensor that has a high degree of sensitivity and can detect torque accurately. An optical sensor analyses light intensity variations when a shaft is turned to determine torque.

It is a very accurate, non-contact torque sensor that can deliver results in real-time. However, external elements such as vibrations, dust, or dirt may have an impact [124,125]. A magnetic sensor measures torque by detecting changes in magnetic fields when a shaft is twisted. It is a non-contact torque sensor that is highly accurate and reliable. However, external magnetic fields might have an impact on them. Table 4 displays the types of sensors available. Torque is measured via piezoelectric sensors, which transform mechanical stress into an electrical output. It is a very sensitive torque sensor that can deliver measurements in real-time. However, external conditions such as temperature and humidity might have an impact on it and may require calibration [126,127]. By observing variations in capacitance between two conducting plates while a shaft is turned, a capacitive sensor detects torque. It is a very accurate, non-contact torque sensor that can deliver results in real-time. However, it could be impacted by outside variables such as humidity and temperature [128].

Table 4. Types of torque sensor

Torque Sensor	Description
Strain gauge	Measures torque by detecting changes in electrical resistance when a load is applied
Optical sensor	Measures torque by analyzing changes in light intensity as a shaft is twisted
Magnetic sensor	Measures torque by detecting changes in magnetic fields as a shaft is twisted
Piezoelectric sensor	Measures torque by converting mechanical stress into an electrical signal
Capacitive sensor	Measures torque by detecting changes in capacitance between two conductive plates as a shaft is twisted.

3.7.2. Methods Used for Torque Analysis

A dynamometer is a tool used to precisely gauge a motor or actuator's torque and rotational speed. It might be necessary to take the prosthetic arm's motor or actuator out nevertheless [129][130]. Another approach for measuring the angular velocity and the acceleration of a prosthetic arm is an (IMU) inertial measurement unit. Although it can estimate the torque the motors or actuators produce, other approaches may be more accurate. A strain gauge can alternatively be connected to the motor or actuator to measure the torque generated as the arm is moved. Even though it's frequently used for small motors or actuators, this method could not be as precise as others. It is possible to track the electrical activity of different muscles in charge of the prosthetic arm using various EMG sensors. Even if it is feasible to calculate the torque produced by the motors or the actuators by examining muscle activity, this approach might not be as precise as others. Additionally, the computer can be used to model the prosthetic arm's motion and determine the torque that the actuators or motors produce [131][132].

Before building a physical prototype, this technique helps to optimize the design of the arm and spot potential problems. It might not be as accurate as other approaches. Whereas the computer simulation method is used to model the motion of the prosthetic arm and estimate the torque generated by the motors or actuators, this is done to test the mobility of the arm [133]. This method is used to optimize the design of the prosthetic arm and identify potential issues before building an actual physical prototype, but it may not be as accurate as other methods.

An extensive evaluation of numerous papers has been conducted spanning over the course of two decades, focusing on the design of prosthetic arms, materials utilized, and different types of amputations. Among the various types of amputations studied, transhumeral amputation, involving the removal of the lower arm, received significant attention from researchers. To address this specific amputation, researchers proposed various designs encompassing aspects such as socket design, components, alignment, prosthetic covers, interface and suspension, weight, and proportions.Electric motors, particularly DC motors and stepper motors, have grown in favor in recent years for use in prosthetic arms. The strong torque output and precise control of DC motors make them well-suited for jobs requiring fine motor control. Stepper motors, on the other hand, offer incremental movements, enabling accurate positioning of the prosthetic limb. Researchers have focused on optimizing motor size, weight, and power consumption to enhance overall performance and usability.

Table 5. Methods of torque measurement devices

Method	Description
Dynamometer	Measures the torque and rotational speed of a motor or actuator
Inertial measurement unit (IMU)	Measures the angular velocity and acceleration of a prosthetic arm
Strain gauge	Attaches to the motor or actuator to measure the torque generated when the arm is moved
EMG	Measures the electrical activity of the muscles used to control the prosthetic arm
Computer simulation	Uses computer modelling to estimate the torque generated by the motors or actuators

The actuation of joints in prosthetic arms relies on electric motors to replicate natural human movement and provide functional control to users. The motor configuration and control system choice varies based on the specific design requirements and desired range of motion. Different types of motors, such as DC motors, stepper motors, or brushless motors, are selected based on factors such as torque requirements, speed, precision, power consumption, and control complexity. Gears are often employed to achieve the desired torque and speed reduction. Motor control systems, comprising sensors, microprocessors, and algorithms, interpret control signals and adjust motor parameters to facilitate precise joint movement. Feedback mechanisms, including position sensors and force sensors, enhance control and improve movement accuracy. Prosthetic arms are equipped with electric motors that enable a wide range of joint motion, allowing users to perform daily activities more easily.

3.8. Data Collection

The intended research aimed to enlist individuals with upper limb impairments to explore their experiences in performing both indoor and outdoor tasks. The study sought to assess participants' perceptions, emotions, obstacles encountered, and concerns regarding causing or experiencing injury. A detailed framework outlining the systematic approach for conducting the survey and analyzing observations is illustrated in Figure 16. 98 Male and 23 Female participants participated in this study. The criterion for selection was upper limb disability due to either amputation or due to absence of limbs or part of limbs.

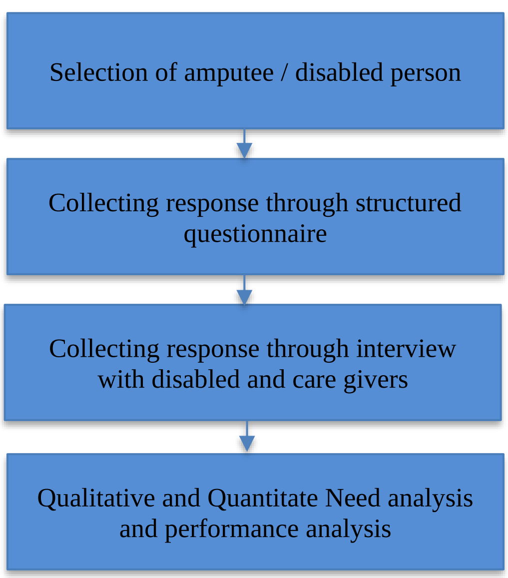

Fig. 16 Response collection and analysis

3.8.1 Cause of disability of the subjects under study

When examining the level of hand amputation, the data indicated that a substantial number of participants had undergone Elbow amputations, with 62 individuals falling into this category. Meanwhile, 44 respondents had undergone shoulder amputations. 2 Persons faced amputation of both limbs; among those, one of the subjects had survived the amputation of both limbs from the shoulder joint. 4 subjects under the survey were suffering from a rare birth defect condition known as Phocomelia, where the proximal aspect of an extremity is absent with the hand or foot attached directly to the trunk.

For 2 subjects, Gangrene leads to serious complications and ultimate amputation of the upper limb. Electric shock was one of the leading causes of amputation. While few had suffered unilateral amputation, 2 subjects had suffered bilateral amputation. The amputations were due to Train accidents, Car accidents, Heavy motor vehicle accidents and Accidents while handling mechanical equipment in the industry and at farms. One of the subjects had his fingers amputated due to frostbite while he was on a climb in Mount Everest in the Himalayan Mountains. Loose hand gloves were given while on the expedition as the reason for the frostbite. Based on the description given by the amputees, a generalized list of necessary activities and patterns has been prepared.

Typical movements of the joints are Lifting, Holding, Moving and Turning. Based on the joints and muscles involved, they are described medically as per the terms given in Table 6. People working in different professions have distinct requirements, and the challenges they face vary.

Therefore, the recommended prosthetic solutions should be tailored accordingly. Table 7 represents the challenges faced by people working in different fields, as observed from the questionnaire conducted and provides the solution to those challenges.

A cutting-edge prosthetic arm that mimics natural movement offers functional control and improves the user's engagement with the environment, which is the end result. Several methods can be used to give control inputs, including myoelectric signals, buttons, and external sensors. Electric motors play a crucial role in achieving gripping and grasping functions in prosthetic hands, allowing for controlled hand and finger movements that replicate human dexterity and strength.

Table 6. Muscular movement for the intended action

Muscular Movement	Action
shoulder flexion/extension, abduction/adduction, and internal/external rotation	Lifting objects
elbow flexion/extension	Holding objects
forearm supination/pronation	Moving objects
wrist flexion/extension and ulnar/radial deviation	Turning objects

Table 7. Occupational challenges and solutions

Profession/Work Field	Challenges Encountered	Critical Arm Component	Recommended Prosthesis
Farming	Difficulty gripping and handling tools	Hand and fingers	Myoelectric grip is strong, lightweight, waterproof and durable
Household	Limited dexterity for daily tasks	Hand and fingers	Multi-articulate fine control, lightweight, waterproof.
Industry Shop Work	Inadequate strength and precision for tasks	Hand and forearm	Robust and adjustable grip with feedback sensors
Office Work	Typing and using a computer mouse	Fingers and wrist	Keyboard-compatible prosthetic fingers with tactile feedback, wrist rotation, lightweight

3.8.2 Prosthetic hand for final motor control

Prosthetic hands can be programmed to execute different grasp patterns, and force sensors provide feedback for precise and delicate grips. The overall control system, powered by rechargeable batteries or external power supplies, interprets user inputs and translates them into motor commands. Proportional control enables modulation of grip strength, while tactile feedback through sensory systems enhances the user's perception of the grasped object. Integrating electric motors into prosthetic arms requires careful consideration of socket design and alignment to optimize the transmission of movement [134]. Effective operation and natural arm movement are guaranteed by the proper motor placement, wiring, and integration of control components. Power distribution and management systems are essential for maximizing battery life and overall performance. Researchers are looking into different actuator technologies for prosthetic arms in addition to electric motors.

McKibben muscles, a type of pneumatic actuator, are known for their weight design, low power-to-weight ratio, and capacity to mimic the behavior of human muscles. Due to their high power density, hydraulic actuators are appropriate for applications requiring heavy lifting and great force output. Prosthetic arms can move in a way that replicates the actual motion of human arms. It considers the freedom of motion of the human arm thanks to SMAs, which are shape memory alloys, while EAPs, which are electroactive polymers, provide weightlessness and cosmetic advantages. Body-powered control, myoelectric control, brain-computer interface (BCI), EMG-driven control, speech-controlled control, and eye-controlled control are only a few of the control techniques used in prosthetic arms. Each technique has pros and cons with regard to cost, difficulty, and precision.

Durable, better-controlled actuators are more effective. Research is being carried out to improve the functionality and user experience of prosthetic arms. With the right actuators, it is also critical to consider the torque required for holding and moving objects when evaluating torque in prosthetic arms. This required torque is influenced by things including the arm's weight, the object being moved, and the level of precision required to complete the task. For prosthetic arms to successfully perform tasks such as lifting, gripping, and manipulating objects, precise torque control is necessary. Extensive research has been done on prosthetic arm design, with a focus on finding a solution for transhumeral amputation and a Machine learning approach for it. For accurate control and a broad range of joint motion, electric motors, especially DC motors and stepper motors, have become common options.

The positioning of the motor, the design of the socket, and the optimization of the control unit must all be carefully considered when integrating electric motors into prosthetic arms. Other actuator technologies, such as pneumatic actuators and shape memory alloys, are also being investigated for their distinct advantages. Different forms of control, from body-powered to sophisticated brain interface-based control, offer varying degrees of intricacy and precision. Ongoing research aims to further improve the strength, control, and efficiency of prosthetic arms, ultimately enhancing the functionality and user experience for individuals with limb loss.

4. Conclusion

This study highlighted advancements in control mechanisms, innovation in material, complexity in calibration and limitations to energy efficiency. Myoelectric control evolution from a simple threshold-based activation to an advanced machine learning-driven algorithm is studied in this work. Traditional materials, namely carbon fiber and aluminum, are durable and lightweight. Recent advancements in biocompatible polymers improve customization and affordability. These innovative materials increase comfort while wearing them for longer durations. Significant challenges are posed due to high cost, the requirement for frequent calibration, and usability issues. Integration of haptic feedback essential for the sense of touch is still in the early development stage.

It is evident that the optimal solution for a prosthetic arm requires careful consideration of various factors. A transhumeral amputation is considered the most studied type of amputation. Carbon fiber composites are frequently utilized because of their excellent strength-to-weight ratio, which enables both strengths and decreased weight for the optimal design of the prosthetic limb for such an amputation. But in case of increased comfort, customization and strength, 3D-printed materials, such as nylon or titanium should be used. When considering the best actuator to use in a prosthetic arm, myoelectric and hydraulic or pneumatics are the two paths designing can take.

Myoelectric actuators, which utilize muscle signals from the user, are widely used in prosthetics due to their ability to detect electrical impulses derived from the rest of the muscles in the remaining part of the limb and convert them into control signals for the prosthetic hand. Whereas hydraulic or pneumatic actuators provide more force and flexibility but may be bulkier. Ultimately, the optimal solution for a prosthetic arm can be derived by finding a balance between ease of use, functionality and user-friendly design. When engineering, material science, robotics, and biomechanics work towards the betterment of arms design, a design that empowers, especially abled individuals and gives them self-dependency can be made affordably in the near future.

4.1. Future Scope

Bionic limbs that closely mimic natural limb movement and sensation are a promising area. These prostheses may incorporate advanced sensors, artificial intelligence, and neural interfaces to enable more intuitive control and provide sensory feedback to the user. Brain-Machine Interfaces have the potential to revolutionize prosthetics. Direct communication between the brain and prosthetic devices offers precise control over limb movement. Research is ongoing in this area, and it may lead to more natural and seamless integration of prostheses with the human body. 3D printing technology has already made prosthetic fabrication more accessible and customizable. The future may see even more sophisticated 3D-printed prostheses tailored to the individual's anatomy and requirements, with improved aesthetics and functionality. Advances in materials science are resulting in lightweight, durable, and biocompatible materials for prosthetic limbs. An increase in comfort results in enhanced performance while reducing the risk of complications. The development of prostheses that provide sensory feedback to users, such as the sensation of touch or temperature, could greatly improve their functionality and user experience. Research into energy-efficient prosthetic designs is ongoing. More efficient power sources and energy-recycling mechanisms could reduce the need for frequent recharging or battery replacement. Prosthetic devices may be equipped with sensors and connectivity, allowing remote monitoring of their function and the wearer's health. This can lead to more timely adjustments and improved user support. Efforts are being made to make advanced prosthetic technology more affordable and accessible to a wider range of people, including those in low-resource settings. This could involve open-source designs, cost-effective manufacturing methods, and partnerships with humanitarian organizations.

Sustainable materials and manufacturing processes are becoming increasingly important in the field of prosthetics to reduce the environmental impact of these devices. Recognizing the importance of psychosocial support, future prosthetic care may include counseling, peer support groups, and mental health services to help users adjust to life with a prosthesis. In the long term, regenerative medicine approaches, such as tissue engineering and limb regeneration, could potentially eliminate the need for traditional prosthetics by allowing the body to regenerate lost or damaged limbs.

The future of prosthetics is likely to be shaped by interdisciplinary collaboration between engineers, materials scientists, neuroscientists, clinicians, and users themselves. As technology continues to advance, prosthetic devices are expected to become more functional, comfortable, and integrated into the lives of individuals with limb loss or limb impairment, ultimately improving their overall quality of life.

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