There are millions of amputees worldwide, and amputation has significantly affected their lives. People with hand losses have difficulties performing the activities of daily living (ADLs). Prosthetic hands have been developed to perform the functions of a human hand by grasping various objects. However, mimicking the actual grasping function of a human hand is still an unresolved research topic. Researchers continue to improve the functionality of hand prostheses to create more efficient and closer to human motion. Herein, the current challenges and approaches for enhancing the grasping function of 3D-printed hand prostheses are investigated. Three technology sectors are discussed for the efficient grasping motion of hand prosthetics: 1) how to recognize the user’s desired grasping gestures by sensing systems; 2) how to power the prosthesis for grasping objects through different actuation systems; and 3) how to perform the grasping motion by 3D design and mechanisms. This article reviews valuable information regarding the current innovations toward improving prosthetic hands’ grasping function to help researchers design more functional hand prostheses.

1. Introduction

There are over 1.7 million amputees only in the US, and this rate number is increasing by 50,000–100,000 new amputations per year. Among these cases, 10% of them are hand-related amputations. Amputation usually happens because of accidents and health disorders, including trauma, malignancy, vascular disease, congenital deformities, and infection. Amputation has a significant effect on people’s lives; some even have to change their jobs after the amputation. This also causes problems in ordinary life and decreases life satisfaction among these people.

To help amputees get back to their everyday lives, several hand prosthesis devices were developed from a long time ago when body-powered prostheses were common. With the current advancement in the field of biotechnology and robotics, innovations are used in the field of prostheses design and control. Modern hand prostheses are more sophisticated than before, equipped with several sensors and actuators to improve their functionality.

A practical prosthetic hand must allow amputees to perform activities of daily living (ADLs). One crucial ability of the human hand is grasping complex-shape objects with various shapes. Several groups have tried to mimic this characteristic of the human hand by bringing on innovations in sensing, control, actuation, and structure design of hand prosthesis. However, designing a prosthesis that can completely mimic the human hand’s function is still concerned.

Basically, to grasp an object efficiently, three main tasks should be considered by the prosthesis. First is perceiving and acquiring a proper gesture to adapt the device’s configuration to the required shape for the desired motion described in Figure 1. These grasping gestures can be categorized into power, precision, and lateral grasp gestures. The second task is adopting an effective grasping force to hold the object without slipping or damaging it. Finally, the grasping action has to be carried out by mechanical mechanisms, and the prosthesis’s structure should be designed to adjust its shape to the form of the grasped object.

Basically, human hand gestures can be divided based on their function into two groups of power and precision and based on their gesture’s shape into two groups of round and flat gestures (Figure 1).

Several design aspects should be considered while designing a prosthetic hand, including aesthetics, cost, functionality, and more. This study aims to gather the current developments in designing a hand prosthesis regarding the approaches to improving artificial hands’ grasping function. A prosthetic hand combines electrical, biological, mechanical, and computational systems. Developing a practical prosthetic hand requires the functionality of all these systems. Three subsystems, including: 1) sensing systems; 2) actuation systems; and 3) 3D designs and mechanisms, can be considered for an artificial hand (Figure 2). Although a lot of researches have tried to develop devices to enhance the grasping function of hand prostheses, all this information is scattered, and no source has organized all these system designs. In this article, a comprehensive exploration of each system’s current innovative design approaches has been made, and the advantages and disadvantages of developed systems are

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Figure 1. Examples of human grasp gestures: the ability of the human hand to adjust its shape to the form of complex-shape objects.

Figure 2. Prosthetic hand consists of a sensing system, actuation system, and structure and mechanisms.

presented to help researchers design a prosthetic hand with a better grasping function.

2. Sensing Systems

Hand motion analysis is crucial for understanding the hand grasping mechanism for performing manipulation tasks. This directly affects the functionality of prostheses; therefore, several groups of researchers focused on designing innovative human hand motion-capturing systems, which can be mainly categorized into five groups: 1) glove-based data capturing; 2) market-based data capturing; 3) electromyography (EMG)-based data capturing; 4) haptic-based data capturing; and 5) vision-based data capturing.Only the EMG method can extract the capturing; 4) haptic-based data capturing; and 5) vision-based data capturing; 3) electromyography (EMG)-based data capturing. Hand motion-capturing systems, which can be mainly categorized into five groups: 1) glove-based data capturing; 2) market-based data capturing; 3) electromyography (EMG)-based data capturing; 4) haptic-based data capturing; and 5) vision-based data capturing.

2.1. Electromyography (EMG)

Recently, human biological signal processing methods, including EMG [9–13] electroencephalography (EEG) [14–16] electrocorticography (ECoG) [17–19] intracortical neural signals [20,21] magnetoencephalography (MEG), [22,23] and blood oxygen levels [24] have been used to perceive the amputee’s desired hand motion. EMG methods have been mostly used among all these methods due to their reliability, affordability, and ease of use. [25]

EMG measures the electrical muscle activity in response to a nerve’s stimulation. [26] There are two methods of measuring the muscle’s responses, including intramuscular EMG [27] and surface EMG (sEMG). [11] The intramuscular EMG is used to directly target a muscle by implanting EMG electrodes inside the human body. This increases the accuracy of EMG measurements but requires clinical operations and possible postsurgery problems. [28] In contrast, sEMG is widely used, especially in EMG armbands, to measure the muscles’ electrical activities in prosthetic hands as they are not invasive and are easy to use. [29–31] sEMG dry electrodes can detect EMG signals on the forearm skin. [32] Using the portable EMG sensor, the electrical signals generated from forearm muscles can be detected and used to represent hand movements. [13] Nevertheless, this method is not as accurate as the intramuscular EMG method, and electrical signal interactions occur between adjacent muscles, which might cause errors in measuring the activity of a specific muscle. [28]

After acquiring EMG signals, raw data has to be filtered because they are very noisy and un-interpretable. [14] As EMG signal is an analog signal, band pass filter is a suitable candidate to remove the noise signal. [35] The filter removes high and low frequencies from the raw signals. [36] Filtered signal is then to be amplified due to the weak amplitude of raw EMG signals. [17] Usually, in the hand prostheses, the electrical contraction response of the flexor or extensor muscles is measured to start grasping. Traditionally, the amplitude of EMG signals was measured, and a threshold was determined to start grasping. [38] This can be used for simple grasping functions; however, it couldn’t provide multigrasping gestures for complicated manipulation tasks.

Lately, electromyogram pattern recognition (EMG-PR) methods have been developed to use the EMG signal’s pattern in addition to its amplitude. Several pattern recognition algorithms based on machine learning (ML) and virtual reality (VR) methods have evolved to process EMG signals and adopt desired grasp patterns. Parajuli et al. [19] investigated real-time EMG-PR methods for perceiving hand’s gestures in prosthetic hands. Based on this research, processing an EMG signal consists of five steps: 1) preprocessing; 2) data segmentation; 3) feature extraction; 4) myoelectric classification; and 5) postprocessing (Figure 3).

In the first step, EMG raw data is filtered to remove unwanted noises and disturbances. Then, the preprocessed EMG signal is segmented using windowing methods (overlapping and non-overlapping methods) to become useful inputs for pattern recognition techniques. Afterward, EMG features in three domains of time, frequency, and time frequency are extracted, and then ML classification algorithms are used to classify the EMG patterns. Finally, in the postprocessing step, classification errors and misclassifications are removed.
Although processing EMG signals provide a secure connection between the amputee’s muscle activities and prosthesis, these methods are slow due to the required computational processes. Also, turning EMG signals into a practical control signal is still challenging because each amputee has a different physiology, muscle forces, and electrode placement.

Figure 3. EMG pattern recognition (EMG-PR): five steps of processing EMG input to distinguish desired grasping patterns. Reproduced under terms of the CC-BY license [39] 2019, MDPI.
2.2. Motion Sensing

Motion sensors are used to improve the prostheses’ grasping motion by providing feedback for closed-loop control of their movements. Mohammadi et al.\[40\] used a potentiometer attached to the shaft of each micro-DC motor to control each finger’s position (Figure 4a). Cheng et al.\[41\] designed a prosthetic finger with embedded angle sensors inside the finger’s joints. Torque sensors and tactile sensors were also fit inside the finger’s structure. With the advancement in the field of sensory and control, the need for providing more accurate grasping and manipulation gestures created multimodal sensory systems for prosthetic fingers. Weiner et al.\[42\] designed a multimodal sensory system for artificial fingers. The little finger and middle finger were embodied with four and six sensors. The sensory system included pressure, shear force, accelerometer, distance sensor, encoder magnet, and joint angle sensors. These sensors were embedded inside the prosthetic finger and covered with 3D printing (Figure 4b).

Also, resistance-based flexor sensors are used to measure the fingers’ rotational angle. These sensors are mainly used in glove-based motion capturing systems. Canizares et al.\[43\] designed a glove-based hand prostheses and used flex sensors to measure the desired finger flexion from the user’s glove (Figure 4c) and applied the rotation to the prosthetic fingers. The prosthetic hand was fabricated using fused deposition modeling (FDM) 3D printing, and DC motors were placed inside the prosthesis’s forearm. These flex sensors are cheap and accurate, but they cannot be used by amputees with hand losses since they are hand-based motion-capture sensors.

Although vision and haptic sensory systems cannot be directly used to detect the amputee’s desired grasping gestures, they could be used to monitor the hand’s grasping gestures to provide sensory feedback information for motion controller unit. Several control technologies have been developed in recent years to implement vision and haptic sensory information to control the prostheses’ motion.\[44–50\]

Inertial measurement unit’s (IMU) information also can be integrated with EMG data to resolve the sensitivity of EMG signals to the physical and physiological variations.\[51–53\] (Figure 4e). Lauretti et al.\[52\] proposed a novel approach for EMG control of transhumeral externally powered prostheses for simultaneously managing prostheses’ multiple DOFs. This study used two inertial sensors and two EMG electrodes to detect the user’s movement. Also, Stival et al.\[51\] proposed a method to integrate sEMG signals with IMU information to provide a subject-independent framework for controlling the robotic hand.

2.3. Tactile Sensing

Tactile sensors are used to measure information of physical interaction between device and environment. Providing tactile

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**Figure 4.** Motion sensors. a) Potentiometers attached to the DC motors inside the palm to measure the position of each finger. Reproduced under terms of the CC-BY license.\[40\] Copyright 2020, PLOS ONE. b) Accelerometer and encoder magnet embedded in finger joints. Reproduced under terms of the CC-BY license.\[42\] Copyright 2019, MDPI. c) Flex sensors attached on gloves to capture finger’s flexion and extension. Reproduced with permission.\[43\] Copyright 2017, IEEE. d) A combination of computer vision, eye-tracking, EMG, and IMU for controlling dexterous grasping gestures. Reproduced with permission.\[130\] Copyright 2019, IEEE. e) Using IMU and EMG signals to control the grasping gestures of prosthetic hands. Reproduced with permission.\[52\] Copyright 2016, IEEE.
feedback on hand prostheses can significantly improve the grasping function of hand prostheses and user experience. Several tactile sensors have been created to mimic biological sensing for users in recent decades. Researchers have been focusing on improving tactile sensors’ characteristics, including linearity, accuracy, repeatability, stability, and dynamic response.

With the current advancement in developing anthropomorphic hands, flexible structures have been used for fabricating prosthetic hands. One major challenge in designing tactile sensors is keeping the performance of tactile sensors while using them within flexible structures. Rigid body sensors with an effective arrangement can be integrated into the soft robot hands. Liang et al.\textsuperscript{[54]} used a functional material arrangement with a suitable structure to develop a high-performance tactile sensory system able to be integrated into soft prosthetic hands (Figure 5a).

Furthermore, entirely soft electronics have been created to match the flexibility of soft prosthetic hands. Rocha et al.\textsuperscript{[55]} fabricated soft-matter-resistive and capacitive pressure and bending sensors for a soft prosthetic hand. In this study, polydimethylsiloxane (PDMS) elastomer was used as base material and structured carbon black (CB) was used as filler to fabricate a conductive CB–PDMS composite. The fabricated CB–PDMS composite was used to make a flexible capacitive pressure sensor. These sensors were placed inside a 3D-printed robot finger and covered with elastomer skin.

Among all tactile sensors, pressure sensors are used to measure the force applied to the object while grasping, which can be used to provide stability during grasping. These pressure sensors are mostly divided into five groups: piezoresistors, capacitive, piezoelectric, triboelectric, and optical sensors. Li et al.\textsuperscript{[56]} discussed the advantages and disadvantages of these sensors. Piezoresistor sensors are highly sensitive, but they are unstable and sensitive to temperature change. Capacitive sensors are suitable for dynamic force measurements with low energy consumption and temperature sensitivity, but they have limited spatial resolution and are noise sensitive. Triboelectric nanogenerator (TENG) sensors are suitable candidates for self-powered pressure sensors in wearable and IoT as they can harvest energy from pressure and friction. Piezoelectric sensors do not need a power supply and are reliable and suitable for vibration.

Figure 5. Tactile sensing systems. a) Integrating pressure sensors with an effective arrangement and structure design into a soft prosthetic hand. Reproduced with permission\textsuperscript{[20]} Copyright 2013, Elsevier. b) Artificial stretchable and smart skin equipped with pressure, temperature, humidity, and electroresistive heaters. Reproduced with permission.\textsuperscript{[54]} Copyright 2014, Springer Nature. c) A neuromorphic sensing system integrated into the prosthetic hand to feel pain and touch. Reproduced with permission.\textsuperscript{[60]} Copyright 2018, Science Robotics.
measurements; however, they have limited spatial resolution and are sensitive to temperature. Kim et al.\cite{57} fabricated a highly sensitive capacitance pressure sensor by optimizing the sensor’s material and structure. In this study, facial fabrication methods, including the breath figureure (BF) method, were used to fabricate a nanoneedle dielectric microstructure and filled between electrodes. Experimental tests showed high sensitivity of sensors close to the human skin in low-pressure ranges (<1 kPa).

Other than pressure sensors, temperature, humidity, and nociception sensors have been developed to provide more human-like feelings for artificial hands. Kim et al.\cite{58} fabricated a novel artificial stretchable skin integrated with temperature, pressure, and humidity sensor arrays embedded into an ultrathin crystalline silicon nanoribbon. The designed artificial skin was equipped with electroresistive heaters to keep the hand prosthetic warm (Figure 5b). Healing is another feature that has been tried to be mimicked by researchers. Benjamin et al.\cite{59} fabricated a self-healing composite with pressure and flexion sensitivity properties. A supramolecular organic polymer with embedded mechanic healing properties. This could be used as artificial skin in prosthetic hands.

Neuromorphic systems are used to mimic the function of biological neural systems to provide sensing and neural modeling. Recently, neuromorphic sensing systems were being used as tactile sensors. Osborn et al.\cite{60} invented a neuromorphic multilayered e-dermis. The e-dermis was made of conductive and piezoresistive traces on textiles layers covered with silicone rubbers to provide touch and pain information to the user (Figure 5c). The amputee could distinguish objects’ shapes and sharpness using the neuromorphic sensing system in this design. In another study, Bao et al.\cite{61} developed a novel neuromorphic pressure sensing system using synaptic transistors to train the prosthetic hand to grasp complex-shape objects. This study demonstrated that a robotic hand could hold an object with a complex shape after several training iterations.

Furthermore, the triboelectric effect can be used for energy harvesting. TENGs are used to develop self-powered sensors in applications such as wearable electronics, the Internet of Things (IoT), medical devices, and prostheses.\cite{62} Recently, researchers have been focusing on developing stretchable triboelectric tactile sensors to detect hand gestures. Bu et al.\cite{63} developed a stretchable triboelectric–photonic smart skin (STPS). The STEP comprises a soft aggregation-induced emission (AIE) substrate with a bonded microrcracked metal film and a stretchable layer of Ag network network. The strain-dependent property of STPS was achieved for lateral tensile sensing. Also, the device was used as a TENG for pressure sensing by generating an electric signal while applying vertical force. The presented sensor was used to cover a robotic hand as artificial skin and showed promising results in recognizing hand gestures with the help of multifunctional sensing mechanisms of photoluminescence and triboelectrification. In a recent study, Zhang et al.\cite{64} developed a self-powered force sensor for tactile sensing using TENGs. In this study, polydimethylsiloxane (PDMS) cylinders were used for force sensing, and a flexible tip array made of CB/MXene/PDMS composites was used as nanogenerators to generate the signal when applying an external force. The fabricated sensor demonstrated high sensitivity in detecting the force amplitude and direction. Also, Zhao et al.\cite{65} developed a highly stretchable organic tribotronic transistor (SOTT), which was composed of a stretchable substrate, silver nanowire electrodes, semiconductor blends, and a nonpolar electrode. The fabricated sensor retained the performance under a thousand cycles of 50% stretch in parallel and perpendicular directions.

3. Actuation Systems

The actuator part of a hand prosthesis is the device’s power source. Using a proper actuation system significantly affects the grasping force and reaction time. Generally, there are two types of power sources for hand prostheses: externally powered and body-powered systems. Body-powered actuation systems require the amputee to exert the grasping force by himself. Smit et al.\cite{66} provided hydraulic cylinders to help the amputee to exert the required grasping force. Nonetheless, body-powered prosthetic hands are restricted to few grasping patterns because of limited power inputs from the user. Recently, externally powered prosthetic hands have been advanced to address these issues. Innovative actuation systems have been recently developed to provide better grasping function. These actuation systems can be categorized into three groups: 1) electric motors; 2) artificial muscles; and 3) pneumatic and fluid actuation systems.

3.1. Electric Motors

Electric motors are used as a conventional actuator system of the prosthesis due to their low cost, availability, and being well developed (in a wide range of torque, speed, and power). DC motors are divided into two groups: brushed and brushless DC motors. Brushless DC motors (BLDC) have been broadly used in different applications due to their high speed, torque, and efficiency. Stepper motors are one type of BLDCs that can provide precise motion control and are used in prostheses applications to provide accurate grasping gestures.\cite{67–69} Also, ultrasonic motors have been used as an actuator due to their large output power relative to their small size.\cite{70} Although electric motors have been commonly used as actuators in hand prostheses, in order to provide abundant torque for grasping, a gear train with a high reduction ratio should be used, which increases the size of motors and causes problems in fitting these motors inside the prostheses. Microgear DC motors are common actuators fit inside the prosthetic hands without enlarging the device and increasing the device’s cost.\cite{71,72} These electric motors are mostly installed in the prosthesis’s arm, palm, or fingers (Figure 6).

Furthermore, different number of actuators have been implemented for prosthetic hands. Several commercial and non-commercial prosthetic hands have used separate actuators to operate each finger individually. Tact,\cite{73} i-LIMB,\cite{74} and Vincent\cite{75} prosthetic hands used six actuators, and i-LIMB Pulse,\cite{76} Bebionic, and Bebionic v2\cite{77} prosthetic hands used five actuators to provide individual finger control. Although using separate actuators offers more flexibility in prosthetic hand motion control, each motor must be smaller as the number of
DC motors increases. Consequently, less grasping force would be generated. To address this issue, underactuated and differential mechanisms have been developed, which are thoroughly explored in Section 4.2.

3.2. Artificial Muscles

Electric motors are efficient in providing power for simple grasping functions; however, when it comes to provide complex grasping gestures, multiple electric motors would be required, which increases the weight of the prosthesis and reduces the functionality of the device. Recently, soft actuators as artificial muscles have been developed by inspiring from the biological function of muscles to address this issue. The main advantage of artificial muscles is providing several actuators with flexibility without increasing the device’s size and weight. Also, they are silent in comparison with electric motors. Nevertheless, artificial muscles have a limited stroke and force capacity.

Piezoelectric, mecanochemical polymers, conducting polymers, and electromagnetics materials have been used to make artificial muscles in many robotic applications; however, most of them are not functional because of low output power. Arjun et al. designed a 3D printed hand prosthesis and used an electrothermal actuator. This study used nylon 6-6 polymer as a low-cost actuator and showed the grasping function of the device using this actuator (Figure 7a). Shape memory alloys (SMAs) are another candidate for artificial muscles which can provide a larger force-to-mass ratio compared with polymer-type actuators. Lee et al. used multiple SMA artificial muscles and increased their length using designated paths to achieve enough output force and range of motion. She et al. also designed a soft robotic finger using SMA actuators. In this study, two SMA wires were embedded inside a soft finger on each side. These SMA wires were surrounded by resistance wires for heating. Accordingly, the prosthetic finger could smoothly move to each side (Figure 7b). Yoter et al. developed a hydraulically amplified self-healing electrostatic (HASEL) actuator as an artificial muscle for prosthetic hands (Figure 7c). They showed that the Peano-hasel actuator is 10.6 times faster with lower electrical energy consumption than DC motor actuators. Recently, some research groups introduced hybrid actuators to take advantage of both artificial muscles and electric motors. Gao et al. designed a hybrid actuator combining SMA and micro-DC motors, in which micro-DC motors were used to provide enough grasping force, while SMA actuators were used to improve the reflex speed to prevent grasped objects from slipping.
3.3. Pneumatic and Hydraulic Actuators

To perform complex grasp synergies, complicated mechanisms are required for rigid structure hand prostheses. Some researchers increased the degree of freedom (DOF) of the prosthesis to provide more flexibility for the device. However, adding mechanisms and sensors to compensate for the lack of mechanical compliance makes the prosthesis’s design sophisticated and expensive. Recently, soft robots have been developed to provide mechanical compliance to adapt to the shape of unknown environments without additional sensors and complex mechanisms. Researchers have used soft materials to fabricate flexible structures for hand prostheses. However, these structures require pliable actuators as well.

Pneumatic and hydraulic actuators have been currently developed to provide soft structures as actuators. Hydraulic systems can be used in prostheses with several DOF to resolve the required numerous electric actuators and bulky prostheses. Fras et al. designed a soft biomimetic prosthesis hand using a pneumatic system to actuate each finger independently. This provided a human-like hand prosthesis able to passively adapt its shape to the grasped object. In this study, conical 3D-printed cores were wound and coated with thin silicon layers using a mold and tightly connected to the pneumatic inlet pipes (Figure 8a). Also, Cargol et al. presented a miniaturist hydraulic system that was used as an actuation system for artificial hands. Biocompatible silicone oil was used as a fluid, and micropumps and fluid reservoir were embedded inside the prosthesis’s palm (Figure 8b). This study showed the device’s adaptability during the grasping and holding of objects compared with the conventional electromechanical actuation systems. Moreover, fluid systems can be used for making artificial muscles. Wu et al. developed an artificial muscle made of twisted and coiled nylon fibers. The actuation system circulates hot and cold water to power the prosthetic hand and provides fast finger movement (Figure 8c).

4. 3D Designs and Mechanisms

4.1. 3D-Printed Prosthetic Designs

3D printing technology has been a promising method for researchers to fabricate customizable, lightweight, cheap, and rapid prosthetic hands. This technology can be used to fabricate both rigid and soft structures.
Grasping an object with a complex shape requires the prosthetic hand’s design to be mechanically compliant. The human hand structure is made of rigid parts (skeletal part) and soft parts (soft tissues) to make a perfectly compliant structure for grasping objects. Articular cartilage mechanism in finger’s joints provides smooth and flexible relative motion between bones. Inspiring by the human hand, researchers developed elastic joints for rigid prostheses. Dunai et al. [68] designed artificial articular cartilages for finger joints to provide a high level of movement by increasing the DOF of each finger. Each phalange was fabricated by 3D printing polylactic acid material, and flexible rubber-made extensor tendons and artificial adductor policies were used to fabricate the flexible joints (Figure 9a). SoftHand Pro (SHP) [102] is another prosthetic hand that uses flexible joints to connect each phalange together. Clinical testing of this device proved the functionality of the device in grasping various objects due to the adaptive and andromorphic design. Alkhatib et al. [103] used 3D printing technology to fabricate flexible joints too. In this study, elastomeric material was used instead of plastic joints to provide flexibility at joints.

Recently, soft robotics emerged to provide compliant, lightweight, and simple structures for prostheses. Designing monolithic soft structures using 3D printing technologies is a favorable way of reducing the weight and complexity of manufacturing a prosthetic hand. Mohammadi et al. in X-limb prosthetic hand [40] used 3D printing technology to fabricate a monolithic finger structure with multiarticulating capability. This prosthetic hand could provide three grasp gestures as well as individual finger motion while having lightweight and low cost to fabricate (Figure 9b). Tawk et al. [104] designed a soft gripper with a soft auxetic structure. In this study, the auxetic structure of soft fingers was optimized using finite-element analysis (FEA) and 3D printed with thermoplastic polyurethane (TPU). Using metamaterial in the soft gripper structure provided a high level of mechanical compliancy to grasp objects of various shapes (Figure 9c). Also, 3D printing technology has been widely used to fabricate embedded sensor structures. Another use of 3D printing technologies is manufacturing the casting mold to produce prosthetic hands. [105–107] Choi et al. [105] replaced the rigid linkage structure of the prosthetic finger with a monolithic compliant bone. A mold was 3D printed with PLA to produce the artificial finger. Sensors were embedded inside the mold and silicone was cast into the mold to form the monolithic artificial finger with embedded sensors.
The fabricated structure was mechanically compliant and impact resistant.

### 4.2. Power Transmission Mechanism

Early myoelectric prosthetic hands could fulfill a single DOF grasping gesture by simultaneously adducting the thumb against the other four digits. Recently, multigrasping patterns are provided to simulate the actual human hand function by adding multiple actuators. However, the increasing number of actuators causes problems regarding the device’s cost, weight, size, and maintenance. Hence, several research groups focused on bringing innovation in power transmission mechanisms instead of power itself. During past decades, differential power transmission mechanisms and underactuated digits have been broadly explored.

Differential mechanisms provide multiple actions from a single actuator by providing additional DOFs. The differential mechanisms can be categorized into 1) linkage-based mechanisms; 2) cable/cord and pulley mechanisms; and 3) rack and pinion mechanisms. Wattanasiri et al.\cite{108} designed a prosthetic hand that could perform neutral, power, and precision gestures with only one actuator. This design used a linkage-based mechanism to provide flexion motions for precision grip and dwell action for power grip for the thumb, while the motion of other digits was identical in each pattern (Figure 10a). This study showed a significant increase in grasping force due to using a powerful actuator. Controzzi et al.\cite{109} designed a transmission mechanism with three actuators that could satisfy most of the daily hand activities. Belter et al.\cite{110} proposed a novel differential mechanism to provide two DOFs from one actuator. The designed prosthetic hand was capable of performing three types of grasping (lateral, precision, power) with a single actuator. The differential mechanism consisted of a cable and pulley system to change the motion of the thumb to provide different grasp gestures (Figure 10b). The designed prosthesis achieved lighter weight, but a latency existed due to the switching mechanism. Xu et al.\cite{111} created a single-actuator hand prosthesis using a continuum differential mechanism. This study integrated a rack and pinion system into a mechanical linkages system to provide a continuum motion for the thumb (Figure 10c). The prototype prosthesis could successfully grasp objects of various shapes. Gao et al.\cite{112} designed a selectively lockable differential mechanism for controlling the angular position of each finger to provide a wide range of grasping gestures. This study developed a belt cam differential mechanism for all fingers except the thumb to provide two different positions (Figure 10d). Also, six lockable positions were intended for
the thumb, which could increase the grasping gesture to 96 (16 × 6) position combinations.

Other than differential mechanisms, underactuated fingers have been widely designed to provide mechanical compliancy to the shape of grasped objects. Generally, there are two types of underactuated mechanisms, including 1) cable/cord and pulley mechanisms and 2) linkage-based mechanisms. Cable/cord and pulley systems usually can support small grasping forces due to friction and elasticity problems. Fei et al. used SMA wires and pulleys as an underactuated mechanism to provide multijoint motion of the designed prosthetic finger (Figure 11a). Also, Pisa/IIT soft hand was designed based on the hand’s synergies using a cable and pulley mechanism. An adaptive synergy actuation system was provided for desired joint motion patterns. Linkage-based mechanisms, however, are used to provide large grasping forces, but these mechanisms are more sophisticated, heavier, and more expensive to fabricate. LiCheng et al. designed an underactuated linkage-based finger with four joints and single DOF linkages. Dimensions and location of linkages were optimized based on the finger configuration while grasping a cylinder. Also, mechanical linkages can be used in hybrid actuation systems with SMA wires and electric motors (Figure 11b). Also, designing the optimal length of each phalange and location of each joint is crucial for providing human-like grasping motion in rigid structure prosthetic hands. Lim et al. used a parametric design method to optimize the length of each linkage and location of each joint to mimic the human hand path during the grasping motion. The designed finger was fabricated using FDM 3D printers. Also, Kashef et al. proposed a robust prosthetic design method by considering the dynamic response of a four-kink underactuated finger. In this study, a forward dynamic model of linkages was used to simulate the angular displacement of links using the constrained Lagrange method and commercial software (MATLAB and Adams). Design parameters including linkages’ dimensions and weights were optimized to increase the conformability of the prosthetic hand to the shape of the grasped object based on the results of dynamic analysis.

5. Key Works and State-Of-The-Art Technologies

In this article, a comprehensive exploration of innovative hand prosthetic designs has been made. Here, key works and state-of-the-art technologies in each section are chosen and emphasized.
EMG signal processing has been recently spotlighted for the perception of the grasping gesture of prosthetic hands. Explainable artificial intelligence (XAI) has emerged to produce explainable AI models, which help human users understand and thereby trust the AI classification results. Recently, XAI has been applied to EMG pattern recognition for hand grasping gesture classification. This method helps to add physiological explanations to how the artificial intelligence classifies the grasping gestures, which improves the classification accuracy, robustness, and computation cost while reducing the number of required EMG electrodes.

Artificial skins with multisensory functions have been developed to mimic the function of human skin. Ionic tactile sensors (ITS) are being developed to emulate the human skin considering not only mechanical behavior but also the human sense of touch. Hydrogel materials have shown promising potential for creating multifunctional and mechanically compliant artificial skin, which can form the next generation of e-skins.

Also, neuromorphic electronics have been developed to mimic biological neural systems. With the help of short-term and long-term memory effects in synaptic transistors, trainable prosthetic hands have been developed in recent years. This feature enables the artificial skin to remember the grasping history after applying several repeating grasping actions, which improve the grasping function of the prosthetic hand over time.

Recent developments in TENG technology for harvesting electronic power can be used to develop self-powered tactile sensors. Using TENG sensors as tactile sensors in prosthetic hands provides a source of renewable energy to detect the grasping gestures of the prostheses without the dependency on external electric powers.

Artificial muscles have been developed in the last decades to emulate human muscle function in different tasks. The prosthetics applications were not an exception and researchers tried to compensate for the loss of muscles for amputees with artificial muscles. Although several human-like soft actuators have been demonstrated in recent years in the field of soft robotics which provide multidirectional, silent, fast, and low-energy-consumption capabilities, there are some challenges that still researchers try to improve in their design. Improving the force density, peak strain, cycle life, and cost are some of these challenges. However, one of the main challenges in this field is mimicking the ability of real muscles in modifying their performance based on the applied forces. Some researchers proposed the self-healing mechanisms in their actuators. Researchers have used the anisotropic behavior of metamaterials to develop artificial joints and fingers, which can show different stiffnesses and deflection behaviors in the designated loading directions. This improves the mechanical compliance of the prosthetic hand to the shape of the grasped object which directly affects the grasping function of the prosthesis. Lattice structures used in the metamaterials could be optimized based on loading conditions to improve the mechanical compliance of prosthetics. Also, integration of metamaterials with embedded sensors could be used in prosthetic hands especially in artificial joints to develop precise and low-power sensory systems.

6. Conclusion and Future Prospects

A prosthetic hand is a comprehensive system consisting of several different subsystems. Here, we summarized recent studies on a 3D-printed prosthetic hand with improved grasping mechanisms specially focused on three subsystems including 1) sensor and control systems; 2) actuation systems; and 3) structural designs and their grasping mechanism. In each chapter, design challenges and approaches for improving prosthetic hands’ grasping function are thoroughly reviewed. This study shows that although significant advancement in prosthesis design have been made in recent years, designing a prosthetic hand that can completely mimic the hand grasping function is still challenging. Table 1 provides some of the challenges of designing a functional prosthetic hand regarding the grasping capability of the device.
We look forward to the 3D-printed prosthetics as one of promising solutions to amputees. Here are some perspectives for three aforementioned subtechnologies. Intramuscular EMG methods can resolve the problems regarding sEMG electrode placement and muscles' signal interactions; however, these methods require surgical treatments.[126,127] For those amputees who lost their hands or forearm muscles, the EMG measurement is not possible. In this case, the brain biological signals such as electrocorticogram (ECoG)[128] and electroencephalogram (EEG)[129] can be used to perceive desired hand motions. Using intraneural stimulations as position feedback can deliver accurate position control of the prosthetic hand. Time electrodes can be placed inside the amputee’s forearm to detect the desired range of flexion and extension for each finger.[22] Regarding the improved actuation, differential and underactuated mechanisms can be used to provide multiple prosthetic motions from a single actuator. This helps to use a more powerful actuation system to deliver higher grasping force.[108] In terms of potential prosthetic designs, soft hand structures can be used to completely conform to the shape of grasped objects.[96] Also, flexible joints can be utilized in rigid structure prosthetic hands to provide more mechanical compliance.[68] Finally, functional artificial skins can provide an embedded tactile sensory system for monitoring grasping force distribution and provide flexible structures to perform a gentle grasping action.[58]

### Conflict of Interest
The authors declare no conflict of interest.

### Keywords
grasping forces, grasping patterns, prosthesis actuators, prosthetic hands, tactile sensing, 3D printing

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**Table 1.** Challenges of designing a prosthetic hand so as to improve the grasping function.

| Subsystem | Challenge | Description |
|-----------|-----------|-------------|
| Sensing System | Grasp gesture perception | Limited number of grasping gestures can be detected using EMG-PR methods. sEMG methods are noisy due to interaction between muscles’ EMG signals. There will be a delay between measuring and processing EMG data and performing a grasping action. EMG electrodes can be displaced during human movement causing errors in perceiving desired gestures. Perceiving the highly accurate angle of each joint using sEMG methods is challenging. Some forearm muscles might not reside for EMG measurements in different kinds of hand amputations. |
| Actuation System | Positioning control | Controlling the angle of each joint requires using several motion sensors. |
| | Space and placement | Placing all actuators inside the limited available space of a prosthetic hand is challenging. |
| | Grasping force | Grasping force depends on the power system, which usually can’t be oversized due to the space limitations. Several actuators are needed to provide multiple gesture motions for the hand prostheses. Increasing size and number of actuators cause increasing the overall weight and size of the prosthetic hand. |
| | Multiple motions | The actuation system should be able to provide various response speeds based on input control signals. |
| | Weight and size | To effectively grasp a complex-shape object, mechanical conformability to the shape of the grasped object is required. The surface of the prosthetic hand should be flexible enough to prevent damages for fragile objects while grasping. Proper grasping mechanism should be designed for fingers to provide human-like grasping motion. |
| | Response time | Fabricating a cheap and customizable prosthetic hand is required for prosthetic hands. |
| Structure and Mechanism | Conformability | Mechanical conformability to the shape of the grasped object is required. The surface of the prosthetic hand should be flexible enough to prevent damages for fragile objects while grasping. |
| | Grasping motion | Proper grasping mechanism should be designed for fingers to provide human-like grasping motion. |
| | Manufacturing | Fabricating a cheap and customizable prosthetic hand is required for prosthetic hands. |

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