IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 5 June 2024, accepted 4 August 2024, date of publication 8 August 2024, date of current version 19 August 2024.
Digital Object Identifier 10.1109/ACCESS.2024.3440007

SURVEY

Robotic Fingers: Advancements, Challenges, and Future Directions–A Comprehensive Review

BHIVRAJ SUTHAR[1], (Member, IEEE), YUSRA ABDULRAHMAN[2,3], (Member, IEEE), AND YAHYA ZWEIRI[2,3], (Member, IEEE)
[1]School of Artificial Intelligence and Data Science, Indian Institute of Technology Jodhpur, Jodhpur 342030, India
[2]Department of Aerospace Engineering, Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates
[3]Advanced Research and Innovation Center (ARIC), Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates

Corresponding author: Bhivraj Suthar (bhivraj@iitj.ac.in)

This work was supported by the Advanced Research and Innovation Center (ARIC), which is jointly funded by Aerospace Holding Company Limited Liability Company (LLC), a wholly-owned subsidiary of Mubadala Investment Company Public Joint Stock Company (PJSC) and Khalifa University for Science and Technology, Abu Dhabi, United Arab Emirates.

ABSTRACT This review provides a comprehensive analysis of recent advancements in the development and applications of robotic fingers. The review focuses on four critical components: mechanism, actuation, sensor and control. A thorough literature search was conducted to identify and evaluate relevant studies, and the results were synthesized and analyzed to provide an overview of the field's current state. The review highlights major contributions, trends, and gaps in the literature and critically evaluates the strengths and limitations of the reviewed studies. The discussion section explores the implications of the findings, including future directions that need to be addressed. The review concludes with a forward-looking outlook on the significance of the field and its potential impact on mechatronics. Overall, this review offers a unique and original contribution to the field by providing a comprehensive overview of the latest developments in robotic fingers.

INDEX TERMS Bio-inspired design, artificial muscles, robotic fingers.

I. INTRODUCTION

field of robotics is a rapidly growing discipline that involves the development of robots for various applications, such as industrial automation and medical devices. As researchers create new and advanced robots that can perform more complex tasks, they focus on developing crucial design and implementation components, such as robotic fingers. These fingers are multi-disciplinary systems with various sensors, actuators, and mechanisms that need to be developed with the help of advanced technologies [1], [2], [3], [4], [5]. Therefore, developing robotic fingers is an essential part of any end-effector for grasping and manipulation tasks.

There are many applications of robotic fingers in various fields, such as medical devices, space exploration, industrial automation, and agriculture. In industrial settings, they can handle complex and fragile components. In 2017, Honarpardaz et al. examined the state-of-the-art techniques for automating the design of gripper fingers and reviewed the latest research in the field [6]. In artificial limbs, robotic fingers could be used to create hands that can mimic the dexterity and movement of humans. In 2016, Kohei Umezawa1 and colleagues demonstrated a soft robotic hand with a tendon-driven structure that can perform various tasks, such as grasping. In medical devices, robotic fingers can be used in minimally invasive procedures, such as cataract surgery. In 2019, Lee et al. demonstrated a device that can be used in this operation [7]. In space exploration, robotic hands can be used to perform tasks that are challenging to do with human hands. In 2017, Park et al. proposed using a robotic finger-based gripper for space exploration [8]. This could be used to collect samples and manipulate objects in deep space. With the wide range of applications of robotic fingers for developing grasping systems, their development is becoming more important. Robotic fingers can be deployed with a drone to grip objects and facilitate package delivery

The associate editor coordinating the review of this manuscript and approving it for publication was Hassen Ouakad.

in the space environment. A biomimetic robot capable of perching on complex surfaces and grasping irregular objects was developed by Meng et al. and a team of researchers in 2021 [9]. Also, the use of grasping systems for harvesting crops in agriculture has increased dramatically in recent years, with a growing interest in automation and precision farming techniques. While multi-fingered grippers, such as the ones presented in [10], exhibit human-like grasping features that are well-suited for crop harvesting, they are complex to regulate and come with a high price tag due to the substantial quantity of actuators needed.

Due to the increasing number of innovations in robotic fingers, the design and implementation of new strategies for creating versatile and capable robotic hands have been proposed. Among the most challenging factors identified in developing robotic fingers are the designs that mimic the human finger and bio-inspired control, the development of a resilient mechanism and actuation, and the integration of control and sensing technologies [2], [11]. Actuation refers to generating motion in the fingers, while control ensures accurate and coordinated finger movements. The mechanism of the fingers determines their structure and how they interact with objects, while sensors provide feedback to the control system to adjust finger movements and forces. These components must work together seamlessly to achieve optimal performance in robotic fingers [12]. Several groups of researchers have been working on addressing the challenges mentioned in the development of robotic fingers. In the area of mechanism, researchers have proposed replicating human finger anatomy to create fingers with a more natural range of motion and greater adaptability [13]. Other researchers have focused on miniaturizing components to enable more advanced and flexible robotic systems [14]. In terms of control, some researchers have developed algorithms that can take advantage of the unique capabilities of robotic fingers, such as their ability to make fine adjustments and perform complex movements [15]. Other groups have explored bio-inspired control, where the robotic hand is controlled in a way similar to how the human hand is controlled [16], [17], [18], [19]. Finally, in the area of sensors, researchers have been working on improving the resolution and accuracy of tactile sensors, as well as developing sensors that can differentiate between different types of touch, such as pressure, texture, and temperature [2], [20]. By addressing these challenges and continuing to innovate in these areas, researchers can create more versatile and capable robotic hands that can perform increasingly complex tasks in various applications.

Despite significant advancements in the design, actuation, sensing, performance, reliability, and durability of robotic fingers, there are still significant gaps in the existing literature. Specifically, the level of dexterity and sensitivity achieved by robotic fingers compared to their human counterparts remains an active area of research [12], [21], [22]. While recent advancements have led to significant improvements in robotic finger capabilities, there are still limitations regarding finger joint mobility, actuation, and

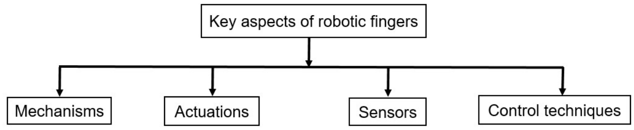

FIGURE 1. Key aspects of robotic fingers.

tactile sensing. Further research is needed to optimize the design and control mechanisms of robotic fingers, allowing them to perform precise and accurate tasks and integrate seamlessly with human-computer interfaces. Ultimately, a better understanding of the development trends of robotic fingers is necessary to enhance their performance and expand their range of potential applications in various industries and future research directions. This review aims to provide a comprehensive analysis of recent advancements in the development and applications of robotic fingers. The focus of the review is on the four key components: actuation, control, mechanism, and sensors, which are critical components of robotic fingers and play an essential role in determining the overall performance of the system. The review critically evaluates the latest developments in these areas, including design and implementation strategies, control methods, and sensing techniques. We will use a comprehensive search strategy to identify relevant studies from various databases, including IEEE Xplore, ScienceDirect, and ACM Digital Library.

The research questions for this systematic review are:

1) What are the latest advancements in the development and applications of robotic fingers, focusing on actuation, control, mechanism, and sensors?
2) What are the research challenges?

The contribution of this review is to provide a comprehensive analysis of the field of robotic fingers and highlight the field's major advancements and future directions. By critically evaluating the reviewed studies, this review provides valuable insights into the strengths and limitations of the current technologies and offers recommendations for future work in the field. As well as provides a comprehensive overview of the current state-of-the-art robotic finger design and evaluation and will serve as a valuable resource for researchers and engineers in robotics.

This paper is structured as follows, Section II overviews robotic fingers and their key aspects, including applications, advantages, and limitations. Section III discusses the research gaps and the future direction. Section IV concludes by summarizing the findings.

II. KEY ASPECTS OF ROBOTIC FINGER

Due to the potential applications of robotic fingers, their development has gained widespread attention in recent years, such as prosthetics, rehabilitation, and industrial automation. The development and design of robotic fingers require a comprehensive understanding of their key components and the overall design process. In this section, we will explore the key aspects of a robotic finger, including its mechanism,

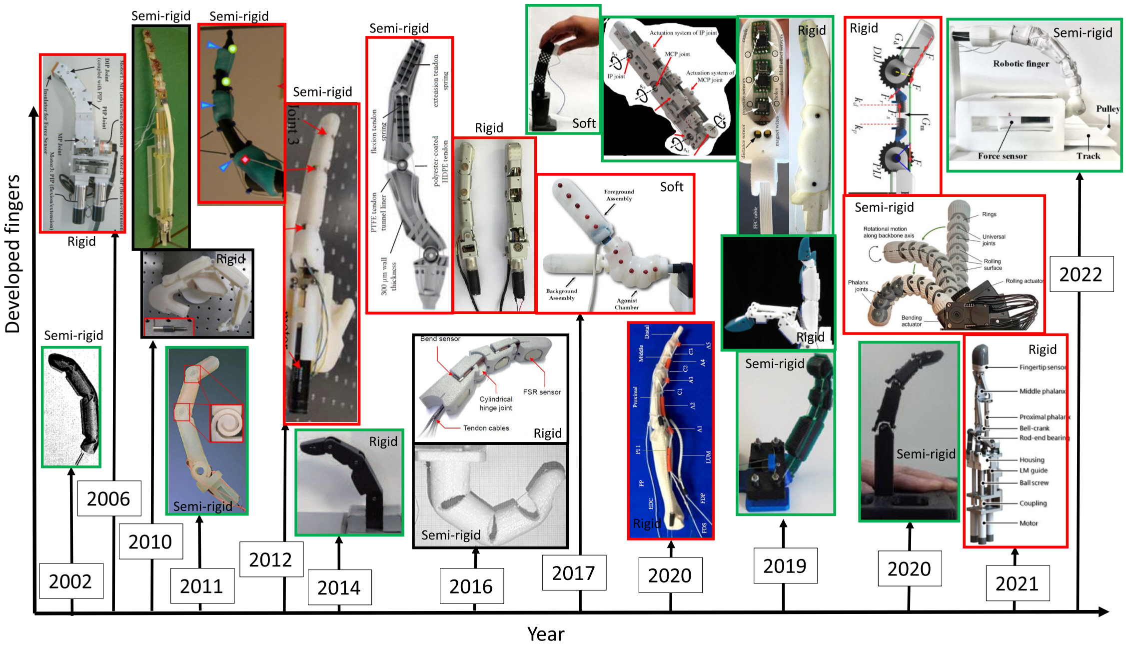

FIGURE 2. Examples of robotic fingers developed between 2002 and 2022.

actuation, sensors, and control system. This section aims to comprehensively understand the essential components and design considerations for developing high-performance robotic fingers.

The robotic finger is an essential component of many robotic systems, including robotic hands and humanoid robots. The design and development of robotic fingers have gained significant attention due to their importance in performing tasks that require dexterity and precision. This section will discuss the four key aspects of a robotic finger that are crucial for its functionality and performance, as shown in Figure 1.

These key areas include the finger mechanism, actuation system, sensors, and control. Understanding these aspects of a robotic finger is crucial for developing efficient and effective robotic systems that can perform complex tasks precisely and accurately.

A. MECHANISM OF ROBOTIC FINGER

This section reviews the current state of the art in mechanism designs for robotics fingers and outlines the major trends and challenges in this area. The mechanism of a robotic finger is a critical component for enabling dexterous manipulation tasks. The development of robotics fingers has seen significant advancements in recent years due to the need for more robust, flexible, and adaptive prosthetic devices [23], [24]. Figure 2 shows robotic finger development over the last two decades, showing examples of rigid, semi-rigid, and soft fingers.

For instance, in 2022 researchers have proposed flexible tendon sheath designs for anthropomorphic robotic fingers, which emulate the natural movement of human fingers [25]. Adaptive underactuated fingers with active rolling surfaces have also been proposed in 2021, which leverage rolling motion to achieve grasping capabilities with minimal actuation [26]. Bioinspired composite fingers with self-locking joints have been developed in 2021, which mimic the locking mechanism of human finger joints to enhance grasping stability [27]. Integrated linkage-driven dexterous anthropomorphic robotic hand designs have been proposed in 2021, which combine mechanical linkages and jointed structures to achieve versatile finger movements [28].

Furthermore, tendon-driven finger designs that are bio-inspired with isomorphic ligamentous joints have been developed in 2020, replicating the tendon-driven mechanism of human fingers [29]. Biomimetic actuation mechanisms have been employed in the design of anthropomorphic fingers in 2019, allowing for natural and efficient finger movements [30]. Adaptive actuation mechanisms for anthropomorphic robot hands have been proposed in 2019, which enable finger adaptability and flexibility in various grasping tasks [31].

In addition, 3D-printable, robust anthropomorphic robot hand designs, including intermetacarpal joints, have been developed in 2019 for easy fabrication and assembly [32]. Smart compliant robotic grippers equipped with 3D-designed cellular fingers have been proposed in 2019, incorporating compliant and deformable finger structures for enhanced grasping capabilities [33]. In 2018, thin, soft muscles have been used to design human-like robotic fingers for achieving dexterous finger movements [34].

Moreover, highly integrated underactuated finger designs for prosthetic hands have been proposed in 2017, which combine multiple degrees of freedom in a compact and efficient design [35]. Simplified compliant anthropomorphic robot hand designs have been developed, which utilize compliant materials and structures for achieving natural finger movements [35]. Empirical characterization of modular variable stiffness inflatable structures has been conducted in 2017, for supernumerary grasp-assist devices, which can provide additional support for robotic hands during grasping tasks [36].

Various mechanisms have been proposed in 2010 and 2016 for robotics fingers, including flexor/extensor-based designs, tendon-driven designs, twisted string actuation-driven designs, and biomimetic designs. The flexor/extensor-based designs use pairs of tendons to achieve flexion and extension, while the tendon-driven designs use pulleys to transmit forces to achieve finger movement [37], [38], [39], [40]. Biomimetic designs, on the other hand, aim to mimic the natural structure and function of the human finger. Recent developments in mechanism design have focused on combining these different approaches to create more versatile and robust robotics fingers [41], [42].

In reviewing the advancements and future directions in robotic fingers, we have adopted a comprehensive approach to examining the various mechanism designs currently being utilized. To achieve this, we have divided the robotic finger mechanisms into three distinct categories: rigid mechanism design, semi-rigid mechanism design, and soft mechanism design.

1) RIGID MECHANISM DESIGN

Designing a robotic finger involves considering various aspects such as mechanical strength, range of motion, speed, accuracy, and control mechanisms. Selecting a suitable rigid mechanism is an essential aspect of designing a robotic finger. In this context, a rigid mechanism refers to the physical structure that links different segments of the robotic finger and allows for movement [23], [43], [44].

Several rigid mechanisms can be used in robotic finger design, including revolute, prismatic, and spherical joints. The choice of the mechanism depends on the specific application and design requirements. A revolute joint is a hinge that allows for rotation along a single axis. This type of joint is commonly used in robotic fingers to provide bending motion. A prismatic joint, on the other hand, allows for linear motion along a single axis. This type of joint can provide grasping and releasing motion in robotic fingers. Spherical joints, also known as ball-and-socket joints, allow for rotation along multiple axes. This type of joint is commonly used in robotic fingers that require a wide range of motion [28], [45], [46].

The design of the rigid mechanism for a robotic finger should also consider the materials used for construction. Common materials used for robotic fingers include aluminum, steel, and titanium. The material choice will depend on the specific strength, weight, and durability requirements [47], [48].

TABLE 1. Advantages and disadvantages of rigid mechanism design of the finger.

Application	Merits	Demerits
Industrial automation	high stiffness and durability	limited range of motion, weight, complexity, and lack of adaptability
Surgical robotics	high stiffness, accuracy, and durability	Limited range of motion and lack of adaptability
Prosthetics	high stiffness, durability, and simplicity	Limited range of motion and lack of adaptability
Rehabilitation	high stiffness, accuracy, and simplicity	Limited range of motion,weight and lack of adaptability
Human-robot interaction	high stiffness, accuracy, and durability	Limited range of motion,weight and lack of adaptability
Agriculture robotics	high stiffness, durability, and simplicity	Limited range of motion, weight, complexity, and lack of adaptability

TABLE 2. Advantages and disadvantages of semi-rigid mechanism design of the finger.

Application	Merits	Demerits
Industrial automation	Provide a balance and compliance, versatile design	Complexity, and limited range of motion compared to fully compliant mechanisms may require more maintenance
Surgical robotics	Provide compliance while maintaining precision and control, adaptable design	Complexity, may require more maintenance and resources for design and manufacturing
Prosthetics	Adaptable design provide compliance for comfortable fit	Limited range of motion compared to fully compliance mechanisms
Rehabilitation	Provide a balance of precision and compliance for effective therapy	Complexity may require more maintenance and resources for design and manufacturing
Human-robot interaction	Provides compliance for safe and comfortable interaction	Complexity, limited range of motion compared to fully compliant mechanisms, may require more maintenance
Agriculture robotics	Adaptable design provides compliance for efficient gripping	Complexity. Limited range of motion compared to fully compliant mechanisms may require more maintenance

Another critical aspect of rigid mechanism design is the incorporation of sensors and actuators. Sensors can provide feedback on the finger's position, force, and torque, while actuators can provide the necessary forces to move the finger.

Table 1 shows some examples of the applications, advantages, and limitations of a rigid design mechanism. One application is in industrial automation where the advantages of using a rigid design mechanism are high stiffness and accuracy, while the limitation is that rigid design has a limited range of motion and can be complex and lack adaptability.

Overall, designing a rigid mechanism for a robotic finger involves considering several factors, including the type of joint, the materials used, and the incorporation of sensors and actuators. The final design should be optimized for the specific application and desired performance characteristics.

2) SEMI-RIGID MECHANISM DESIGN

A semi-rigid mechanism design for a robotic finger is a type of mechanism that combines the advantages of both rigid and compliant mechanisms. In a semi-rigid mechanism design, the finger comprises rigid and flexible components that work together to provide a range of motion and compliance greater than what can be achieved with purely rigid mechanisms [42], [49], [50].

The semi-rigid mechanism design typically consists of two or more links connected by joints, which can be either rigid or flexible. The flexible links are usually made of rubber, silicone, or compliant mechanisms that can bend and twist in response to external forces. On the other hand, the rigid links are typically made of materials such as metal or plastic that provide high stiffness and strength [51]. The flexible links can be arranged in various configurations to provide degrees of compliance and motion. For example, a semi-rigid mechanism design might include a flexible joint between two rigid links, which allows the finger to bend and twist in a specific direction. Alternatively, a semi-rigid mechanism design might consist of multiple flexible joints arranged in a series, which provides greater flexibility and range of motion [52]. Semi-rigid mechanism design is particularly well-suited for applications that require a combination of precision and compliance, such as grasping objects of varying shapes and sizes. The compliance of the flexible links allows the finger to adapt to the shape of the object being grasped. In contrast, the rigidity of the rigid links provides the necessary stiffness and strength to maintain a secure grip [53].

One advantage of the semi-rigid mechanism design is its ability to provide compliance without sacrificing precision. The compliance of the flexible links allows the finger to adjust to variations in the shape and size of the object being grasped. In contrast, the rigidity of the rigid links provides the necessary precision and control for accurate positioning and force application. Another advantage of the semi-rigid mechanism design is its ability to provide great versatility and adaptability. Adjusting the configuration and material properties of the flexible and rigid components allows the design to meet the specific requirements of a wide range of applications [54]. Table 2 shows some advantages and limitations of semi-rigid mechanism design and its applications. One application is in industrial automation, where the advantage is it provides a balance of precision, compliance, and versatility. On the other hand, the limitation of semi-rigid design in industrial automation is that it can be very complex and has a limited range of motion compared to a fully compliant mechanism.

In summary, a semi-rigid mechanism design for a robotic finger is a hybrid of rigid and compliant mechanisms that combines the advantages of both mechanisms. This design allows for a degree of flexibility and compliance greater than what can be achieved with purely rigid mechanisms while still providing the necessary stiffness and strength for precision and control.

TABLE 3. Advantages and disadvantages of soft mechanism design of the finger.

Application	Merits	Demerits
Industrial automation	Adaptable design, high compliance and range of motion	May be less precise and accurate than rigid design, may be more difficult to manufacture and maintain
Surgical robotics	Compliance for safe and precise manipulation, adaptable design	May be less precise and accurate than rigid design, may be more difficult to manufacture and maintain
Prosthetics	Compliance for a comfortable fit, adaptable design	May be less precise and accurate than rigid design, limited range of motion compared to fully compliance mechanisms
Rehabilitation	Provide a balance of precision and compliance for effective therapy	May be less precise and accurate than rigid design, may be more difficult to manufacture and maintain
Human-robot interaction	Provides compliance for safe and comfortable interaction	May be less precise and accurate than rigid design and may be more difficult to manufacture and maintain
Agriculture robotics	Adaptable design provides compliance for efficient gripping	May be less precise and accurate than rigid design, limited range of motion compared to fully compliance mechanisms

3) SOFT MECHANISM DESIGN

A soft mechanism design for a robotic finger involves using soft and compliant materials to create flexible and versatile fingers that can adapt to the shape of objects and exert precise forces. Soft mechanism designs can be made of various materials, including elastomers, silicone, and textiles, and can take on a variety of shapes and configurations [55], [56], [57].

One common approach to soft mechanism design is to use flexible materials to create pneumatic or hydraulic actuators that control the motion of the fingers. In this design, pressurized fluid is used to inflate and deflate the actuators, which in turn causes the fingers to bend or flex. Using flexible materials allows for a high degree of compliance and range of motion, which can be useful for tasks that require delicate manipulation or the ability to grasp objects of varying shapes and sizes [42], [58].

Another approach to soft mechanism design is to use shape-memory materials, such as shape-memory alloys or polymers, to create fingers that can change shape in response to temperature changes or electrical stimuli. These materials can be programmed to adopt a particular shape or configuration at a certain temperature or when exposed to a specific electric field, allowing the fingers to be controlled with precision and accuracy [59], [60].

Soft mechanism designs have several advantages over traditional rigid designs that can be seen in Table 3. For one, they are more adaptable and versatile, able to conform to a wider range of object shapes and sizes. Soft mechanisms can also be safer in specific applications, such as human-robot interaction or rehabilitation robotics, as they are less likely to cause injury or damage in accidental contact. Additionally, compliance with soft mechanisms can reduce the risk of damage to fragile objects being manipulated [61].

However, there are also some limitations to soft mechanism designs. For one, they may be less precise and accurate than rigid designs, as the compliance of the materials can make it more difficult to exert the necessary forces or achieve the desired level of control. Soft mechanisms can also be more challenging to manufacture and maintain than rigid designs, as flexible materials may require specialized equipment and expertise [62].

In summary, soft mechanism designs for robotic fingers involve the use of flexible and compliant materials to create fingers that are adaptable, versatile, and capable of exerting precise forces. These designs have a number of advantages over traditional rigid designs but also present some challenges in terms of precision and manufacturing.

4) RESEARCH GAP IN MECHANISM DESIGN FOR A ROBOTIC FINGER

Despite significant progress in developing robotic fingers with different mechanisms methods such as rigid, semi-rigid, and soft, there are still several research gaps that need to be addressed:

- **Replication of Human Finger Anatomy:** Human fingers have a complex and intricate anatomy, allowing them to perform various tasks. Current robotic fingers lack this level of complexity, which limits their functionality. Future research should focus on developing mechanisms that can replicate the complex anatomy of human fingers.
- **Miniaturization of Components:** Human fingers are relatively small and delicate, which requires the use of small and precise components. However, current robotic fingers lack the required level of miniaturization, which limits their versatility and adaptability. Future research should focus on developing miniaturized components that can enable the development of more versatile and adaptable robotic fingers.
- **Design Optimization:** The design optimization of robotic fingers is critical for achieving the desired level of functionality and performance. However, the current state-of-the-art design optimization techniques lack the sophistication required to optimize the complex structure and mechanism of robotic fingers. Future research should focus on developing advanced design optimization techniques to enable the development of more optimized and efficient robotic fingers.
- **Integration of Materials and Electronics:** Human fingers are made up of a combination of materials, including bone, muscle, and tissue, and are equipped with sensory receptors and nerves. Current robotic fingers lack the integration of materials and electronics required to replicate the function of human fingers. Future research should focus on developing mechanisms that can integrate various materials and electronics to replicate the function of human fingers.

TABLE 4. Advantages and disadvantages of rigid actuation for the finger.

Application	Merits	Demerits
Industrial assembly	high force output, high accuracy	limited flexibility, limited adaptability to changing task requirements
Medical Prosthetic	high force output, durability	Limited flexibility, potential discomfort for user
Rehabilitation therapy	high force output, precise control	Limited flexibility, potential discomfort for user
Personal robotics	high force output, reliability	Limited flexibility, limited adaptability to changing task requirements
Fine motor skill tasks	high accuracy, precision control	Limited flexibility, potential damage to delicate objects

In summary, the research gap in the structure and mechanism design of robotic fingers to achieve a structure like the human finger design involves several challenges, including the replication of human finger anatomy, miniaturization of components, integration of materials and electronics, and design optimization.

B. ACTUATION OF ROBOTIC FINGER

This section reviews the current state of the art in actuation designs for robotics fingers and outlines the major trends and challenges in this area. The actuation of the robotic finger is critical for robotics because it enables the robotic system to move and perform tasks. Actuators are the components responsible for converting electrical, hydraulic, or pneumatic energy into mechanical motion. These actuators are the "muscles" of the robotic system, and their performance determines the accuracy, speed, and efficiency of the robot's movements [63]. Figure 3 shows a robotic finger's different types of actuation.

We have divided the robotic finger actuation system into three distinct categories: rigid, semi-rigid, and soft.

1) RIGID ACTUATION

Rigid actuators are commonly used in robotic finger mechanisms to provide movement and force to the finger joints. These actuators typically use rigid materials such as metal or plastic and different types of mechanisms to generate the force required to move the finger [64], [65].

Several types of rigid actuators can be used in robotic finger design, including:

- Rotary actuators: Rotary actuators convert rotational motion into linear motion and can provide movement and force to the finger joints. These actuators typically use a motor and gear mechanism to generate the rotary

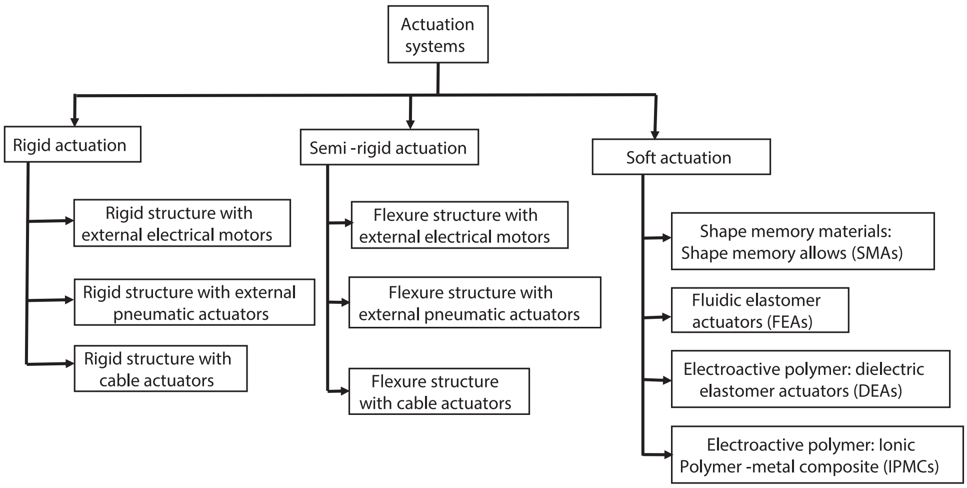

FIGURE 3. Various types of actuation for a robot finger.

motion, which is then converted into linear motion to move the finger joint [65].

- Linear actuators: Linear actuators provide linear movement and force to the finger joints. These actuators can be powered by pneumatic or hydraulic systems, electric motors, or other mechanisms. They can also use different mechanisms, such as belts or screws, to provide linear movement to the finger joint [66].
- Shape memory alloys: Shape memory alloys (SMAs) are materials that can change shape in response to temperature or other stimuli changes. SMAs can be used as actuators to force and move the robotic finger joints. When heated, SMAs can change shape and force the finger joint to move [59], [67].
- Piezoelectric actuators: Piezoelectric actuators use the piezoelectric effect to generate movement and force. These actuators use a material that can generate an electric charge when subjected to mechanical stress, such as pressure or vibration. The electric charge can then provide force to move the finger joint [68].

Rigid actuators have several advantages in robotic finger design, as shown in Table 4. They can provide high force output and accuracy, which can benefit tasks requiring significant force or precise control. Additionally, rigid actuators are typically more durable and reliable than other actuators, which can improve the lifespan and performance of the robotic finger.

2) SEMI-RIGID ACTUATION

Semi-rigid actuators are a type of actuator that combine the stiffness and strength of rigid actuators with the compliance and flexibility of soft actuators [31], [38], [69]. They are designed to provide a balance between force and flexibility, making them ideal for applications that require both strength and dexterity, such as robotic fingers. Several types of semi-rigid actuators are commonly used in robotic fingers, including:

TABLE 5. Advantages and disadvantages of semi-rigid actuation for the finger.

Application	Merits	Demerits
Prosthetics	provides a natural range of motion and force similar to human finger	May be more expensive than other actuation methods
Industrial automation	Provide high force and stiffness for handling heavy objects	may require additional maintenance due to the use of fluid or air pressure
Surgical robotics	Provides high precision and control for delicate procedures	May be limited in range of motion and force compared to other actuation methods
Human-robot interaction	Provides a more natural and comfortable interaction with robots	May be limited in terms of size and weight for portable and wearable applications
Entertainment and gaming	Provides a more immersive and realistic experience for user	May require additional power and control systems

- Shape memory alloy springs: Shape memory alloy (SMA) springs are a type of semi-rigid actuator that uses the shape memory effect of the material to provide force. The spring can be compressed or stretched and then recover its original shape when heated. They are lightweight, compact, and can produce a large range of motion [70].
- Pneumatic artificial muscles: Pneumatic artificial muscles (PAMs) are a type of semi-rigid actuator that uses compressed air to produce force. They are made of a flexible material that expands and contracts in response to changes in air pressure. They are lightweight, can produce a large range of motion, and can be easily integrated into existing pneumatic systems [71].
- Hydraulic artificial muscles: Hydraulic artificial muscles (HAMs) are similar to PAMs, but use hydraulic fluid

instead of compressed air to produce force. They are typically made of a flexible polymer that can expand and contract in response to changes in hydraulic pressure. They are often used in industrial applications where high forces are required [72].

- Flexure structure and joints: Flexure structures are a type of semi-rigid actuator that uses materials' elasticity to produce motion. They are typically made of metal or composite materials and can provide high stiffness and strength while allowing for small amounts of deflection. They are often used in applications that require precise positioning and low friction [51], [73], [74].

Each type of semi-rigid actuator has advantages and limitations, and the choice of the actuator will depend on the specific application and performance requirements, some of these can be found in Table 5. For example, SMA springs are often used in applications where a large range of motion is required, while PAMs are often used in applications where a lightweight and compact design is important.

3) SOFT ACTUATION

Soft actuators for robotic fingers are a promising area of research that aims to mimic the flexibility and dexterity of human fingers. Soft actuators use flexible and compliant materials, such as polymers or elastomers, to generate motion and force. Actuation methods for robotics fingers include traditional hydraulic or pneumatic actuation and newer approaches such as shape memory alloys, electroactive polymers, and ionic polymer-metal composites. These newer materials enable more precise control of finger movement, better energy efficiency, and reduced weight [54].

Several types of soft actuators can be used for robotic fingers, including:

- Pneumatic artificial muscles (PAMs): PAMs use pressurized air or other gases to expand and contract, creating motion and force. They can be easily controlled and are highly adaptable to complex shapes and motions. PAMs are commonly used in applications requiring high compliance and safety, such as rehabilitation robotics and prosthetics [71], [75].
- Dielectric elastomer actuators (DEAs): DEAs are made of thin layers of elastomers that deform when an electric field is applied. They are lightweight, highly compliant, and can produce large deformation and force. DEAs are commonly used in applications requiring low weight and high flexibility, such as soft robotics and wearable devices [76], [77].
- Shape memory alloys (SMAs): SMAs are metals that can change shape when heated or cooled. They are lightweight, highly durable, and can produce large deformation and force. SMAs are commonly used in applications requiring high precision and control, such as surgical robotics and micro-robotics [70], [78].
- Hydrogels: Hydrogels are crosslinked polymer networks that absorb and retain large amounts of water. They are highly compliant, biocompatible, and easily tailored to specific shapes and properties. Hydrogels are commonly used in applications requiring high sensitivity and responsiveness, such as haptic interfaces and artificial skin [20], [79].

TABLE 6. Advantages and disadvantages of soft actuation for the finger.

Application	Merits	Demerits
Prosthetics	provides a more natural feel and movement similar to human finger, more comfortable to wear for longer periods of time, safer for contact with human skin	Limited force and torque output compared to rigid actuators, more prone to wear and tear, affecting longevity
Gripping and Manipulation	Soft actuators can conform to the shape of objects, providing better grip and manipulation, safer for contact with delicate objects	Limited force and torque output compared to rigid actuator, can be slower in response time
Haptic feedback	Soft actuators can provide a more realistic and immersive haptic feedback, can provide a wider range of tactile feedback	Limited force and torque output compared to rigid actuators, can be slower in response time
Wearable feedback	Soft actuator can be more comfortable to wear for longer periods of time, can be more compact and lightweight, allowing for better portability.	Limited force and torque output compared to rigid actuators, can be more prone to wear and tear, attecting longevity

Soft actuators offer advantages over rigid and semi-rigid actuators, including increased safety, adaptability, and flexibility, a list of advantages and limitations can be found in Table 6. However, they also present several challenges, such as the need for sophisticated control systems, the potential for mechanical failure, and difficulty achieving high force and precision. Further research is needed to optimize the design, control, and integration of soft actuators for robotic fingers in various applications.

4) RESEARCH GAP IN ACTUATION FOR A ROBOTIC FINGER

Despite significant progress in developing robotic fingers with different actuation methods, such as rigid, semi-rigid, and soft, there are still several research gaps that need to be addressed:

- **Limited dexterity and adaptability:** Many robotic fingers have limited dexterity and adaptability, which limits their ability to grasp objects with varying shapes and sizes.
- **Lack of real-time control:** Some robotic fingers rely on pre-programmed movements or fixed gripper configurations, which limits their ability to adapt to changing environments and grasp objects in real time.
- **Insufficient grasping force:** Many robotic fingers lack the necessary grasping force to pick up heavy objects or to manipulate objects in complex tasks.

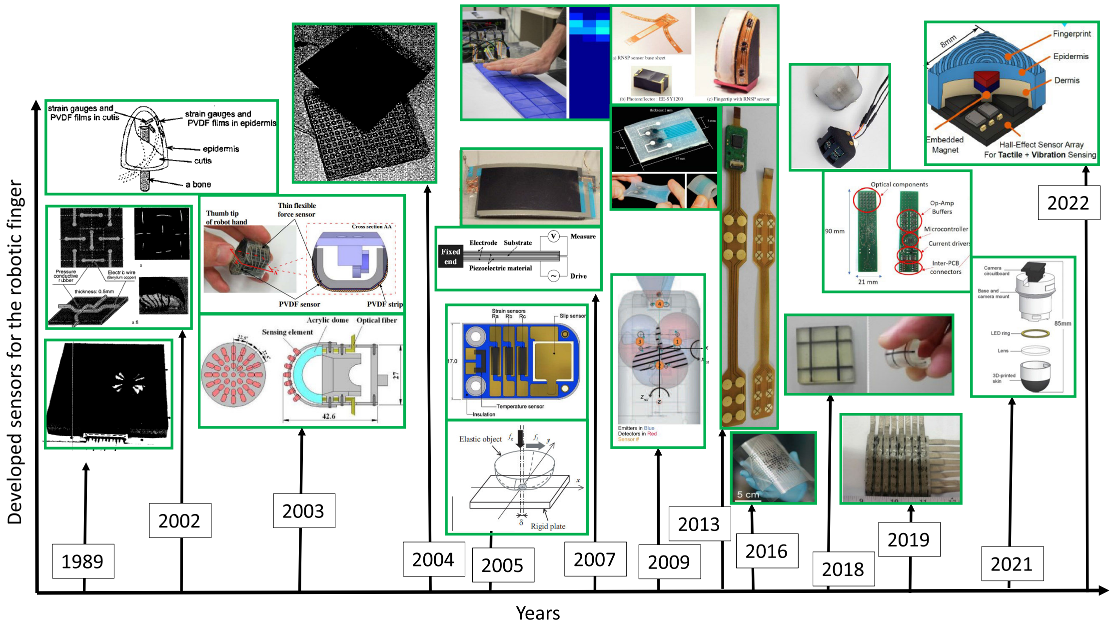

FIGURE 4. Examples of sensors for robotics fingers developed between 1989 and 2022.

TABLE 7. Advantages and disadvantages of the rigid sensor for the finger.

Application	Merits	Demerits
Force sensing	Accurate measurement of force applied to the finger	Rigid sensors may not be sensitive enough for some applications
Position sensing	Accurate measurement of joint angles and position of each finger segment	Rigid sensors may add weight and complexity to the finger
Temperature sensing	Reliable monitoring of the temperature of motors and other components	Rigid sensors may require calibration and maintenance
Pressure sensing	Accurate measurement of fluid or gas pressure in hydraulic or pneumatic actuators	Rigid sensors may be affected by external vibration or shocks
Torque sensing	Accurate measurement of the torque generated by motors or other components	Rigid sensors may be expensive and difficult to install

In summary, the research gap in the actuation of robotic fingers to achieve an actuator like the human finger flexion and extensor muscle involves several challenges, including the replication of human muscle, miniaturization of components, integration of materials and electronics, and design optimization.

C. SENSOR FUSION OF ROBOTIC FINGER

This section reviews the current state of the art in sensory designs for robotics fingers and outlines the major trends and challenges in this area. Sensors are critical for a robotic finger because they provide information about its position, velocity, and force. This information is essential for the control system to adjust the finger's motion and force accurately. Without sensors, the finger's motion and force would be difficult to control, making it challenging for the robot to perform manipulation tasks accurately. The sensory system of a robotic finger is a critical component that enables it to perceive and interact with its environment. The sensors provide feedback to the control system, which adjusts the actuation to achieve the desired movement [80]. Figure 4 shows examples of robotic finger sensors between 1989 and 2022.

Tactile sensing, inspired by the complex sensing capabilities of biological systems, has gained significant attention in robotics and automation research. Tactile sensors are critical for enabling robots to perceive and interact with their environment, including material classification, object manipulation, and human-robot interaction. Over the years, researchers have developed a wide range of tactile sensor designs and characterization methods to enhance the sensory capabilities of robots [81].

In 2022, there has been significant progress in designing and developing biomimetic tactile sensors for material classification [82]. These sensors can mimic the human sense of touch and discriminate between different materials based on their texture, hardness, and surface properties. Additionally, tactile sensors for parallel grippers have been extensively studied in 2021, focusing on their design and characterization [83]. These sensors are crucial for providing feedback to robotic grippers, enabling them to effectively grasp objects with varying shapes and sizes.

Furthermore, experimental evaluation of tactile sensors for compliant robotic hands has been conducted in 2021 to improve their performance in real-world scenarios [84]. Vision-based tactile sensors have also been developed in 2021 to combine the advantages of visual perception and tactile sensing for robust object recognition and manipulation [85].

In addition to traditional tactile sensing approaches, novel techniques such as direct-printed tactile sensors for gripper control have been developed in 2018 [86] and flexible 3D tactile sensor systems for anthropomorphic artificial hands have been developed in 2012 to enhance the tactile perception of robotic hands [87].

Moreover, capacitive tactile proximity sensors have been utilized for safe human-robot interaction in various applications [88]. Soft strain sensors based on ionic and metal liquids have been explored for their potential in tactile sensing applications [89]. Optical proximity sensors have been employed for reactive grasping in robots [90] and for knotting tasks with multi-fingered hands [91].

Furthermore, tactile sensors in the form of sheets using pressure conductive rubber with electrical-wires stitched method have been developed for various applications, such as detecting contact force and slip [92], sensing the texture of surfaces [93], and prosthetic hand applications [94].

Dynamic tactile sensing for object identification has been explored as well [95], along with anthropomorphic soft fingertips with multimodal sensors for surface texture perception [96].

Finally, model-based object recognition using large-field passive tactile sensors has been studied in earlier research [97], showcasing the evolution of tactile sensing technologies over the years.

In this section, we review the various types of sensors used in robotic fingers, we have divided the robotic finger sensory system into three distinct categories: rigid, semi-rigid, and soft.

1) RIGID SENSORS

Rigid sensors are made from rigid materials and are commonly used in robotic fingers for measuring and detecting physical properties such as force, torque, position, and temperature. Here are some types of rigid sensors commonly used in robotic fingers:

- Strain gauges: Strain gauges are sensors that measure the strain or deformation of a material when a force is applied to it. They are commonly used in robotic fingers to measure the force applied to the finger when grasping an object [98].
- Encoders: Encoders are sensors that measure the position or rotation of a shaft or motor. They are commonly used in robotic fingers to measure each finger segment's joint angles and position [99], [100].
- Load cells: Load cells are sensors that measure the amount of force or weight applied to them. They are commonly used in robotic fingers to measure the force applied to the finger when grasping an object [101].
- Temperature sensors: Temperature sensors are sensors that measure the temperature of a material or environment. They are commonly used in robotic fingers to monitor the temperature of the motors and other components of the finger [102].
- Pressure sensors: Pressure sensors measure the pressure of a fluid or gas. They are commonly used in robotic fingers for sensing the fluid pressure used in hydraulic or pneumatic actuators [2], [102].

TABLE 8. Advantages and disadvantages of semi-rigid sensors for the finger.

Application	Merits	Demerits
Prosthetic	Can provide feedback on grasping force, detect object slippage, improve user's sense of touch	May not provide sufficient sensitivity for fine manipulation, may be uncomfortable or bulky for the user
Industrial	Can provide precise force and position feedback, operate in the harsh environment, improve productivity and safety	May be expensive, may require frequent calibration and maintenance
Medical	Can provide feedback on tissue stiffness, can assist in minimally invasive surgery, can improve surgical precision	May not be compatible with a certain medical procedures, require sterilization and proper handling

Table 7 shows some rigid sensors' applications, advantages, and limitations. One application of rigid sensors is sensing force, where the advantage is accurate measurement of the force applied to the finger, rigid sensors are limited in the sensitivity aspect.

Overall, rigid sensors are an important component of robotic fingers, as they provide feedback for control and help ensure safe and effective operation. Different types of sensors can be used depending on the specific application and desired sensing requirements.

2) SEMI-RIGID SENSORS

Semi-rigid sensors have some flexibility but are still relatively stiff compared to soft sensors. These sensors can provide some of the benefits of both rigid and soft sensors, making them a potentially useful option for robotic fingers.

- Strain gauges: Small, flexible sensors commonly used in robotic fingers to measure strain caused by external forces. They are often used in force sensing applications to measure the force applied to a robotic finger. Relatively simple and inexpensive, but may require careful calibration for accurate readings [103], [104]
- Flex sensors: Thin, flexible strips that change resistance when bent, used to measure the angle or position of a joint in a finger segment. Easy to use and inexpensive, but may not be as accurate as other position-sensing methods [105].
- Piezoresistive sensors: Sensors that change resistance in response to pressure or strain, often used in

TABLE 9. Advantages and disadvantages of soft sensors for the finger.

Application	Merits	Demerits
Prosthetics and Rehabilitation	Flexibility and Comfort: Soft sensors can provide enhanced comfort and flexibility in robotic fingers, improving wearability and user experience for prosthetics or rehabilitation devices.	Calibration and Maintenance: Soft sensors may require frequent calibration and maintenance to ensure accurate and reliable performance over time in robotic fingers.
Industrial Automation	Intrinsically Safe: Soft sensors can be designed to be intrinsically safe, allowing for their use in hazardous environments without posing a risk of injury or damage in robotic fingers.	Sensitivity to Environmental Factors: Soft sensors may be sensitive to environmental factors such as temperature, humidity, and pressure, which can affect their performance and reliability in industrial settings.
Precision Manipulation	Flexibility and Dexterity: Soft sensors can provide robotic fingers with enhanced flexibility and dexterity, allowing for delicate and precise manipulation tasks.	Limited Durability: Soft sensors may have lower durability compared to traditional sensors, and may degrade over time due to wear and tear in robotic fingers.

pressure-sensing applications. Highly sensitive and can provide precise measurements, but may be more expensive and complex compared to other types of sensors [106].

Table 8 shows some semi-rigid sensors' applications, advantages, and limitations. For prosthetic applications, semi-rigid sensors are good at providing feedback for grasping and can improve the user's touch. However, they are limited in terms of sensitivity and may be bulky.

Overall, semi-rigid sensors can offer a good compromise between the stiffness of rigid sensors and the flexibility of soft sensors, allowing for accurate sensing while maintaining some degree of compliance and adaptability.

3) SOFT SENSORS

Soft sensors are made from flexible, deformable materials and can conform to the shape of the object they are sensing. In robotic fingers, soft sensors can provide feedback on the position, force, and/or tactile properties of the fingers during manipulation tasks [107], [108], [109]. Here are some types of soft sensors that are commonly used in robotic fingers:

- Strain sensors: These sensors detect changes in strain or deformation in the material when it is subjected to pressure or force. They can be made from conductive polymers, carbon nanotubes, or piezoresistive materials [110], [111], [112].
- Capacitive sensors: These sensors detect changes in capacitance when the sensor comes into contact with an object. They can be made from flexible, conductive materials like graphene, silver nanowires, or conductive polymers [113], [114].
- Optical sensors: These sensors use light to detect changes in the shape or position of the sensor. They can be made from flexible materials such as elastomers or liquid crystal polymers [115], [116], [116].
- Tactile sensors: These sensors detect changes in pressure or force when the sensor comes into contact with an object. They can be made from piezoelectric polymers or flexible pressure-sensitive materials [117], [118], [119], [120].

Soft sensors offer several advantages over traditional rigid sensors, these can be found in Table 9, including improved sensitivity, conformability, and flexibility. They are particularly well-suited for applications where the sensor must conform to the shape of an object or surface, such as in prosthetics, wearable devices, or medical robotics. However, soft sensors also have some limitations, including lower accuracy and repeatability than rigid sensors and susceptibility to wear and tear over time.

4) RESEARCH GAP IN THE SENSOR FOR A ROBOTIC FINGER

Despite significant progress in developing robotic fingers with different sensors methods, such as rigid, semi-rigid, and soft, there are still several research gaps that need to be addressed:

- Limited accuracy and interpretation of touch sensations, such as texture, pressure, and temperature, in tactile sensors for robotic fingers.
- Lack of proprioceptive feedback sensors that can accurately sense the position and movement of robotic fingers without frequent calibration.
- Insufficient sensors that can provide feedback on the interaction between robotic fingers and the surroundings, such as force or resistance encountered during object manipulation.
- Need for advancements in materials science and engineering to develop sensors that can replicate human skin and achieve sensor fusion in robotic fingers.
- Challenges in miniaturization of components, integration of materials and electronics, and design optimization for sensor development in robotic fingers.

In summary, the research gap in the sensing of robotic fingers to achieve a sensory system and sensor fusion like the human skin involves several challenges, including the replication of human skin, miniaturization of components, integration of materials and electronics, and design optimization.

D. CONTROL TECHNIQUES OF ROBOTIC FINGER

This section reviews the current state of the art in control designs for robotics fingers and outlines the major trends and challenges in this area. The control techniques of a robotic finger are essential because they determine how the finger interacts with objects and performs tasks. The control system for a robotic finger is responsible for generating commands that drive the actuators and sensors to achieve the desired finger motion and force [28].

The control system is a crucial component of a robotic finger that regulates the finger's movements and maintains stability [121]. The goal of the control system is to generate the desired motion of the finger, which can be achieved through various control approaches, including open-loop control and closed-loop control.

In open-loop control, the controller provides a pre-defined input signal to the actuator, which then moves the finger to the desired position. This approach is relatively simple and easy to implement. Still, it does not account for external disturbances, such as friction or load variations, which can affect the accuracy of the movement [105], [122].

In contrast, closed-loop control relies on sensor feedback to adjust the input signal to the actuator, ensuring that the finger moves to the desired position accurately. This approach is more complex and requires additional sensors to provide feedback, but it is generally more accurate and robust than open-loop control [123].

The control system of a robotic finger is responsible for interpreting sensor data, determining the desired actions, and issuing commands to the actuators to execute those actions. The specific architecture and design of the control system will depend on the specific application and desired level of performance. Some common control systems used in robotic fingers include:

- Proportional-Integral-Derivative (PID) This is a widely used control method that uses feedback from sensors to adjust the position, velocity, or force of the finger based on a setpoint. This method is simple to implement and can provide good results in applications that require precise positioning and force control, such as in assembly tasks [124].
- Impedance control:Impedance control is a method used to control the motion of a robot by adjusting its mechanical impedance to match the impedance of the environment. This method allows the finger to adapt to the environment and improve grasping capabilities. It's suitable for applications that require a high level of dexterity, such as grasping and manipulating small objects [125], [126].
- Hybrid force-position control: This method combines force and position control to provide high precision and control while also allowing the finger to adapt to the environment. It's suitable for applications that require a high level of precision and force control, such as in delicate tasks such as microsurgery [127].
- Model-based control: Model-based control: This method uses a mathematical model of the finger to predict its behavior and generate control commands. This can improve the performance and stability of the finger, but it can also be more complex to implement. This method is suitable for applications requiring high performance and stability, such as industrial robots [128], [129]
- Adaptive control: Adaptive control methods use feedback from sensors to adjust the control parameters of the finger in real time, allowing the finger to adapt to changes in the environment or the task. This method is suitable for applications that require the finger to adapt to changing conditions, such as in search and rescue tasks [80].
- Fuzzy Logic control: This method uses a fuzzy logic system to make decisions based on sensor data. It can handle uncertain or incomplete information, useful in environments with noise or errors [130], [131].
- Machine learning-based control: Machine learning-based control for a finger is a promising area of research with the potential to enhance robotic fingers' capabilities significantly. One potential approach is to use machine learning algorithms to train a model to predict the optimal control signals for a given task based on sensor input. This approach has the advantage of adapting to changing conditions and tasks, as the model can be retrained on new data as needed [132], [133].

  Another potential approach is the use of reinforcement learning, where the robotic finger learns how to perform a specific task based on a reward signal through trial and error. This approach has been used successfully in other areas of robotics and could be applied to finger control. However, reinforcement learning can be computationally expensive and may require a large amount of training data to be effective [134], [135].

  A third approach is to use a hybrid control system that combines traditional control methods with machine learning. For example, the finger could be controlled using a traditional feedback control algorithm. The machine learning algorithm is used to adjust the controller's parameters in real-time based on sensor input. This approach has the advantage of leveraging the strengths of traditional control methods and machine learning [136].

1) RESEARCH GAP IN THE CONTROL FOR A ROBOTIC FINGER

Despite significant progress in developing robotic fingers with different control methods, there are still several research gaps that need to be addressed:

- Research gap in control for robotic fingers: Lack of adaptable control algorithms that can adjust to different tasks and environments.
- Need for more flexible control algorithms that can adapt to changing conditions to enhance the capabilities of robotic fingers in various applications.
- Research gap in control algorithms that take advantage of unique capabilities of robotic fingers, such as fine adjustments and complex movements.
- Room for improvement in developing advanced control algorithms to enable robotic fingers to perform tasks

beyond their current capabilities, such as delicate surgery or intricate assembly work.

- Research needed to leverage machine learning techniques for controlling robotic fingers in real-world situations, beyond simple tasks or simulated environments.
- Developing machine learning techniques for effective control of robotic fingers can greatly enhance their capabilities, enabling them to perform a wider range of tasks with improved efficiency and accuracy.

In summary, the research gap in the control system of robotic fingers to achieve a control system with feedback like the brain-inspired control involves several challenges, including the replication of the control algorithm and accuracy.

III. RESEARCH GAP AND FUTURE DIRECTIONS

The development of robotic fingers has been an active area of research for many years, with significant progress made in recent years in areas such as mechanism design, actuation, sensors, and control. However, despite these advancements, research gaps still need to be addressed to improve the performance and capabilities of robotic fingers. Designing robot fingers that can match the dexterity and skill of human fingers has been a significant challenge, even to this day. One significant challenge is the restricted amount of physical space accessible for carrying out actuation, transmission, sensing, and incorporating electronics. One solution is adding a forearm unit, but this approach has limitations in portability and range of applications. As a result, many research groups have focused on developing intrinsically actuated hands as an alternative.

In this section, we will discuss these research gaps and identify potential future directions for research in this area. This includes exploring new materials and fabrication techniques for finger design, developing new actuation methods to improve dexterity and adaptability, enhancing sensors' resolution and accuracy, and developing new control algorithms that take advantage of the unique capabilities of robotic fingers. By addressing these research gaps and pursuing these future directions, we can unlock the full potential of robotic fingers and enable them to perform increasingly complex tasks in various applications, including manufacturing, healthcare, and service robotics.

A. RESEARCH GAP

This section will focus on identifying and discussing the research gaps that exist in the development of robotic fingers. While significant progress has been made in recent years in areas such as mechanism design, actuation, sensors, and control, there are still challenges that need to be addressed to improve the performance and capabilities of robotic fingers. By analyzing the current state of the art in robotic finger research, we will identify the key research gaps in mechanism design, actuation, sensors, and control. Additionally, we will discuss potential future directions for research to address these gaps and push the boundaries of what is currently possible with robotic fingers.

One research gap is in the mechanism design for a robotic finger. Although many designs have been proposed, there is still a need to replicate the complex anatomy of the human finger and miniaturized components. There is also a need to optimize the design and integrate materials and electronics to improve performance and reduce the size and weight of the finger.

Another research gap is in the actuation of a robotic finger. There are limitations regarding dexterity, adaptability, and grasping force, and real-time control is often lacking. One main limitation is the lack of an actuation system that behaves like human finger muscles' such as extensors and flexors. Addressing these issues could significantly improve the performance of robotic fingers and enable them to perform more complex tasks.

Sensors are also critical for robotic fingers, and research gaps remain. For example, tactile sensors struggle to differentiate between different types of touch, such as pressure, texture, and temperature and may have limited resolution. Sensors are also often limited in their accuracy and require frequent calibration to maintain their accuracy.

Finally, there are research gaps in the control of robotic fingers. Many algorithms are designed for specific tasks or environments and may not be adaptable to new situations. There is also a need to develop control algorithms that can take advantage of the unique capabilities of robotic fingers, such as their ability to make fine adjustments and perform complex movements.

Addressing these research gaps could significantly improve the performance and capabilities of robotic fingers and enable them to perform more complex tasks in various applications, including manufacturing, healthcare, and service robotics.

All of these gaps can be summarized as follows:

- Lack of attention to certain types of mechanisms, sensors, actuators, or control strategies: Some research may have focused on certain types of mechanisms, sensors, actuators, or control strategies, while others may have been understudied or ignored.
- Limited focus on certain applications: Some research may have focused on certain applications of robotics fingers, such as grasping objects in manufacturing or assembly tasks, while other applications may have been understudied or ignored.
- Lack of attention to certain design considerations: Some research may have focused on certain design considerations, such as cost or size, while other considerations may have been understudied or ignored.

B. FUTURE RESEARCH DIRECTIONS

As we have seen in III-A section, there are still research gaps that need to be addressed to improve the capabilities and performance of robotic fingers. In this section, we will discuss potential future directions for research to address these gaps and push the boundaries of what is currently possible with robotic fingers. By pursuing these directions, we can enable robotic fingers to perform increasingly complex tasks in various applications, including manufacturing, healthcare, and service robotics. We will explore new materials and fabrication techniques for finger design, develop new actuation methods to improve dexterity and adaptability, enhance sensors' resolution and accuracy, and develop new control algorithms that take advantage of the unique capabilities of robotic fingers. Additionally, we will discuss how these advancements can lead to new applications and industries where robotic fingers can have a significant impact. We expect to see significant developments in the field of artificial hand sensors within the next decade:

- Finger Structure and Joint: Future research could focus on developing more realistic finger structures that mimic the properties of human fingers, such as their size, shape, and mobility. This could involve using new materials, such as biomimetic materials, to create more realistic finger structures.

  For finger joints, future research could focus on developing finger joints that are more adaptable and flexible, such as joints that can change shape or bend in different directions. This could improve robotic fingers' range of motion and dexterity, enabling them to perform more complex movements.
- Finger Materials: Future research could focus on developing new materials that can replicate the properties of human tissues, such as muscle fibers and tendons. These materials could be used to create more adaptable and flexible robotic fingers that can better replicate the dexterity and precision of human fingers.
- Finger Mechanisms: Future research could focus on developing more advanced finger mechanisms, such as soft robotics and tendon-driven mechanisms, that can better replicate the movements of human fingers. These mechanisms could be more adaptable and flexible, enabling robotic fingers to perform a wider range of tasks.
- Actuation: Future direction for actuators in finger-like structures is the development of actuators that can mimic the properties of human muscle. These actuators would need to be lightweight, compact, and able to produce forces similar to human muscles. The shape memory alloys and smart materials can better replicate the forces and movements of human muscles. These systems could be more responsive and adaptable, enabling robotic fingers to perform a wider range of tasks.
- Sensors: Future research could focus on developing more advanced sensor technologies, such as tactile and force sensors, on providing more accurate and precise feedback to robotic fingers. This could improve the fine motor control and manipulation capabilities of robotic fingers. The ongoing progress in the miniaturization of sensors and electronics is anticipated to hasten the development of synthetic skins for robot hands, providing increased spatial resolution and multiple modes of sensing. These technological breakthroughs will enable the creation of highly sensitive and responsive tactile sensors that mimic human skin's sensitivity. Such advancements in artificial skin technology will pave the way for more advanced and adaptable robotic systems, potentially improving their dexterity, safety, and effectiveness in various applications.
- Controls: Future research could focus on developing more advanced control algorithms, such as machine learning algorithms, enabling robotic fingers to learn and adapt to different tasks and environments. This could improve the adaptability and flexibility of robotic fingers, enabling them to perform more complex tasks.
- Finger Applications: Future research could focus on developing robotic fingers for various applications, such as prosthetics, surgery, and rehabilitation. The fingers could be designed to be more adaptable to different tasks and environments, enabling them to perform more complex movements and grasp objects with greater precision.

IV. CONCLUSION

In conclusion, the development of miniaturized robot fingers is a rapidly advancing field that offers vast opportunities for future research and innovation. While research gaps still need to be addressed in mechanism design, actuation, sensors, and control to improve the performance and capabilities of miniaturized robot fingers, the potential for these advancements to impact various applications and industries is vast. With new materials and fabrication techniques, improved actuation methods, enhanced sensor resolution and accuracy, and new control algorithms, miniaturized robot fingers can perform increasingly complex tasks in various applications, from minimally invasive surgery to micro-manufacturing and micro-assembly. By pursuing these future directions, we can unlock the full potential of miniaturized robot fingers and create a future where humans and robots can work together seamlessly to achieve our common goals. We can look forward to a world where miniaturized robot fingers make our lives easier and more efficient and where we can enjoy the benefits of their capabilities in a wide range of applications.

ACKNOWLEDGMENT

(Bhivraj Suthar and Yusra Abdulrahman contributed equally to this work.)

REFERENCES

[1] J. Hernandez, M. S. H. Sunny, J. Sanjuan, I. Rulik, M. I. I. Zarif, S. I. Ahamed, H. U. Ahmed, and M. H. Rahman, "Current designs of robotic arm grippers: A comprehensive systematic review," *Robotics*, vol. 12, no. 1, p. 5, Jan. 2023.

[2] A. Saudabayev and H. A. Varol, "Sensors for robotic hands: A survey of state of the art," *IEEE Access*, vol. 3, pp. 1765–1782, 2015.

[3] H.-H. Liu, L.-J. Li, B. Shi, C.-W. Xu, and E. Luo, "Robotic surgical systems in maxillofacial surgery: A review," *Int. J. Oral Sci.*, vol. 9, no. 2, pp. 63–73, Jun. 2017.

[4] S. Zeising, A. S. Thalmayer, M. Lübke, G. Fischer, and J. Kirchner, ''Localization of passively guided capsule endoscopes—A review,'' *IEEE Sensors J.*, vol. 22, no. 21, pp. 20138–20155, Nov. 2022.

[5] H. Zhou and G. Alici, ''Non-invasive human-machine interface (HMI) systems with hybrid on-body sensors for controlling upper-limb prosthesis: A review,'' *IEEE Sensors J.*, vol. 22, no. 11, pp. 10292–10307, Jun. 2022.

[6] M. Honarpardaz, M. Tarkian, J. Ölvander, and X. Feng, ''Finger design automation for industrial robot grippers: A review,'' *Robot. Auto. Syst.*, vol. 87, pp. 104–119, Jan. 2017.

[7] C. Lee, W. J. Park, M. Kim, S. Noh, C. Yoon, C. Lee, Y. Kim, H. H. Kim, H. C. Kim, and S. Kim, ''Pneumatic-type surgical robot end-effector for laparoscopic surgical-operation-by-wire,'' *Biomed. Eng. OnLine*, vol. 13, no. 1, pp. 1–19, Dec. 2014.

[8] I.-W. Park, T. Smith, H. Sanchez, S. Wun Wong, P. Piacenza, and M. Ciocarlie, ''Developing a 3-DOF compliant perching arm for a free-flying robot on the international space station,'' in *Proc. IEEE Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2017, pp. 1135–1141.

[9] J. Meng, J. Buzzatto, Y. Liu, and M. Liarokapis, ''On aerial robots with grasping and perching capabilities: A comprehensive review,'' *Frontiers Robot. AI*, vol. 8, p. 405, Mar. 2022.

[10] K. Chen, T. Li, T. Yan, F. Xie, Q. Feng, Q. Zhu, and C. Zhao, ''A soft gripper design for apple harvesting with force feedback and fruit slip detection,'' *Agriculture*, vol. 12, no. 11, p. 1802, Oct. 2022.

[11] L. Zou, C. Ge, Z. Wang, E. Cretu, and X. Li, ''Novel tactile sensor technology and smart tactile sensing systems: A review,'' *Sensors*, vol. 17, no. 11, p. 2653, Nov. 2017.

[12] B. Zhang, Y. Xie, J. Zhou, K. Wang, and Z. Zhang, ''State-of-the-art robotic grippers, grasping and control strategies, as well as their applications in agricultural robots: A review,'' *Comput. Electron. Agricult.*, vol. 177, Oct. 2020, Art. no. 105694.

[13] S. R. Kashef, S. Amini, and A. Akbarzadeh, ''Robotic hand: A review on linkage-driven finger mechanisms of prosthetic hands and evaluation of the performance criteria,'' *Mechanism Mach. Theory*, vol. 145, Mar. 2020, Art. no. 103677.

[14] C. Borst, M. Fischer, S. Haidacher, H. Liu, and G. Hirzinger, ''DLR hand II: Experiments and experience with an anthropomorphic hand,'' in *Proc. IEEE Int. Conf. Robot. Autom.*, vol. 1, Sep. 2003, pp. 702–707.

[15] C. De Pascali, G. A. Naselli, S. Palagi, R. B. N. Scharff, and B. Mazzolai, ''3D-printed biomimetic artificial muscles using soft actuators that contract and elongate,'' *Sci. Robot.*, vol. 7, no. 68, p. 4155, Jul. 2022.

[16] K. Koyama, Y. Suzuki, A. Ming, and M. Shimojo, ''Grasping control based on time-to-contact method for a robot hand equipped with proximity sensors on fingertips,'' in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Sep. 2015, pp. 504–510.

[17] Y. Li, P. Wang, R. Li, M. Tao, Z. Liu, and H. Qiao, ''A survey of multifingered robotic manipulation: Biological results, structural evolvements, and learning methods,'' *Frontiers Neurorobot.*, vol. 16, p. 53, Apr. 2022.

[18] K. B. Shimoga, ''Robot grasp synthesis algorithms: A survey,'' *Int. J. Robot. Res.*, vol. 15, no. 3, pp. 230–266, Jun. 1996.

[19] S. A. Powell, ''A review of anthropomorphic robotic hand technology and data glove based control,'' Ph.D. dissertation, Virginia Tech, Blacksburg, VA, USA, 2016.

[20] X. Cheng, F. Zhang, and W. Dong, ''Soft conductive hydrogel-based electronic skin for robot finger grasping manipulation,'' *Polymers*, vol. 14, no. 19, p. 3930, Sep. 2022.

[21] A. Morales, B. León, E. Chinellato, and R. Suárez, ''Editorial: Current challenges and future developments in robot grasping,'' *Frontiers Robot. AI*, vol. 9, p. 194, Jul. 2022.

[22] Y. Sun, J. Falco, M. A. Roa, and B. Calli, ''Research challenges and progress in robotic grasping and manipulation competitions,'' *IEEE Robot. Autom. Lett.*, vol. 7, no. 2, pp. 874–881, Apr. 2022.

[23] E. Difonzo, G. Zappatore, G. Mantriota, and G. Reina, ''Advances in finger and partial hand prosthetic mechanisms,'' *Robotics*, vol. 9, no. 4, p. 80, Oct. 2020.

[24] Y. Tong and J. Liu, ''Review of research and development of supernumerary robotic limbs,'' *IEEE/CAA J. Autom. Sinica*, vol. 8, no. 5, pp. 929–952, May 2021.

[25] Y. Zhu, G. Wei, L. Ren, Z. Luo, and J. Shang, ''An anthropomorphic robotic finger with innate human-finger-like biomechanical advantages. Part II: Flexible tendon sheath and grasping demonstration,'' *IEEE Trans. Robot.*, vol. 39, no. 1, pp. 505–520, Feb. 2023.

[26] J. M. Gómez-de-Gabriel and H. A. Wurdemann, ''Adaptive underactuated finger with active rolling surface,'' *IEEE Robot. Autom. Lett.*, vol. 6, no. 4, pp. 8253–8260, Oct. 2021.

[27] Q. Hu, H. Huang, E. Dong, and D. Sun, ''A bioinspired composite finger with self-locking joints,'' *IEEE Robot. Autom. Lett.*, vol. 6, no. 2, pp. 1391–1398, Apr. 2021.

[28] U. Kim, D. Jung, H. Jeong, J. Park, H.-M. Jung, J. Cheong, H. R. Choi, H. Do, and C. Park, ''Integrated linkage-driven dexterous anthropomorphic robotic hand,'' *Nature Commun.*, vol. 12, no. 1, p. 7177, Dec. 2021.

[29] G. Lee and Y. Choi, ''Bio-inspired tendon-driven finger design with isomorphic ligamentous joint,'' *IEEE Access*, vol. 8, pp. 18240–18251, 2020.

[30] Z. Zhang, T. Han, J. Pan, and Z. Wang, ''Design of anthropomorphic fingers with biomimetic actuation mechanism,'' *IEEE Robot. Autom. Lett.*, vol. 4, no. 4, pp. 3465–3472, Oct. 2019.

[31] G. P. Kontoudis, M. Liarokapis, K. G. Vamvoudakis, and T. Furukawa, ''An adaptive actuation mechanism for anthropomorphic robot hands,'' *Frontiers Robot. AI*, vol. 6, p. 47, Jul. 2019.

[32] W. S. You, Y. H. Lee, H. S. Oh, G. Kang, and H. R. Choi, ''Design of a 3D-printable, robust anthropomorphic robot hand including intermetacarpal joints,'' *Intell. Service Robot.*, vol. 12, no. 1, pp. 1–16, Jan. 2019.

[33] M. Kaur and W. S. Kim, ''Toward a smart compliant robotic gripper equipped with 3D-designed cellular fingers,'' *Adv. Intell. Syst.*, vol. 1, no. 3, Jul. 2019, Art. no. 1900019.

[34] A. A. Mohd Faudzi, J. Ooga, T. Goto, M. Takeichi, and K. Suzumori, ''Index finger of a human-like robotic hand using thin soft muscles,'' *IEEE Robot. Autom. Lett.*, vol. 3, no. 1, pp. 92–99, Jan. 2018.

[35] M. Cheng, L. Jiang, F. Ni, S. Fan, Y. Liu, and H. Liu, ''Design of a highly integrated underactuated finger towards prosthetic hand,'' in *Proc. IEEE Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2017, pp. 1035–1040.

[36] L. Tiziani, A. Hart, T. Cahoon, F. Wu, H. H. Asada, and F. L. Hammond, ''Empirical characterization of modular variable stiffness inflatable structures for supernumerary grasp-assist devices,'' *Int. J. Robot. Res.*, vol. 36, nos. 13–14, pp. 1391–1413, Dec. 2017.

[37] T. Würtz, C. May, B. Holz, C. Natale, G. Palli, and C. Melchiorri, ''The twisted string actuation system: Modeling and control,'' in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics*, Jul. 2010, pp. 1215–1220.

[38] G. Palli, C. Natale, C. May, C. Melchiorri, and T. Wurtz, ''Modeling and control of the twisted string actuation system,'' *IEEE/ASME Trans. Mechatronics*, vol. 18, no. 2, pp. 664–673, Apr. 2013.

[39] I. Sainul, S. Deb, and A. Deb, ''A three finger tendon driven robotic hand design and its kinematics model,'' in *Proc. 28th Int. Conf. CAD/CAM, Robot. Factories Future*. Kolkata, India: Springer, 2016, pp. 313–321.

[40] R. Ozawa, K. Hashirii, Y. Yoshimura, M. Moriya, and H. Kobayashi, ''Design and control of a three-fingered tendon-driven robotic hand with active and passive tendons,'' *Auto. Robots*, vol. 36, nos. 1–2, pp. 67–78, Jan. 2014.

[41] E. Rombokas, M. Malhotra, E. Theodorou, Y. Matsuoka, and E. Todorov, ''Tendon-driven variable impedance control using reinforcement learning,'' in *Proc. Robot., Sci. Syst. VIII*, vol. 8, Jul. 2012, pp. 369–376.

[42] P. Kieliba, D. Clode, R. O. Maimon-Mor, and T. R. Makin, ''Robotic hand augmentation drives changes in neural body representation,'' *Sci. Robot.*, vol. 6, no. 54, May 2021, Art. no. eabd7935.

[43] S.-L. Qiao, R.-Q. Liu, H.-W. Guo, Y.-X. Liu, and Z.-Q. Deng, ''Configuration design of an under-actuated robotic hand based on maximum grasping space,'' *Chin. J. Mech. Eng.*, vol. 31, no. 1, pp. 1–9, Dec. 2018.

[44] M. A. A. Wahit, S. A. Ahmad, M. H. Marhaban, C. Wada, and L. I. Izhar, ''3D printed robot hand structure using four-bar linkage mechanism for prosthetic application,'' *Sensors*, vol. 20, no. 15, p. 4174, Jul. 2020.

[45] H. Park and D. Kim, ''An open-source anthropomorphic robot hand system: HRI hand,'' *HardwareX*, vol. 7, Apr. 2020, Art. no. e00100.

[46] B. Suthar and S. Jung, ''Design and development of a co-axial passive flexion mechanism-based gripper for irregular objects,'' in *Proc. 21st Int. Conf. Control, Autom. Syst. (ICCAS)*, Oct. 2021, pp. 1701–1704.

[47] M. Craddock, E. Augustine, S. Konerman, and M. Shin, ''Biorobotics: An overview of recent innovations in artificial muscles,'' *Actuators*, vol. 11, no. 6, p. 168, Jun. 2022.

[48] P. Rea, ''On the design of underactuated finger mechanisms for robotic hands,'' in *Advances in Mechatronics*. London, U.K.: IntechOpen, 2011, pp. 131–154. [Online]. Available: https://www.intechopen.com/chapters/18894

[49] Y. Zhang, W. Zhang, J. Yang, and W. Pu, "Bioinspired soft robotic fingers with sequential motion based on tendon-driven mechanisms," *Soft Robot.*, vol. 9, no. 3, pp. 531–541, Jun. 2022.
[50] I. Hussain, F. Renda, Z. Iqbal, M. Malvezzi, G. Salvietti, L. Seneviratne, D. Gan, and D. Prattichizzo, "Modeling and prototyping of an underactuated gripper exploiting joint compliance and modularity," *IEEE Robot. Autom. Lett.*, vol. 3, no. 4, pp. 2854–2861, Oct. 2018.
[51] A. McLaren, Z. Fitzgerald, G. Gao, and M. Liarokapis, "A passive closing, tendon driven, adaptive robot hand for ultra-fast, aerial grasping and perching," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Nov. 2019, pp. 5602–5607.
[52] M. Li, B. He, Z. Liang, C.-G. Zhao, J. Chen, Y. Zhuo, G. Xu, J. Xie, and K. Althoefer, "An attention-controlled hand exoskeleton for the rehabilitation of finger extension and flexion using a rigid-soft combined mechanism," *Frontiers Neurorobot.*, vol. 13, p. 34, May 2019.
[53] L. Wang, Y. Yang, Y. Chen, C. Majidi, F. Iida, E. Askounis, and Q. Pei, "Controllable and reversible tuning of material rigidity for robot applications," *Mater. Today*, vol. 21, no. 5, pp. 563–576, Jun. 2018.
[54] F. Ouyang, Y. Guan, C. Yu, X. Yang, Q. Cheng, J. Chen, J. Zhao, Q. Zhang, and Y. Guo, "An optimization design method of rigid-flexible soft fingers based on dielectric elastomer actuators," *Micromachines*, vol. 13, no. 11, p. 2030, Nov. 2022.
[55] X. Dong, X. Luo, H. Zhao, C. Qiao, J. Li, J. Yi, L. Yang, F. J. Oropeza, T. S. Hu, Q. Xu, and H. Zeng, "Recent advances in biomimetic soft robotics: Fabrication approaches, driven strategies and applications," *Soft Matter*, vol. 18, no. 40, pp. 7699–7734, 2022.
[56] Y. Zhang and M. Lu, "A review of recent advancements in soft and flexible robots for medical applications," *Int. J. Med. Robot. Comput. Assist. Surg.*, vol. 16, no. 3, Jun. 2020, Art. no. e2096.
[57] L. Zongxing, L. Wanxin, and Z. Liping, "Research development of soft manipulator: A review," *Adv. Mech. Eng.*, vol. 12, no. 8, Aug. 2020, Art. no. 168781402095009.
[58] J. Meng, L. Gerez, J. Chapman, and M. Liarokapis, "A tendon-driven, preloaded, pneumatically actuated, soft robotic gripper with a telescopic palm," in *Proc. 3rd IEEE Int. Conf. Soft Robot. (RoboSoft)*, May 2020, pp. 476–481.
[59] F. Simone, G. Rizzello, S. Seelecke, and P. Motzki, "A soft five-fingered hand actuated by shape memory alloy wires: Design, manufacturing, and evaluation," *Frontiers Robot. AI*, vol. 7, Dec. 2020, Art. no. 608841.
[60] T. Dayyoub, A. V. Maksimkin, O. V. Filippova, V. V. Tcherdyntsev, and D. V. Telyshev, "Shape memory polymers as smart materials: A review," *Polymers*, vol. 14, no. 17, p. 3511, Aug. 2022.
[61] T. Shahid, D. Gouwanda, S. G. Nurzaman, and A. A. Gopalai, "Moving toward soft robotics: A decade review of the design of hand exoskeletons," *Biomimetics*, vol. 3, no. 3, p. 17, Jul. 2018.
[62] P. Capsi-Morales, C. Piazza, M. G. Catalano, G. Grioli, L. Schiavon, E. Fiaschi, and A. Bicchi, "Comparison between rigid and soft poly-articulated prosthetic hands in non-expert myo-electric users shows advantages of soft robotics," *Sci. Rep.*, vol. 11, no. 1, pp. 1–15, Dec. 2021.
[63] N. H. Chuc, N. H. L. Vuong, D. Kim, H. Moon, J. C. Koo, Y. Lee, J.-D. Nam, and H. R. Choi, "Design and control of a multi-jointed robot finger driven by an artificial muscle actuator," *Adv. Robot.*, vol. 24, no. 14, pp. 1983–2003, Jan. 2010.
[64] S.-Y. Jung, S.-K. Kang, M.-J. Lee, and I. Moon, "Design of robotic hand with tendon-driven three fingers," in *Proc. Int. Conf. Control, Autom. Syst.*, 2007, pp. 83–86.
[65] H. Hua, Z. Liao, and J. Zhao, "Design, analysis, and experiment of an underactuated robotic gripper actuated by linear series elastic actuator," *J. Mech. Robot.*, vol. 15, no. 2, Apr. 2023, Art. no. 021002.
[66] T. Mańkowski, J. Tomczyński, K. Walas, and D. Belter, "PUT-hand—Hybrid industrial and biomimetic gripper for elastic object manipulation," *Electronics*, vol. 9, no. 7, p. 1147, Jul. 2020.
[67] W. Wang and S.-H. Ahn, "Shape memory alloy-based soft gripper with variable stiffness for compliant and effective grasping," *Soft Robot.*, vol. 4, no. 4, pp. 379–389, Dec. 2017.
[68] V. Bundhoo, E. Haslam, B. Birch, and E. J. Park, "A shape memory alloy-based tendon-driven actuation system for biomimetic artificial fingers, part I: Design and evaluation," *Robotica*, vol. 27, no. 1, pp. 131–146, Jan. 2009.
[69] Y. Wei, Y. Ma, and W. Zhang, "A multi-jointed underactuated robot hand with fluid-driven stretchable tubes," *Robot. Biomimetics*, vol. 5, no. 1, pp. 1–10, Dec. 2018.
[70] H. Rodrigue, W. Wang, M.-W. Han, T. J. Kim, and S.-H. Ahn, "An overview of shape memory alloy-coupled actuators and robots," *Soft Robot.*, vol. 4, no. 1, pp. 3–15, 2017.
[71] V. Skaramagkas, G. Andrikopoulos, and S. Manesis, "Towards essential hand tremor suppression via pneumatic artificial muscles," *Actuators*, vol. 10, no. 9, p. 206, Aug. 2021.
[72] P. T. Phan, M. T. Thai, T. T. Hoang, N. H. Lovell, and T. N. Do, "HFAM: Soft hydraulic filament artificial muscles for flexible robotic applications," *IEEE Access*, vol. 8, pp. 226637–226652, 2020.
[73] M. Liarokapis and A. M. Dollar, "Post-contact, in-hand object motion compensation for compliant and underactuated hands," in *Proc. 25th IEEE Int. Symp. Robot Human Interact. Commun. (RO-MAN)*, Aug. 2016, pp. 986–993.
[74] J. Gan, J. Zhang, M.-F. Ge, and X. Tu, "Designs of compliant mechanism-based force sensors: A review," *IEEE Sensors J.*, vol. 22, no. 9, pp. 8282–8294, May 2022.
[75] J. Zhang, J. Sheng, C. T. O'Neill, C. J. Walsh, R. J. Wood, J.-H. Ryu, J. P. Desai, and M. C. Yip, "Robotic artificial muscles: Current progress and future perspectives," *IEEE Trans. Robot.*, vol. 35, no. 3, pp. 761–781, Jun. 2019.
[76] J.-H. Youn, S. M. Jeong, G. Hwang, H. Kim, K. Hyeon, J. Park, and K.-U. Kyung, "Dielectric elastomer actuator for soft robotics applications and challenges," *Appl. Sci.*, vol. 10, no. 2, p. 640, Jan. 2020.
[77] F. Zhou, M. Zhang, X. Cao, Z. Zhang, X. Chen, Y. Xiao, Y. Liang, T.-W. Wong, T. Li, and Z. Xu, "Fabrication and modeling of dielectric elastomer soft actuator with 3D printed thermoplastic frame," *Sens. Actuators A, Phys.*, vol. 292, pp. 112–120, Jun. 2019.
[78] E. Deng and Y. Tadesse, "A soft 3D-printed robotic hand actuated by coiled SMA," *Actuators*, vol. 10, no. 1, p. 6, Dec. 2020.
[79] Y. Lee, W. J. Song, and J.-Y. Sun, "Hydrogel soft robotics," *Mater. Today Phys.*, vol. 15, Dec. 2020, Art. no. 100258.
[80] F. Veiga, B. Edin, and J. Peters, "Grip stabilization through independent finger tactile feedback control," *Sensors*, vol. 20, no. 6, p. 1748, Mar. 2020.
[81] M. Park, Y. J. Park, X. Chen, Y.-K. Park, M.-S. Kim, and J.-H. Ahn, "MoS_2-based tactile sensor for electronic skin applications," *Adv. Mater.*, vol. 28, no. 13, pp. 2556–2562, 2016.
[82] K. Dai, X. Wang, A. M. Rojas, E. Harber, Y. Tian, N. Paiva, J. Gnehm, E. Schindewolf, H. Choset, V. A. Webster-Wood, and L. Li, "Design of a biomimetic tactile sensor for material classification," in *Proc. Int. Conf. Robot. Autom. (ICRA)*, May 2022, pp. 10774–10780.
[83] A. Cirillo, M. Costanzo, G. Laudante, and S. Pirozzi, "Tactile sensors for parallel grippers: Design and characterization," *Sensors*, vol. 21, no. 5, p. 1915, Mar. 2021.
[84] W. A. Friedl and M. A. Roa, "Experimental evaluation of tactile sensors for compliant robotic hands," *Frontiers Robot. AI*, vol. 8, p. 241, Oct. 2021.
[85] U. H. Shah, R. Muthusamy, D. Gan, Y. Zweiri, and L. Seneviratne, "On the design and development of vision-based tactile sensors," *J. Intell. Robotic Syst.*, vol. 102, no. 4, pp. 1–27, Aug. 2021.
[86] J.-K. Lee, H.-H. Kim, J.-W. Choi, K.-C. Lee, and S. Lee, "Development of direct-printed tactile sensors for gripper control through contact and slip detection," *Int. J. Control, Autom. Syst.*, vol. 16, no. 2, pp. 929–936, Apr. 2018.
[87] T. Zhang, H. Liu, L. Jiang, S. Fan, and J. Yang, "Development of a flexible 3-D tactile sensor system for anthropomorphic artificial hand," *IEEE Sensors J.*, vol. 13, no. 2, pp. 510–518, Feb. 2013.
[88] S. E. Navarro, M. Marufo, Y. Ding, S. Puls, D. Göger, B. Hein, and H. Wörn, "Methods for safe human-robot-interaction using capacitive tactile proximity sensors," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Nov. 2013, pp. 1149–1154.
[89] J.-B. Chossat, Y.-L. Park, R. J. Wood, and V. Duchaine, "A soft strain sensor based on ionic and metal liquids," *IEEE Sensors J.*, vol. 13, no. 9, pp. 3405–3414, Sep. 2013.
[90] K. Hsiao, P. Nangeroni, M. Huber, A. Saxena, and A. Y. Ng, "Reactive grasping using optical proximity sensors," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2009, pp. 2098–2105.
[91] Y. Yamakawa, A. Namiki, M. Ishikawa, and M. Shimojo, "One-handed knotting of a flexible rope with a high-speed multifingered hand having tactile sensors," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2007, pp. 703–708.

[92] B. Choi, H. Ryeol Choi, and S. Kang, "Development of tactile sensor for detecting contact force and slip," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Aug. 2005, pp. 2638–2643.
[93] M. Ohka, H. Kobayashi, and Y. Mitsuya, "Sensing characteristics of an optical three-axis tactile sensor mounted on a multi-fingered robotic hand," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Aug. 2005, pp. 493–498.
[94] A. Cranny, D. P. J. Cotton, P. H. Chappell, S. P. Beeby, and N. M. White, "Thick-film force and slip sensors for a prosthetic hand," *Sens. Actuators A, Phys.*, vols. 123–124, pp. 162–171, Sep. 2005.
[95] G. Heidemann and M. Schopfer, "Dynamic tactile sensing for object identification," in *Proc. IEEE Int. Conf. Robot. Autom.*, vol. 1, Apr. 2004, pp. 813–818.
[96] Y. Tada, K. Hosoda, Y. Yamasaki, and M. Asada, "Sensing the texture of surfaces by anthropomorphic soft fingertips with multi-modal sensors," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, vol. 1, Oct. 2003, pp. 31–35.
[97] J. W. Roach, P. K. Paripati, and M. Wade, "Model-based object recognition using a large-field passive tactile sensor," *IEEE Trans. Syst., Man, Cybern.*, vol. 19, no. 4, pp. 846–853, Jul./Aug. 1989.
[98] B.-G. Bok, J.-S. Jang, and M.-S. Kim, "Texture identification of objects using a robot fingertip module with multimodal tactile sensing capability," *Appl. Sci.*, vol. 11, no. 11, p. 5256, Jun. 2021.
[99] P. Weiner, C. Neef, Y. Shibata, Y. Nakamura, and T. Asfour, "An embedded, multi-modal sensor system for scalable robotic and prosthetic hand fingers," *Sensors*, vol. 20, no. 1, p. 101, Dec. 2019.
[100] A. S. A. Kumar, B. George, and S. C. Mukhopadhyay, "Technologies and applications of angle sensors: A review," *IEEE Sensors J.*, vol. 21, no. 6, pp. 7195–7206, Mar. 2021.
[101] J. Park, P. Heo, J. Kim, and Y. Na, "A finger grip force sensor with an open-pad structure for glove-type assistive devices," *Sensors*, vol. 20, no. 1, p. 4, Dec. 2019.
[102] W. Yang, M. Xie, X. Zhang, X. Sun, C. Zhou, Y. Chang, H. Zhang, and X. Duan, "Multifunctional soft robotic finger based on a nanoscale flexible temperature–pressure tactile sensor for material recognition," *ACS Appl. Mater. Interfaces*, vol. 13, no. 46, pp. 55756–55765, Nov. 2021.
[103] A. Pavone, G. Stano, and G. Percoco, "One-shot 3D printed soft device actuated using metal-filled channels and sensed with embedded strain gauge," *3D Printing Additive Manuf.*, vol. 10, no. 6, pp. 1251–1259, Dec. 2023.
[104] A. Mohammadi, J. Lavranos, H. Zhou, R. Mutlu, G. Alici, Y. Tan, P. Choong, and D. Oetomo, "A practical 3D-printed soft robotic prosthetic hand with multi-articulating capabilities," *PLoS ONE*, vol. 15, no. 5, May 2020, Art. no. e0232766.
[105] A. Belford, S. A. Moshizi, A. Razmjou, and M. Asadnia, "Using miniaturized strain sensors to provide a sense of touch in a humanoid robotic arm," *Frontiers Mech. Eng.*, vol. 6, Oct. 2020, Art. no. 550328.
[106] J. Zhang, H. Yao, J. Mo, S. Chen, Y. Xie, S. Ma, R. Chen, T. Luo, W. Ling, L. Qin, Z. Wang, and W. Zhou, "Finger-inspired rigid-soft hybrid tactile sensor with superior sensitivity at high frequency," *Nature Commun.*, vol. 13, no. 1, p. 5076, Aug. 2022.
[107] D. Li, J. He, Z. Song, K. Yao, M. Wu, H. Fu, Y. Liu, Z. Gao, J. Zhou, L. Wei, Z. Zhang, Y. Dai, Z. Xie, and X. Yu, "Miniaturization of mechanical actuators in skin-integrated electronics for haptic interfaces," *Microsyst. Nanoeng.*, vol. 7, no. 1, p. 85, Oct. 2021.
[108] Y. Qiu, S. Sun, X. Wang, K. Shi, Z. Wang, X. Ma, W. Zhang, G. Bao, Y. Tian, Z. Zhang, H. Ding, H. Chai, A. Liu, and H. Wu, "Nondestructive identification of softness via bioinspired multisensory electronic skins integrated on a robotic hand," *NPJ Flexible Electron.*, vol. 6, no. 1, p. 45, Jun. 2022.
[109] A. Nag, S. C. Mukhopadhyay, and J. Kosel, "Wearable flexible sensors: A review," *IEEE Sensors J.*, vol. 17, no. 13, pp. 3949–3960, Jul. 2017.
[110] K. T. Fujimoto, J. K. Watkins, T. Phero, D. Litteken, K. Tsai, T. Bingham, K. L. Ranganatha, B. C. Johnson, Z. Deng, B. Jaques, and D. Estrada, "Aerosol jet printed capacitive strain gauge for soft structural materials," *npj Flexible Electron.*, vol. 4, no. 1, p. 32, Nov. 2020.
[111] Y.-T. Wu, T. Yan, and Z.-J. Pan, "Wearable carbon-based resistive sensors for strain detection: A review," *IEEE Sensors J.*, vol. 21, no. 4, pp. 4030–4043, Feb. 2021.
[112] A. Palumbo, Z. Li, and E.-H. Yang, "Trends on carbon nanotube-based flexible and wearable sensors via electrochemical and mechanical stimuli: A review," *IEEE Sensors J.*, vol. 22, no. 21, pp. 20102–20125, Nov. 2022.
[113] J. Rosen, B. Hannaford, and R. M. Satava, Eds., *Surgical Robotics: Systems Applications and Visions*. Springer, 2011.
[114] D. M. Aukes, B. Heyneman, J. Ulmen, H. Stuart, M. R. Cutkosky, S. Kim, P. Garcia, and A. Edsinger, "Design and testing of a selectively compliant underactuated hand," *Int. J. Robot. Res.*, vol. 33, no. 5, pp. 721–735, Apr. 2014.
[115] H. Sun, K. J. Kuchenbecker, and G. Martius, "A soft thumb-sized vision-based sensor with accurate all-round force perception," *Nature Mach. Intell.*, vol. 4, no. 2, pp. 135–145, Feb. 2022.
[116] O. Faris, H. Alyammahi, B. Suthar, R. Muthusamy, U. H. Shah, I. Hussain, D. Gan, L. Seneviratne, and Y. Zweiri, "Design and experimental evaluation of a sensorized parallel gripper with optical mirroring mechanism," *Mechatronics*, vol. 90, Apr. 2023, Art. no. 102955.
[117] Z. Kappassov, J.-A. Corrales, and V. Perdereau, "Tactile sensing in dexterous robot hands—Review," *Robot. Auto. Syst.*, vol. 74, pp. 195–220, Dec. 2015.
[118] H.-J. Kim, K. Sim, A. Thukral, and C. Yu, "Rubbery electronics and sensors from intrinsically stretchable elastomeric composites of semiconductors and conductors," *Sci. Adv.*, vol. 3, no. 9, Sep. 2017, Art. no. e1701114.
[119] P. Saccomandi, E. Schena, C. Oddo, L. Zollo, S. Silvestri, and E. Guglielmelli, "Microfabricated tactile sensors for biomedical applications: A review," *Biosensors*, vol. 4, no. 4, pp. 422–448, Nov. 2014.
[120] S. Zhang, Z. Chen, Y. Gao, W. Wan, J. Shan, H. Xue, F. Sun, Y. Yang, and B. Fang, "Hardware technology of vision-based tactile sensor: A review," *IEEE Sensors J.*, vol. 22, no. 22, pp. 21410–21427, Nov. 2022.
[121] G. Borghesan, G. Palli, and C. Melchiorri, "Design of tendon-driven robotic fingers: Modeling and control issues," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2010, pp. 793–798.
[122] J. Wang and A. Chortos, "Control strategies for soft robot systems," *Adv. Intell. Syst.*, vol. 4, no. 5, May 2022, Art. no. 2100165.
[123] E. D'Anna, G. Valle, A. Mazzoni, I. Strauss, F. Iberite, J. Patton, F. M. Petrini, S. Raspopovic, G. Granata, R. Di Iorio, M. Controzzi, C. Cipriani, T. Stieglitz, P. M. Rossini, and S. Micera, "A closed-loop hand prosthesis with simultaneous intraneural tactile and position feedback," *Sci. Robot.*, vol. 4, no. 27, Feb. 2019, Art. no. eaau8892.
[124] E. Rombokas, E. Theodorou, M. Malhotra, E. Todorov, and Y. Matsuoka, "Tendon-driven control of biomechanical and robotic systems: A path integral reinforcement learning approach," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2012, pp. 208–214.
[125] Z. Chen, N. Y. Lii, T. Wimboeck, S. Fan, M. Jin, C. H. Borst, and H. Liu, "Experimental study on impedance control for the five-finger dexterous robot hand DLR-HIT II," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2010, pp. 5867–5874.
[126] A. B. Cruz, M. Radke, K. Haninger, and J. Krüger, "How can the programming of impedance control be simplified?" *Proc. CIRP*, vol. 97, pp. 266–271, Jan. 2021.
[127] V. P. Jiménez, O. F. Avilés Sánchez, and M. M. Mauledoux, "Hybrid force-position control three fingers end effector," in *Applied Mechanics and Materials*, vol. 346. Wollerau, Switzerland: Trans Tech Publications, 2013, pp. 75–82.
[128] M. Thieffry, "Model-based dynamic control of soft robots," Ph.D. dissertation, Center Res. Signal Automat., Université Polytechnique des Hauts-de-France, Valenciennes, France, 2019.
[129] L. Shi, C. Mucchiani, and K. Karydis, "Online modeling and control of soft multi-fingered grippers via Koopman operator theory," in *Proc. IEEE 18th Int. Conf. Autom. Sci. Eng. (CASE)*, Aug. 2022, pp. 1946–1952.
[130] X.-H. Liu, X.-H. Chen, X.-H. Zheng, S.-P. Li, and Z.-B. Wang, "Development of a GA-fuzzy-immune PID controller with incomplete derivation for robot dexterous hand," *Sci. World J.*, vol. 2014, no. 1, pp. 1–10, 2014.
[131] Q. M. Li and Y. P. Lv, "A fuzzy PID control method for the grasping force of an underactuated prosthetic hand," in *Applied Mechanics and Materials*, vol. 551. Wollerau, Switzerland: Trans Tech Publications, 2014, pp. 514–522.
[132] P. Weiner, J. Starke, S. Rader, F. Hundhausen, and T. Asfour, "Designing prosthetic hands with embodied intelligence: The KIT prosthetic hands," *Frontiers Neurorobot.*, vol. 16, Mar. 2022, Art. no. 815716.

[133] H. Xue, S. Wen, C. Yang, and H. Liu, "Model based reinforcement learning for robot grasping trajectory generation," in *Proc. IEEE 4th Int. Conf. Adv. Robot. Mechatronics (ICARM)*, Jul. 2019, pp. 720–726.
[134] P. M. Khin, J. H. Low, M. H. Ang, and C. H. Yeow, "Development and grasp stability estimation of sensorized soft robotic hand," *Frontiers Robot. AI*, vol. 8, Mar. 2021, Art. no. 619390.
[135] S. Joshi, S. Kumra, and F. Sahin, "Robotic grasping using deep reinforcement learning," in *Proc. IEEE 16th Int. Conf. Autom. Sci. Eng. (CASE)*, Aug. 2020, pp. 1461–1466.
[136] X. Wang, Y. Li, and K.-W. Kwok, "A survey for machine learning-based control of continuum robots," *Frontiers Robot. AI*, vol. 8, p. 280, Sep. 2021.

BHIVRAJ SUTHAR (Member, IEEE) received the B.E. degree from the College of Technology and Engineering, India, in 2010, the M.Tech. degree from Indian Institute of Technology, Delhi, in 2015, and the Ph.D. degree in robotics from Korea University of Technology and Education, South Korea, in 2020. He is currently an Assistant Professor with the School of Artificial Intelligence and Data Science, Indian Institute of Technology Jodhpur, India. His research interests include bio-inspired robotics and artificial intelligence.

YUSRA ABDULRAHMAN (Member, IEEE) received the B.Sc. degree from The University of Arizona, in 2014, and the M.Sc. and Ph.D. degrees from Massachusetts Institute of Technology and Masdar Institute of Science and Technology Cooperative Program (MIT and MICP), in 2016 and 2020, respectively. She is currently an Assistant Professor with the Department of Aerospace Engineering, Khalifa University. Her expertise lies in robotics, artificial intelligence (AI), and non-destructive testing (NDT). She has received awards from the UAE Ministry of Energy and Industry for her research contributions.

YAHYA ZWEIRI (Member, IEEE) received the Ph.D. degree from the King's College London. He is currently a Professor with the Department of Aerospace Engineering and the Director of the Advanced Research and Innovation Center, Khalifa University, United Arab Emirates. His research interests include robotics with particular emphasis on applied artificial intelligence aspects and vision systems.