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3D Printing in the Design and Fabrication of Anthropomorphic Hands: A Review

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In this article, 3D-printed anthropomorphic hands for prosthetic or robotic applications are reviewed as 3D printing has transformed manufacturing by enabling the creation of intricate structures layer by layer, offering design freedom and efficiency. This review categorizes 3D-printed anthropomorphic hands based on actuation, transmission, joint, and functional features like sensing and grasp patterns. It also assesses the level of anthropomorphism and validation methods by presenting criteria in prosthetic and robotic applications. Then, the article discusses 3D printing technologies in their usage and types, highlighting the advantages of multi-material capabilities and integration of different hand components. Future directions on structural components, anthropomorphism, validation, and use of 3D printing are discussed, focusing on trends that only 3D printing technology can achieve in anthropomorphic hand development.

1. Introduction

3D printing is an additive manufacturing process that creates a physical 3D object from the digital model by adding materials layer-by-layer, giving advantages over conventional subtractive manufacturing methods. Complex structures such as internal cavities that traditional machining cannot replicate can easily be fabricated with 3D printing, offering design freedom to designers and engineers. 3D printing also enables the consolidation of multiple parts, improving the strength and performance of the final product and reducing weights added from joining elements. Design iterations and customization of a structure or mechanism become much more efficient without a specialized setup or a long lead time. Therefore, different 3D printing technologies have been utilized in various fields like aerospace, architecture, healthcare, automotive, and robotics.

In the last couple of decades, researchers in the robotics field have been utilizing these advantages of 3D printing technology when developing an anthropomorphic hand. As a human hand is capable of dexterous movements and acute sensing with 21 joints, 34 muscles, and flexible skin in its compact size, it is very challenging for engineers to mimic the complex structure and advanced functionalities of a human hand in the form of a prosthetic or robotic hand. However, high-resolution 3D printing technology such as material jetting or stereolithography (SLA) can effectively build complex joint structures with cavities or arbitrary curvatures of a human hand. 3D printing a mold is also cost-effective and efficient in design iterations when fabricating soft skin or compliant joints compared to conventional machining. A wide range of 3D printing materials enables engineers to realize different material properties and colors. Recently, as functional 3D printing materials like conductive or piezoelective materials are also becoming available,[1–4] it is possible to embed circuitry and sensors within a small, confined space which is beneficial for designing an anthropomorphic hand. With advances in the multi-material capabilities of fused deposition modeling (FDM) or Polyjet technologies,[5,6] engineers can realize the material properties of different hand components in a single print job. Moreover, engineers even attempt to 3D-print the entire articulated robotic structure in a single step which can eliminate the complex manual assembly process of an anthropomorphic hand.[7–9]

In this article, recent developments in 3D-printed anthropomorphic hands are reviewed. Since they have shown novel ways of creating functional anthropomorphic hands, it is necessary to highlight the different components of a 3D-printed anthropomorphic hand. An anthropomorphic hand, either prosthetic or robotic, is evaluated based on categories including actuation, transmission, joint structure, and other functional features. Then, the level of anthropomorphism and validation methods of the 3D-printed anthropomorphic hands are discussed. Lastly, 3D printing technologies are investigated based on their types and how they are used in fabricating anthropomorphic hands. The article concludes with suggestions on future directions of the required features of a more sophisticated anthropomorphic hand and 3D printing technologies with their materials.

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2. Results

2.1. Joint Structure

Making appropriate gestures and motions like a human hand is one of the most important functionalities of an anthropomorphic hand. In doing so, a joint structure plays a significant role by determining how the motion and posture of a hand are made. Among many ways of manufacturing, 3D printing technologies have expanded the design domain of joint structures with the capability to realize complex geometries by building materials layer by layer. In **Figure 1**a, various joint types that researchers used to mimic the biomechanics of a human hand are shown. A pin joint is the most widely used joint type in 3D-printed anthropomorphic hands since it is simple in its kinematics with a fixed axis of rotation and is easy to design and fabricate.[10–18] A universal joint, which is a variation of a pin joint, is applied to generate two degrees of freedom (DoF) in motion like the human metacarpophalangeal (MCP) or thumb carpometacarpal (CMC) joint.[19,20] A ball joint is also implemented as an alternative to a universal joint and can be applied to mimic the 2-DoF motion of the thumb CMC joint of a robotic hand.[21] Flexure, which uses material deformation within the elastic range, has also been applied to finger joints by direct 3D printing of soft materials like thermoplastic polyurethane (TPU) or smart composite microstructure.[22-27] Flexure can also be 3D-printed in combination with other rigid materials using multi-material 3D printing.[28] For pneumatically actuated hands, soft chambers are applied in the finger joint structure for high compliance against the external environment.[29,30] A few robotic and prosthetic hands implement rolling contact joints to generate finger joint motions.[31,32] Some robotic hands try to replicate the anatomical structures of a human hand with a bio-inspired joint, which consists of the bones and ligaments just like a human hand anatomy to mimic the natural finger joint motion.[33,34]

2.2. Actuation

The primary functionality of an anthropomorphic hand is grasping different objects for manipulation or activities of daily living (ADLs). The actuation type of a 3D-printed anthropomorphic hand is highly correlated with the corresponding 3D-printed joint structure. In **Figure 2**, actuation types used in the 3D-printed anthropomorphic hand are shown. Reaching 75% of all anthropomorphic hands reviewed in this article, electrical motors like servos, geared motors, and linear actuators are the most popular choices for actuation as they are widely available and applicable to various joint types such as flexure and pin joints.[35–46] Pneumatic actuation is often used for soft chamber joints in robotic hands as pneumatic actuation is less likely to be used in prosthetics due to the weight and bulkiness of the pneumatic pumps.[29,47] However, there is only one example of pneumatic actuation implemented in a prosthetic hand with a compact

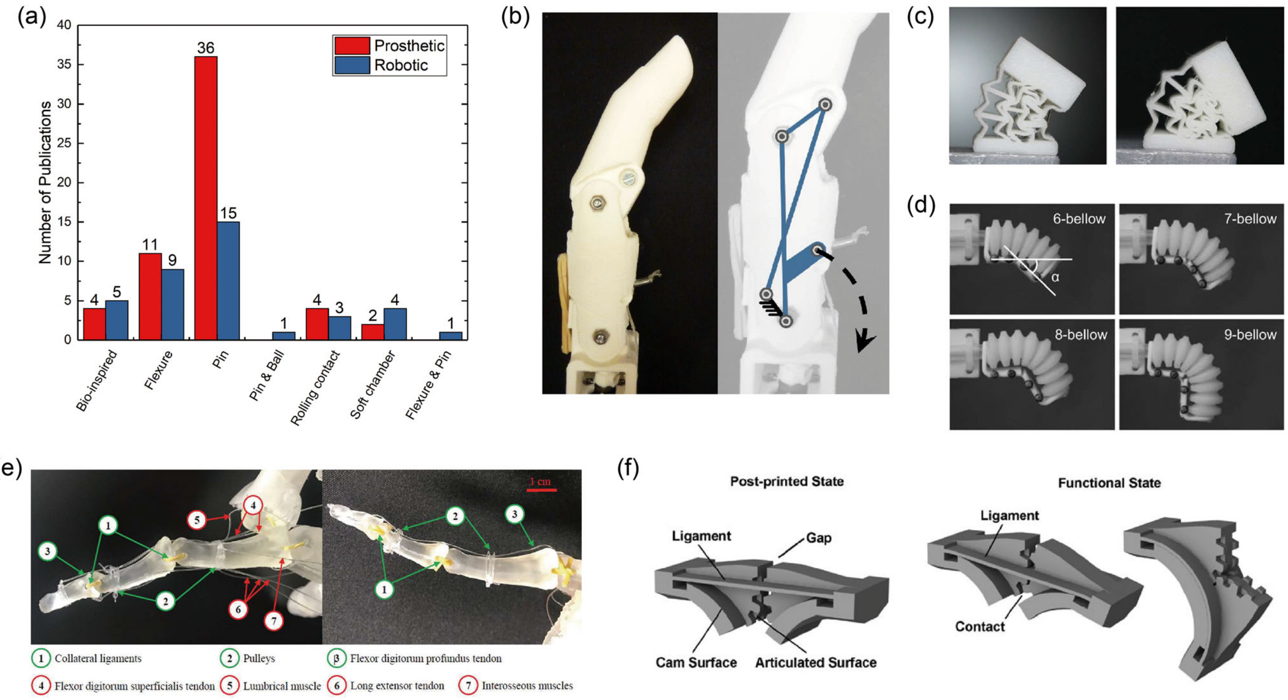

Figure 1. Joint structures in 3D-printed anthropomorphic hands. a) Number of research papers with specific joint types. b) Tact hand's finger four-bar linkage mechanism with pin joints for coupled flexion motion of the MCP and proximal interphalangeal (PIP) Joint. Reproduced with permission.[110] Copyright 2023, IEEE. c) A metamaterial flexure joint with multi-stiffness for a relatively large range of motion for a compliant joint to mimic the flexion motion of a human finger.[111] d) Finger joint made of soft pneumatic chambers which are tunable based on patterns of bellows. Reproduced with permission.[112] Copyright 2023, Elsevier. e) A bio-inspired joint that mimics the anatomy of a human hand with 3D-printed bone structures and rubber ligaments.[113] f) A 3D printable, monolithic rolling contact joint that is tightened as it rotates along its contact surfaces, mimicking collateral ligaments of a human MCP joint. Reproduced with permission.[70] Copyright 2023, Mary Ann Liebert.

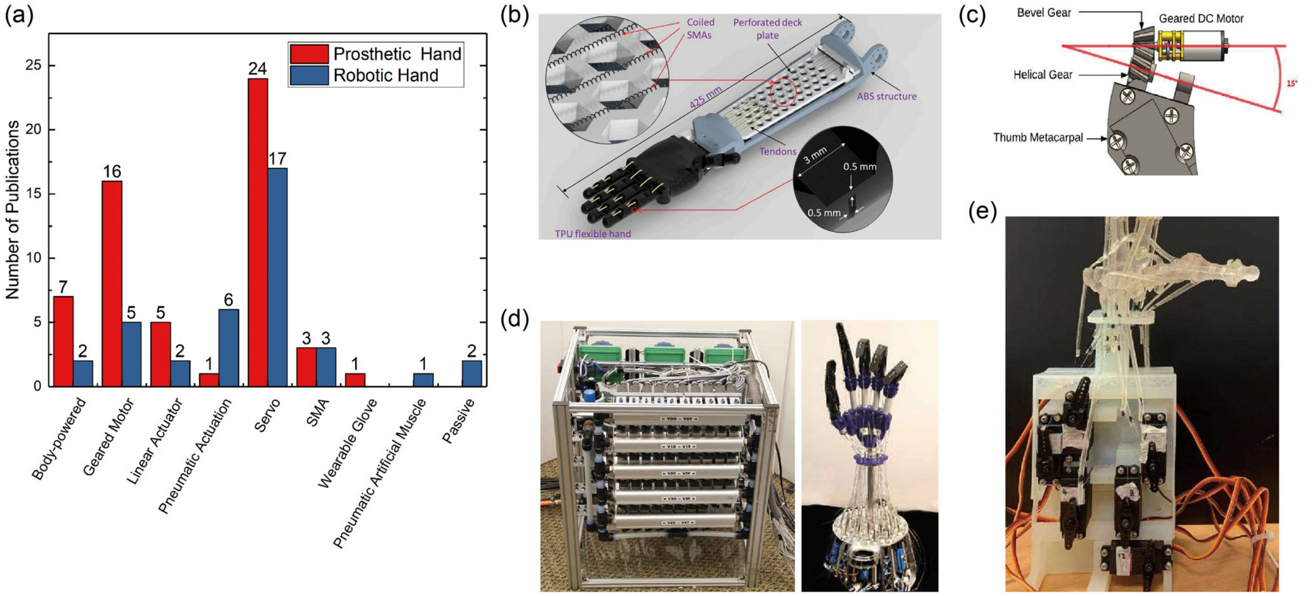

Figure 2. Actuation types of a 3D-printed anthropomorphic hand. a) Number of research papers with specific actuation types used in prosthetic and robotic hands. b) SMA wires placed at the forearm region to flex each prosthetic finger via shrinkage upon heat.[114] c) Geared motor with helical gear to mimic the opposition motion of a thumb.[79] d) A pneumatic actuation system for BCL Hand for 13 DoFs of actuation for 4-fingered robotic hand. Reproduced with permission.[29] Copyright 2023, IEEE. e) 5 servos driving 3D printed tendons of three-fingered anthropomorphic robotic hand.[115]

actuation system worn around the waist.[48] Robotic and prosthetic hands have also implemented shape memory alloy (SMA) as an actuator due to its compactness, lightweightness, and simplicity in mechanism design.[49–52] However, the examples are not abundant because of practical issues such as slow response, high energy consumption, and low force exertion. A few rare actuation types include artificial pneumatic muscle (PAM),[53] similar to pneumatic actuation, and a wearable glove, which actuates a soft hand structure with only sensing components for prosthetic usage.[54] Some prosthetic and robotic hands do not include actuation at all. Some prosthetic hands are body-powered in which the movements of the residual wrist of an amputee actuate the finger joints,[55–57] and a robotic hand is just a passive structure that is implemented into a robotic arm for piano play application.[58] There is one paper that does not specify its actuation type, although it is assumed to be a geared motor for a cable-driven system.[59]

2.3. Transmission

Just like how 3D-printed joint structures and actuator types are correlated, transmission types are also highly related to joint and actuator types. Different transmission types used in prosthetic and robotic hands are shown in **Figure 3**. The majority use the cable to transmit the force generated from the rotation of a geared motor,[60] change of angle by servo and displacement made by SMA,[61] actuating flexure,[62] pin,[63] bio-inspired,[64] and rolling contact joints.[65] Although it cannot exert pushing force, the cable can pull multiple finger joints from a single actuator source. Expanding its capabilities in under-actuation where joint DoFs are larger than actuation DoFs, a few examples actuate multiple fingers and even entire hands via one or few cables.[66–68] Some use air pressure from pneumatic pumps to drive finger joints made of soft chambers but are mainly applied to robotic hands.[30,47,69] Some hands implement 3D-printed tendons for transmission, expanding the printability of an entire hand structure.[24,70,71] However, they are not as prevalent as other transmission types since they can be less effective in transmitting force than cables and air pressure due to friction between 3D-printed structures and plastic deformation of the 3D-printed tendons. Linkages, especially four bar linkages, are also used to transmit force to the fingertip and generate desired motions of the finger joint of a few anthropomorphic hands.[72,73] Other means of transmission include gears, timing belts, and combinations of previously mentioned transmission types, which enable the coupled motion of multiple joints from a single actuator.[74,75]

2.4. Other Features

Some qualitative features like grasping patterns and sensing capability are discussed in this section. A complete list of all hands and their features and functionalities is shown in supplementary materials (**Table 1**). The number of grasping patterns an anthropomorphic hand can make is a crucial indicator of the hand's functionality. However, it is difficult to compare the grasping patterns of the 3D-printed anthropomorphic hands in this review since they have different categorizations. Therefore, power grasp, tripod grasp, and lateral pinch are selected in this review as three distinctive and frequently used ones to evaluate the 3D-printed anthropomorphic hands among numerous grasping patterns. Most hands can make multiple grasping postures like power and tripod grasp as their fingers move individually. However, in some cases of multi-finger under-actuation, the hands can only power grasp but cannot make precision grapes like a tripod grasp.[51,65] Passive or active

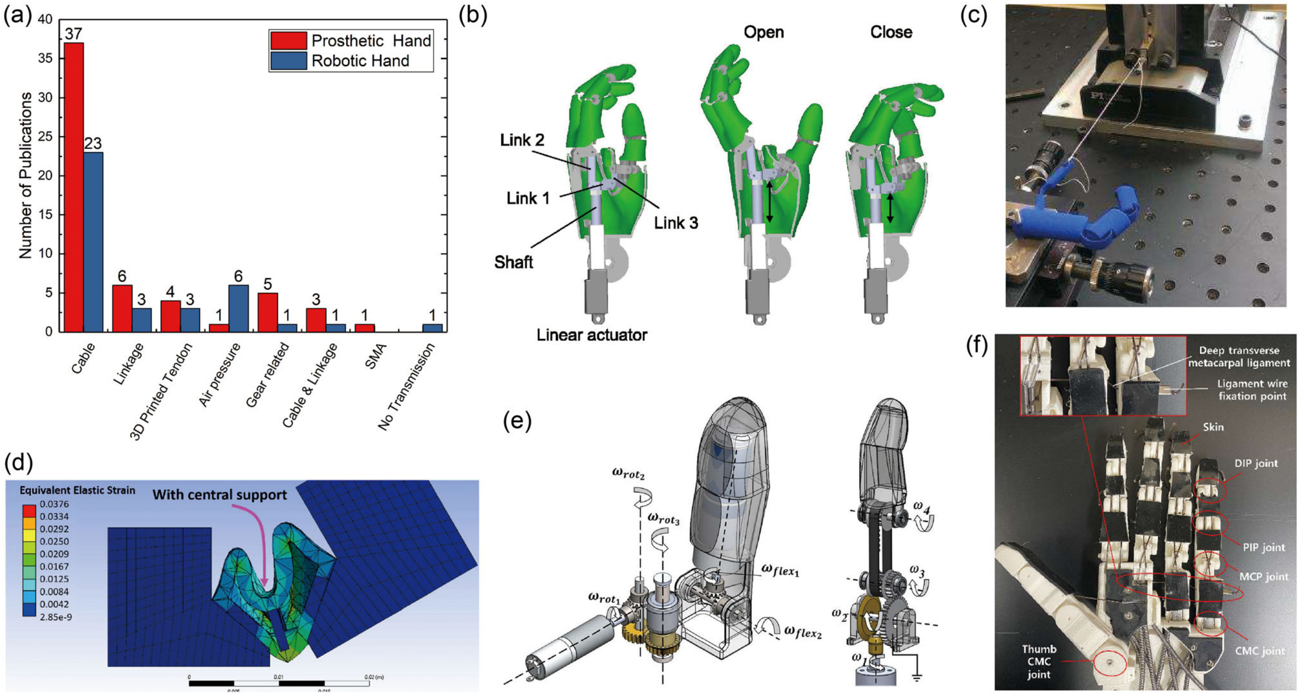

Figure 3. Transmission types of a 3D-printed anthropomorphic hand. a) Number of research papers with specific transmission types used in prosthetic and robotic hands. b) Linkage mechanisms to open and close the hand with a single actuator to actuate the MCP joint of a finger to enable power grasping of a hand.[116] c) 3D printed tendons with binary cross-sectional areas for transmitting force from actuator to fingertip while preventing plastic deformation.[117] d) Finite element analysis of a pneumatic chamber actuated by negative air pressure as it bends towards the flexion direction of a finger joint.[118] e) Multiple gears to actuate the ad/abduction motion of a thumb and gears with a timing belt to transmit torques to MCP and PIP joints from a single actuator. Reproduced with permission.[119] Copyright 2023, IEEE. f) A cable-driven differential mechanism to mimic the functionality of flexor digitorum profundus (FDP) and flexor digitorum superficialis (FDS) of a human hand for robust grasping. Reproduced with permission.[93] Copyright 2023, IEEE.

Table 1. Criteria to determine the level of anthropomorphism of a hand.

Category	Criteria
Appearance	Outer contours with smooth curve surfaces or anatomically similar to a human hand
Joint DoFs	2+ joints per finger except thumb/Joint placement based on the anatomy of a human hand
Movements	Based on human biomechanics in terms of trajectory and range of motion of the joints
Skin	Any attempts to replicate appearance or material properties of human skin at fingertips or palm
Sensing capability	Any attempts to measure actuator signal such as position, force, current
	Or reaction force/contact detection created from grasped object
Feedback	Any attempts to inform what has been measured from sensing capabilities to the wearer
	Except for the visual information (prosthetic only)

thumb ab/adduction DoFs enable lateral grasping like a pinch. In contrast, a thumb without ab/adduction DoF is often fixed at an opposed orientation to grasp objects with various diameters with power or tripod grasp.[76–78] Only 60 percent of all reviewed anthropomorphic hands can make all three grasps. Many 3D-printed anthropomorphic hands lack functionality other than grasping but some utilize sensing capabilities to improve the functionality of the hands. Motor encoders and hall sensors are commonly used sensors to estimate the finger posture from how much the motor has driven.[74,79–81] Force sensing resistors at the fingertips is a more direct way of sensing because it is not a position but it measures force being applied to the hand by the grasped object.[82] Some use a camera to detect an object being securely grasped at the palm of the anthropomorphic hand[83] or a gyroscope for fingertip angle measurements.[84] For a prosthetic hand, intention detection from the user is mandatory as it cannot automatically make decisions in regard to object manipulation. The most common methods used are surface Electromyography.[85] Other methods include pressing buttons or even the movement of residual body parts such as the wrist.[72] Haptic feedback to users can be highly effective for prosthetic usage since it helps the user to embody the prosthetic device as a part of their own body by bidirectional communication of intention and feedback. However, every prosthetic hand does not have any form of haptic feedback capability except for one.[48]

2.5. Wrist Mechanism

In manipulating objects and tools in various activities, a wrist mechanism plays a critical role in coordination with a hand. Although there have been some attempts to develop general wrist mechanisms, it is rare to find research on 3D-printed, anthropomorphic ones. As it has complicated bone and ligament structures that constitute the 3-DoF movements, a human wrist structure is not generally replicated but replaced with simple mechanical joints in prosthetic and robotic applications. Therefore, 3D-printed wrist mechanisms are reviewed in addition to the hands to understand the potential functionality of 3D-printed anthropomorphic hands. **Figure 4** shows examples of 3D-printed wrist mechanisms applied in robotic and prosthetic uses. Detailed data about each research paper is presented in Table S3, Supporting Information. Out of 11 research papers on 3D-printed wrist design, four papers, along with an anthropomorphic hand, present a simple 1-DoF wrist mechanism that generates flexion/extension[84,86] or pronation/supination[42,87] motion. Some papers realize more than one DoF motion of a human wrist.[88–91] 3D printing is utilized for joint assembly parts fabrication in most papers; however, one presents a 3D-printed spring element with embedded sensing capability implemented in the wrist for sports activities,[86] expanding 3D printing capability. In terms of anthropomorphism, only two papers replicate the motion and functionality of a human wrist using rolling-sliding joints with high load capacity.[92,93]

2.6. Level of Anthropomorphism

An anthropomorphism represents the human-like properties of an artificial creation, but the properties are ambiguous without definitive criteria. Considering diverse aspects of human-like properties, requirements are defined to evaluate the level of anthropomorphism of the hands reviewed in this article. Table 1 shows the criteria for each category of anthropomorphism. The criteria cannot be perfect as they cannot account for qualitative aspects of how naturally a hand moves or how a hand feels during human interaction. Nevertheless, diverse aspects of a human hand like aesthetics, grasping functionality, and sensing/feedback capabilities are included in the criteria. **Figure 5**a shows a portion of the papers satisfying each category of anthropomorphism. Figure 5b,c,d presents a few highly anthropomorphic hands with aesthetics, movements, and sensing capabilities. Most hands satisfy the criteria of joint DoFs and joint motions, which means they move and make gestures similar to a human hand. However, about half of the hands did not satisfy the aesthetic criteria of smooth curvatures or anatomical representation. Also, sensing capabilities and skin replication are realized in less than half of the hands. Considering that the requirements for sensing and skin account for even a simple implementation of hall sensors in the DC motor or small rubber pads at the fingertips, the level of the skin replication and sensing capabilities of 3D-printed anthropomorphic hands are at their preliminary stage. For a prosthetic application, an anthropomorphic hand should be perceived as a part of the body for amputees. To perceive an artificial hand as part of the body, not only the intention of a user should be conveyed intuitively to the hand as input, but the hand should inform what has been sensed or measured from itself to the users intuitively, making a feedback system critical in realizing an anthropomorphic hand. However, only one of the reviewed prosthetic hands is equipped with haptic feedback functionality.

2.7. Level of Validation

Although the references reviewed in this article present the hands in various ways, how they validate their hands' performances should be evaluated to understand the maturity of the 3D-printed anthropomorphic hands. **Table 2** shows the criteria for the level of validation of 3D-printed prosthetic and robotic hands. Figure 5e shows the portion of anthropomorphic hands that satisfies specific validation criteria. Figure 5f,g are examples of qualitative validation for a robotic hand and an application to an amputee for prosthetic usage, respectively. All papers reviewed in this article presented physical hand prototypes using various 3D printing technologies. However, some prosthetic and robotic hands did not validate the performance of the hand in their works other than showing their designs. To verify functionality as hands, 62 and 85 percent of the prosthetic and robotic hands, respectively, show the grasping capabilities of the hands with a few objects. To evaluate their work more quantitatively, 29% and 53% of the prosthetic and robotic hands utilized well-known hand functionality metrics such as Yale-CMU-Berkeley (YCB) object sets and Karpandji Test or custom-made force measurement setups. Lastly, 19 and 10 percent of the prosthetic and robotic hands implemented their hands for possible use cases. While most prosthetic hands have also done grasping force measurements and object handling

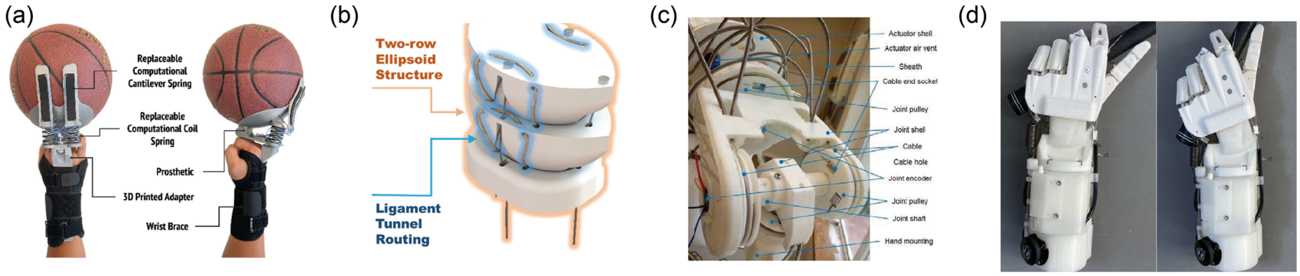

Figure 4. 3D-printed wrist mechanisms. a) 3D-printed spring coils and beams with conductive filaments that measure force and strain from sports activities.[86] b) A bio-inspired, rolling-and-sliding wrist joint to enable large ROM and high load capacity like a human wrist.Reproduced with permission.[92] Copyright 2023, IEEE. c) 3-DoF wrist mechanism of a 6-DoF robotic manipulator design that is actuated by 12 soft pneumatic actuators with a large workspace and low working air pressure. Reproduced with permission.[120] Copyright 2023, IEEE. d) A bio-inspired, rolling/sliding wrist joint mechanism for golf swing in which the radial/ulnar deviation motion is generated using a clutch and a spring. Reproduced with permission.[93] Copyright 2023, IEEE.

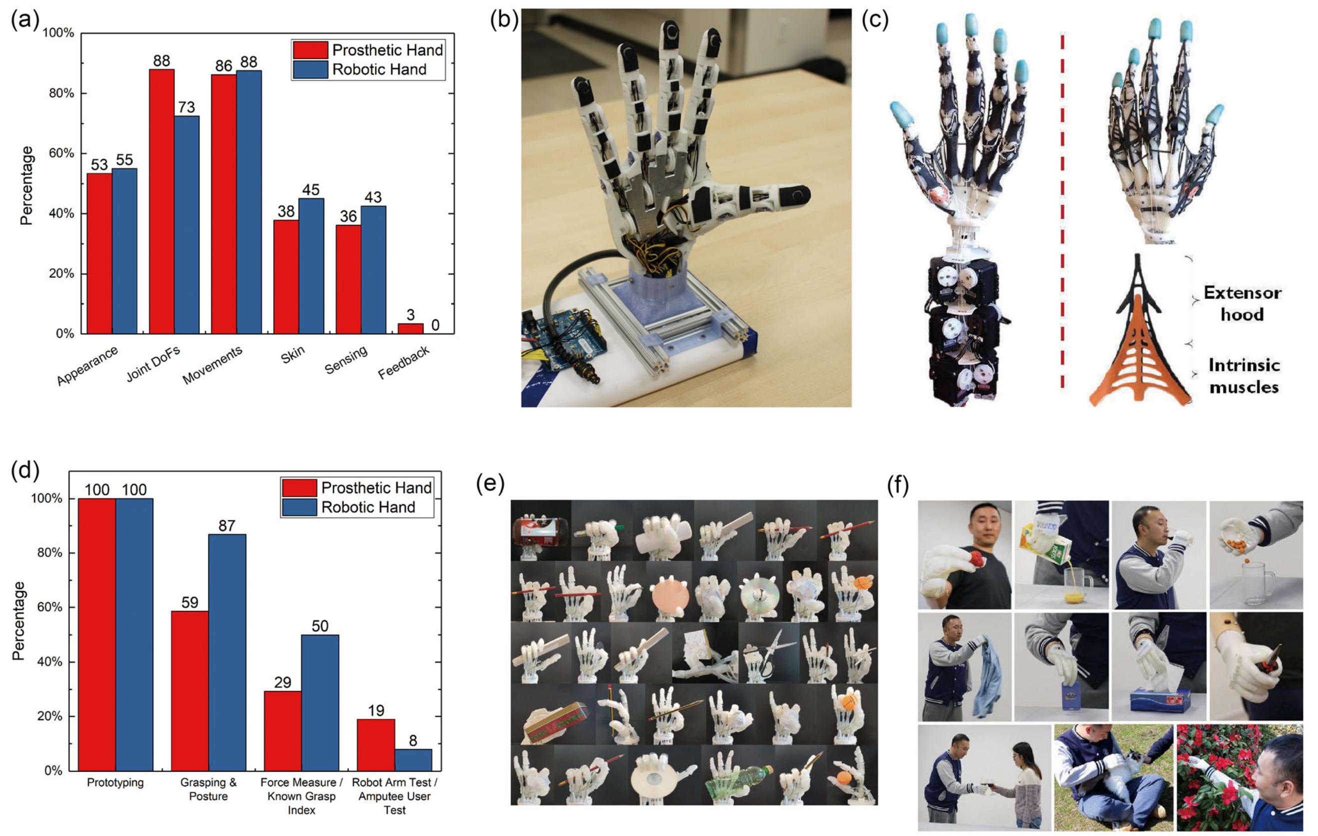

Figure 5. Level of anthropomorphism and validation of the 3D-printed anthropomorphic hands. a) Percentage of research papers satisfying the categories of anthropomorphism. b) Highly anthropomorphic robotic hand for machine learning purposes satisfying appearance, joint DoFs, movements, skin, and sensing capability of the anthropomorphism categories.[83] d) Highly anthropomorphic hand to replicate the anatomy of a human hand that satisfies appearance, joint DoFs, and movements of the anthropomorphism categories.[121] e) Percentage of research papers satisfying the categories of validation. f) A robotic hand performing 33 grasping gestures of Feix for qualitative grasping evaluation. Reproduced with permission.[33] Copyright 2023, IEEE. g) Soft pneumatically actuated prosthetic hand worn by an amputee to perform activities of daily living (ADLs). Reproduced with permission.[48] Copyright 2023, Springer.

Table 2. Criteria to determine the level of validation of a hand.

Category	Criteria
Prototyping	A prototype fabrication with pictures only or making some grasping patterns
Qualitative evaluation	Grasping experiment with a few objects or making a few grasping postures
Quantitative evaluation	Well-known grasping indexes (Karpandji Test, Cutkosky grasp, YCB object set usage)/Fingertip force or joint torque measurements
Application	Clinical test with amputee (prosthetic)/Robotic arm implementation (robotic)

experiments before putting them on a user for a clinical test, a few researchers skip the other validations and apply them directly to amputees, making them questionable in their basic functionality. For robotic hands, implementing the hands into a robotic arm or a humanoid is rare since not all robotic hands have a specific use case. Some robotic hands are used as dummy hands for future prosthetic uses or as a standalone test bench for machine learning.

3. Discussion

3.1. 3D Printing

3.1.1. How 3D Printing Is Used

3D printing offers a range of advantages, including cost-effectiveness, customization capabilities, and the ability to fabricate intricate geometrical designs. Therefore, it has been used extensively in anthropomorphic hand design, serving various purposes. **Figure 6**a shows the distinct roles of 3D printing in the prosthetic and robotic hands, and examples of each are shown in Figure 6b,c,d,e.

As of the current stage of development, 3D printing in anthropomorphic hand design and fabrication is utilized to fabricate mechanical structures of articulated mechanisms. Except for the peripheral parts like cable pulleys and covers for electronics, an appropriate 3D printing utilization mainly depends on joint types. For pneumatically actuated hands, joint structures are generally soft polymer chambers. Given the limited availability of soft materials in current technologies, 3D printing of airtight and highly deformable structures for pneumatic actuation is still

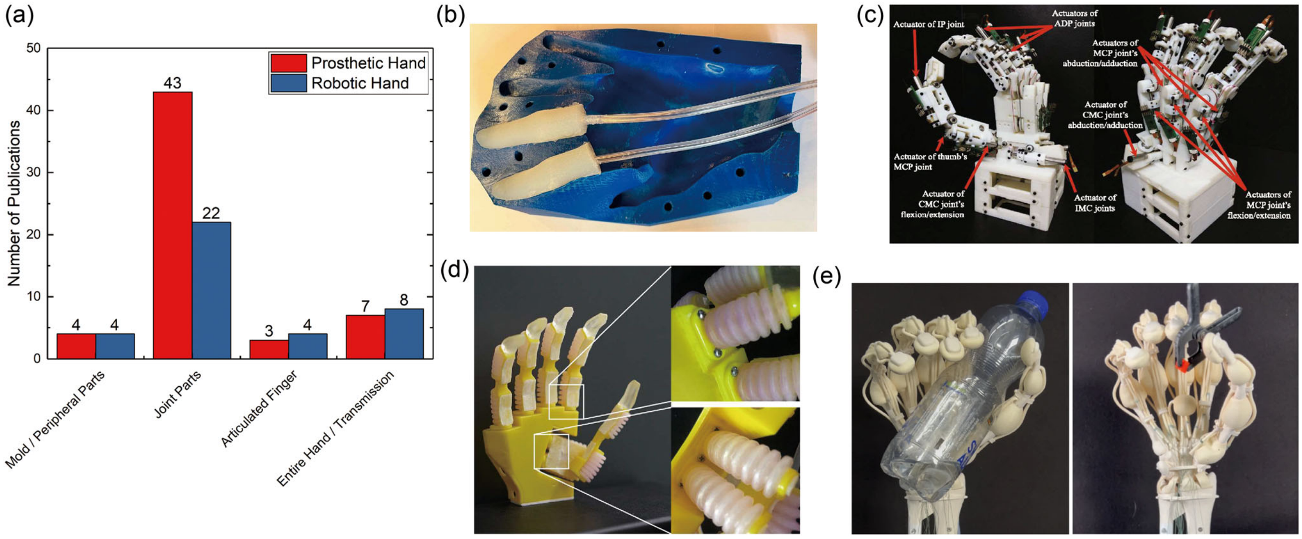

Figure 6. How 3D Printing is utilized in 3D anthropomorphic hands. a) Number of research papers that used 3D printing technology for specific purposes during the fabrication of an anthropomorphic hand. b) A passive, soft finger structure with only sensing components inside without actuation. A 3D-printed mold used to manufacture curvatures of human hand.[54] c) A robotic hand with complex internal and joint parts that are 3D printed and manually assembled. Reproduced with permission.[122] Copyright 2023, Springer. d) 3D-printed finger mechanisms with pneumatic chambers are assembled onto the palm structure to form the hand. Reproduced with permission.[112] Copyright 2023, IEEE. e) An articulated robotic hand with soft sensing chambers and tendons printed in a single print job. A vision-based jetting system enables 3D-printing of softer materials without the use of a flattening roller.[123]

challenging. Therefore, 3D-printed molds are often utilized for soft pneumatic chamber fabrication. However, most prosthetic and robotic hands leverage 3D printing in joint structure assembly. Since a pin joint is the simplest type, most hands 3D-print the yoke of a joint and assemble it with pins. A few researchers attempted to fabricate finger mechanisms in a single print job, including flexure-based hand structure or rigid-soft hybrid finger mechanisms. Furthermore, some papers present anthropomorphic hands that are 3D-printed as entirely monolithic structures or with transmissive tendons, differential systems like a Whipple tree structure, and pneumatic chambers for sensing. Depending on the 3D printing technology, components of an anthropomorphic hand are fabricated with a single material with optimized geometries or multi-material to replicate their various properties like hardness.

3.1.2. Which 3D Printing Is Used

To gain a comprehensive understanding of how 3D printing is utilized in anthropomorphic hand design, specific 3D printing techniques have been categorized. In **Figure** 7a, the number of papers using a particular type of 3D printing in the hand design is shown, and Figure 7c–f serve as illustrative examples representing the employment of FDM, Polyjet, SLA, and selective laser sintering (SLS), respectively. 3D-printing material used in the references can be found in the Table S1 and S2, Supporting Information.

For both robotic and prosthetic hands, FDM technology predominates. This prevalence can be attributed to its global availability and a wide range of materials such as PLA, ABS, and TPU. In prosthetics, where cost-effectiveness plays a pivotal role in device acceptance rate, the affordability of FDM 3D printing can be more desirable over other 3D printing methods. Renowned for its high resolution and digital material property tuning, Polyjet technology has been adopted by a few anthropomorphic hands with soft-rigid hybrid structures. A few anthropomorphic hands utilize selective laser melting (SLM) or SLS for fabrication. Without support structure, SLM or SLS enables fabricating intricate joint designs for assembly or finger mechanisms in a single print job. With exceptionally high resolution and great surface finishes, SLA has been utilized in anthropomorphic hand designs that mimic the anatomical structures of a human hand.

In Figure 7b, specific 3D printing types used in highly anthropomorphic hands are shown, where highly anthropomorphic hands refer to the ones that satisfy more than four categories of anthropomorphism discussed in the previous section. In robotic and prosthetic hands, FDM technology is still the most preferred choice in fabrication. Notably, 3D printers with multi-material capabilities like Polyjet and FDM are more often utilized than printers with a single material such as SLA or SLS.

3.2. Future Directions

3.2.1. Joints, Transmission, Actuation

There is no definitively best joint type for 3D-printed anthropomorphic hand design; however, the optimal type seems to be a hybrid structure with rigid and soft components. Rigid pin joints are simple in design but lack compliance, which may limit safe interaction with unstructured environments such as humans. While soft pneumatic chambers exhibit high compliance against

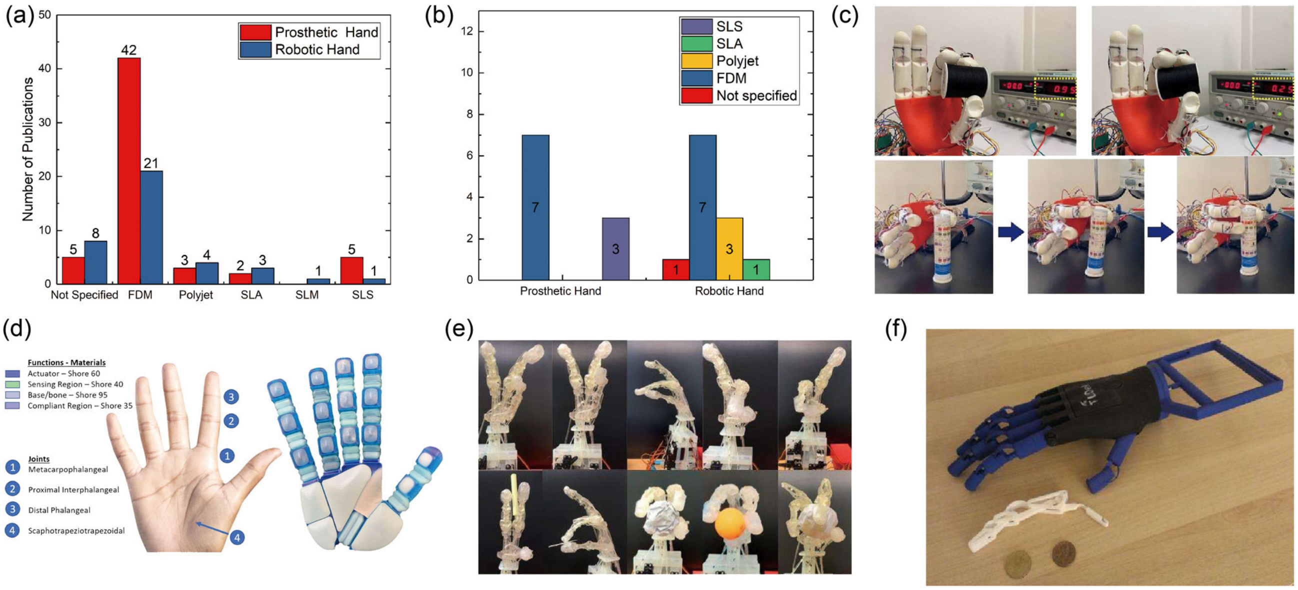

Figure 7. 3D Printing types of highly anthropomorphic hands. a) Number of research papers with specific types of 3D printing used in an anthropomorphic hand. b) Number of highly anthropomorphic prosthetic and robotic hands that satisfy more than four categories of anthropomorphism with specific 3D printing type. c) A prosthetic hand with monolithic flexure finger mechanisms using TPU material in an FDM 3D printer.[124] d) A robotic hand made with digital materials in Polyjet technology to incorporate various shore hardness for palm, finger joints, and sensing pads. Reproduced with permission.[118] Copyright 2023, IEEE. e) An anatomical replication of a human hand's joints and tendons, fabricated without assembly using SLA 3D printing.[115] f) A prosthetic hand consisting of flexure joints and tendons fabricated using nylon powders of SLS 3D printer.[117]

the external environment, making them suitable for grasping delicate objects or interacting with the external environment, their force exertion is lower than that of other rigid joint structures. Therefore, for hands that exert high force and have compliance, the hybrid structure of soft and stiff materials for the joints seems to be an appropriate choice. Current examples with potential hybrid material implementation include rolling contact joints, pneumatic chambers with constraining layers, and bio-inspired joints. Fabrication of such structures and 3D printing technologies with multi-material capabilities will benefit as they remove complex assembly of intricate geometry of small parts and realize various material properties within a joint structure. Single-step fabrication of such structures will make the overall manufacturing much easier as well with reduced labor on assembly of hand components.

Utilizing 3D printing in the transmission of anthropomorphic hands is quite a challenging task. Traditional transmissions like linkages, gears, and timing belts can effectively deliver forces to fingers, which is appropriate for robotic hands that require precise motion and force. However, 3D printing does not play many roles in such transmission mechanisms other than facilitating the fabrication of intricate internal geometry for gears and linkages to be sited. To best exploit 3D printing in the transmission of anthropomorphic hands, a transmissive path should be designed to be 3D-printed like outer geometries for anthropomorphic hands. Some potential ways of customizing the transmissive path include pneumatic or tendon path design. Due to inherent safety with the environment, tendon and air pressure can be effective transmission as they are back-drivable and capable of absorbing impacts. They are also effective in prosthetic applications in which reducing the weight/inertia of hands located distally is crucial for practical usage; heavy actuators can be located on the proximal side of the hand, reducing the overall inertia of the system. For air pressure, pneumatic chambers are 3D-printed in such a way as to facilitate the joint motion of a human finger. Currently, only limited materials enable the airtightness of 3D-printed anthropomorphic hands; therefore, more designs to support the airtightness are expected to be investigated in terms of 3D printing techniques and material development. For tendons, most researchers have been using cables that are assembled to the hand. A few 3D-printed tendons or a Whipple tree show their potential as a proof-of-concept. However, further research on designing 3D-printed tendons with reduced frictional effect or cable-like inextensible but flexible characteristics is required. New 3D printable materials with very low frictional coefficients or with cable-like behavior will open unforeseen design space for 3D-printed anthropomorphic hands.

For actuation, either pneumatic actuators or electric motors seem to be an appropriate choice for 3D-printed anthropomorphic hand design. Pneumatic actuators like pumps or PAM with high force output and compliance due to shock absorption can be applied to a robotic hand. However, it seems not promising in the case of prosthetics. It can be burdensome for amputees to carry a relatively heavy and bulky pneumatic actuation system. Therefore, electric motors are the more promising choice of actuation for prosthetic hands, for being compact and exerting large force. Although SMA can be compact and lightweight, low bandwidth and mandatory cooling system is not viable in practical usage. The same applies to shape memory polymers (SMPs) which are used in some low-frequency, low-force applications as actuators. Although SMP as an actuator can be compactly embedded within 3D-printed articulated structures, many advances in SMP materials in actuation force and speed are required to apply SMPs to anthropomorphic hands.

3.2.2. Other Features

Making various grasping patterns like power and precision grasp is crucial in hand functionality. Among many joints in a human hand, the Thumb CMC joint enables different grasping patterns using opposition motion. Therefore, an anthropomorphic hand should have 2-DoF thumb CMC joints for flexion and opposition for versatile grasping tasks. Examples of 2-DOF thumb structures in anthropomorphic hands can be found in robotic and prosthetic hands, which are not 3D printed.[94–96] 3D-printing such complicated structures in a single print job without post-assembly will greatly ease the manufacturing process of dexterous anthropomorphic hands.

There have been some attempts to add sensors to hand structures; however, many are just proof-of-concept with sensor wires and connections dangling around the hand structures. To be applied to a robotic arm or an amputee outside lab environments, a hand with embedded sensors and their connections while maintaining an anthropomorphic appearance is desirable. 3D printing can help achieve intricate internal geometries for embedding sensing channels within the joints.[97] Utilizing functional materials like piezo-magnetic or conductive materials to embedded sensing modalities and their connections to a control board can be an attractive solution to single-step 3D-print monolithic, functional hand structure. For feedback modalities, there have been some attempts to integrate haptic feedback systems into 3D-printed prosthetic hands. However, 3D printing did not play a significant role in designing the feedback system.[98,99] The hands primarily utilize 3D printing to lower the overall hand price so that the whole system is more affordable to wide users. 3D-printed soft, elastic materials can be used for the interface between the feedback actuator and human skin to alleviate any pain caused. However, more investigation on different feedback modalities is required to foster specific utilization of 3D printing in the design of the system.

The wrist is vital in manipulating grasped objects such as in sports or other ADLs. However, for robotic applications, it may not be necessary to integrate the wrist mechanism into robotic arms with seven DoFs. In contrast, prostheses need wrist mechanisms for sophisticated manipulation tasks. Since a human wrist is compact and has high degrees of freedom, it is extremely challenging to even replicate basic movements of the wrist in the limited volumetric space with actuation and sensing. Novel ideas of compact joint structures, regardless of their actuation types, would be the starting point for wrist-integrated anthropomorphic hands.

3.2.3. Anthropomorphism and Validation

Based on the criteria suggested in this review, the anthropomorphism of a hand can be defined to evaluate its design. While joint DoFs and motion generations are commonly well-satisfied among the reviewed hand, the appearance of many hands resembles that of a man-made structure with flat facets. 3D printing can manufacture an object with intricate geometry, so it can be utilized to realize anthropomorphic appearance. In the design stage, 3D scanning can help replicate the curved surfaces of an anthropomorphic hand. In skin replication, mimicking skin material properties can help grasp different objects with slip prevention from friction and compliance from skin deformation. Now that a wide range of soft materials are commercially available, soft and sticky skins can be 3D-printed separately or with structure via multi-material 3D printing. Sensing capability, as mentioned in a previous section, needs to be integrated with hand structures for better grasping performance of anthropomorphic hands. Although crucial in device embodiment for amputees, haptic feedback of 3D-printed prosthetic hands has not been investigated extensively. Various modalities should be explored and assessed for their effectiveness in prosthetic hand embodiment. The level of validation level of an anthropomorphic hand can be defined to evaluate the maturity of the hand. Many reviewed anthropomorphic hands just showed some grasping postures for validation of their hands. For 3D-printed hands to be mature enough to be applied in the real world, well-known grasping metrics and user tests, either with amputees or robotic arms, should be done so that they do not remain on just proofs-of-concept.

3.2.4. 3D Printing

While 3D printing is a viable option for mold and joint assembly part fabrication, it is not the one-and-only solution and can be replaced by alternative manufacturing methods, such as machining. Nevertheless, 3D printing is efficient in fabricating intricate structures with exceptional customizability. It also enables consolidated parts to be easily manufactured, reducing the number of components required and the complexity of manufacturing. Expanding the advantage, 3D printing a finger or an entire hand structure can dramatically reduce the number of parts and assembly process of the hand components, freeing up the confined space inside the hand and reducing weights from joining elements that are preferable in prosthetic hands. As the entire hand structures should be of multiple functionality, 3D printing with multi-material capability will be desirable. Since SLS and SLA are inherently challenging to incorporate different materials due to material bath/chamber usage, FDM and Polyjet will be preferred in future anthropomorphic hand manufacturing. Especially, FDM will be the optimal manufacturing method in prosthetic hands, where affordability is one of the most significant factors of device acceptance.[100,101] As 3D printing technologies have evolved rapidly in the past few decades, emerging technologies like 4D printing and multi-process 3D printing can offer new avenues for enhancing anthropomorphic hand functionality. 4D-printed objects can change their shape over time via specific external stimuli, and many researchers utilized 4D printing for self-assembly,[102,103] actuation,[104,105] and sensing.[106] Such utilization has potential in anthropomorphic hand design, enhancing manufacturability and functionality achieved by 3D printing technology. Multi-process 3D printing can be another approach applicable to an anthropomorphic hand.

Since every 3D printing technology has pros and cons, multi-process 3D printing can eliminate the downsides of different 3D printing technologies and leverage the benefits;[107] for example, printing in high resolution while conductive ink deposition can make highly conductive traces within complicated 3D objects.[108,109] Integrated systems of PCB-making and 3D printing can be beneficial in achieving a compact, functional hand with electronics in a single process.

4. Conclusion

In this review, a total of 95 papers related to 3D-printed anthropomorphic hands in robotic and prosthetic applications. First, components of 3D-printed anthropomorphic hands like joint structure, actuator, transmission, and other features are categorized to understand their design trends. The level of anthropomorphism and validation of the 3D-printed anthropomorphic hands are then defined and evaluated. 3D printing and its usage on each component are discussed to shed light on future directions of 3D-printed anthropomorphic hand designs. While many papers presented hand designs and fabrication methods that can be replaced by other manufacturing methods like machining, hands that can only be designed and fabricated with 3D printing technology are also presented. This review serves as guidelines to evaluate a 3D-printed anthropomorphic hand in terms of anthropomorphism, validation level, and 3D printing utilization. It also serves as guidelines for what some areas are missing out on in developing a 3D-printed anthropomorphic hand. With growing interest in advanced 3D printing technologies and sophisticated anthropomorphic hands, this review can be used as an informative reference to understand current maturity and future directions in the development of 3D-printed anthropomorphic hands.

5. Experimental Section

The primary keywords for the search are 3D printing, anthropomorphic, robot hands, and prosthetic hands; any combination of two or more keywords is searched on bibliographic databases such as Google Scholar and Scopus. The time period of the search was limited to 2010. Among different formats, only journal papers and conference proceedings are included in this review. Once appropriate resources are found from the databases, related ones that they cited and that cite them are included for screening.

The resources found from the keywords are checked for eligibility by screening the title and abstract. Only the research papers with a physical device, either a proof-of-concept prototype or a device for clinical tests, are included in this review. Physical devices without anthropomorphic features, such as a two-finger gripper with a parallel finger arrangement, are excluded. Any resource related to a partial hand or an individual finger design is also excluded. Lastly, explicit use of 3D printing in any form during fabrication is mandatory for the review.

After the screening, each resource is classified as a robotic or prosthetic hand. A resource that has mentioned prosthetic requirements in the introduction or has conducted hand assessments for prosthetic use is classified as a prosthetic hand; otherwise, a resource is classified as a robotic hand. As a result, 95 journal papers and proceedings, 38 on robot hands, and 57 on prosthetic hands are selected for the review.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

anthropomorphism, prosthetic hand, robotic hand, 3d printing

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