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Mechanical Aspects of Robot Hands, Active Hand Orthoses and Prostheses: a Comparative Review

Jens Vertongen, Derek Kamper, Gerwin Smit, and Heike Vallery

***Abstract*—The large interest in robot hands and active hand prostheses has in recent years been joined by that in active hand orthoses. Despite the differences in intended uses, these three categories of artificial hand devices share key characteristics. Examination of the commonalities could stimulate future design. Thus, we undertook a comparative review of publications describing robot hands, active prostheses, and active orthoses, with a focus on mechanical structure, actuation principle, and transmission. Out of a total of 510 papers identified through the literature search, 72 publications were included in a focused examination. We identified trends in the design of artificial hands and gaps in the literature. After comparing their mechanical aspects, we propose recommendations for future development.**

***Index Terms*—Hands, robotics, prosthetics, orthotics, dexterity**

I. Introduction

ARTIFICIAL hands such as active hand orthoses, prostheses and robot grippers are growing fields of research. Design requirements for the three hand categories differ, but share some characteristics among them. Hand orthoses have to be very lightweight and comfortable for the user while exerting enough force to mitigate hand impairments. The limited available space of orthoses constrains the design of overall devices. Prostheses have to be lightweight as well, with a focus on grasping objects in activities of daily living (ADLs) and a cosmetic appearance that closely resembles a human hand. Robot grippers often focus on precision, force and dexterity, while weight and aesthetics are less important.

The human hand, a marvel in dexterity, effective grasping and manipulation, features 27 bones, 21 degrees of freedom (DOFs) and 34 muscles. This combination results in a large range of motion (ROM) of the fingers. Many artificial hands mimic its structure in pursuit of similar functionality.

Several reviews of hand orthoses [1], hand prostheses [2] and robot hands [3] have been published. However, no review was identified that compares their mechanical aspects.

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This review provides a structured overview of mechanical aspects of artificial hands to aid their future design and development. The mechanical aspects covered are actuation, transmission and mechanical structure.

II. Methods

We largely followed the PRISMA guidelines [4] and the Cochrane handbook [5] to conduct this review.

A. Search Protocol

1) Eligibility Criteria: We divided the inclusion criteria into three categories: device criteria, mechanical aspects and publication criteria. We focused on the mechanical design of devices for ADLs and general robotics applications. Therefore, we excluded devices designed for special purposes (e.g. military, aerospace, haptic input devices). The mechanical design includes actuation, transmission and structure of artificial hands. Specific inclusion and exclusion criteria were:

- Device types:
  - Include: Hand orthoses, prosthetic and robot hands
  - Exclude: Gloves, non-anthropomorphic grippers
- Device purpose:
  - Include: Medical, rehabilitation, assistive, research devices
  - Exclude: Military, aerospace, haptic input devices
- Mechanical domain criteria:
  - Include: Actuation, transmission and structure
  - Exclude: Energy source, sensors and control, human-machine interaction and non-structural cosmetics
- Publication criteria:
  - Include: Digital journal and conference papers that describe the mechanical design of active devices
  - Exclude: Books, review papers and patents

2) Information Sources: We searched four bibliographic databases on February 26, 2019: Scopus, ScienceDirect, Web of Science and PubMed. We did not search journals or conference proceedings outside of these databases, nor physical copies of non-digitized papers. We did not include patents either. We did include related work through hand-searching the reference list of included records.

3) Search strategy: The full-search database query was: *[Orthos?s OR Orthotic OR Prosthes?s OR Prosthetic OR Robot* OR Exo* OR Glove OR Artificial*] AND [Develop* OR Design OR Construct* OR Mechanic* OR Active] AND [Hand OR Grasp* OR Grip*]*

The '?' and '*' in the query are wildcards for database searching. We adapted this string slightly to each database's search string restrictions.

B. Study Selection

1) Screening and eligibility: We removed duplicates and irrelevant records by screening titles in EndNote. We also excluded non-eligible records by screening titles and abstracts. The full overview, presented in section III-B, contains the remaining records.

2) Keyword selection: We searched titles and abstracts of the records in the full overview for relevant keywords (force, performance, weight, power, experiment, evaluation, verify, test) in Rayyan [6]. These keywords indicated numerical results and simplified the selection process. We excluded the records that did not match any of these keywords and examined the full-text papers of the remaining records. Papers that described the mechanical design and reported numerical values of force and weight were included in the focused overview, presented in section III-C.

C. Data collection

1) Collection process: For the full overview, we searched through the title and abstracts for different technologies. For the focused overview, we retrieved relevant information of the mechanical aspects from the full-text papers, by using a data collection checklist. We classified this information in a structured spreadsheet.

2) Data items full overview: Using the following data items, we extracted information from the papers in the full overview, to identify general publication trends, actuation methods, transmission types and other notable developments:

- Number of publications per year
- Electric, Pneumatic, Hydraulic, Shape memory alloy (SMA), Twisted and coiled polymer muscle (TCPM)
- Underactuation, cable transmission (tendon, wire)
- 3D printing (additive manufacturing/rapid prototyping)

3) Data items focused overview: We used the following data items for the focused overview, to extract mechanical domain characteristics, important morphological features and numerical values of performance:

- Device information (author, date)
- Actuation, transmission, mechanical structure
- Thumb and wrist, force, weight, DOF, ROM
- Bandwidth (frequency of opening and closing the hand)

III. Results

A. Study Selection

1) Screening: The search of Scopus (1307), ScienceDirect (999), Web of Science (888) and PubMed (212) delivered a total of 3406 records. Through the reference lists of several included papers, we added an additional eight records. These are related to some database papers, such as previous work and other publications from the same authors. They went through the same selection process described in section II-B. We searched them for additional information on some devices from the initial database search.

2) Exclusion and eligibility: Fig. 1 shows the full exclusion process, indicating the removal of duplicates as well as irrelevant and non-eligible papers, leading to the full overview. It also shows the exclusion due to keyword selection and full-text paper removal. Several old records had no available digital full-text paper other than a citation. The full overview contains 510 eligible papers. The remaining 72 papers, after selection, form the focused overview.

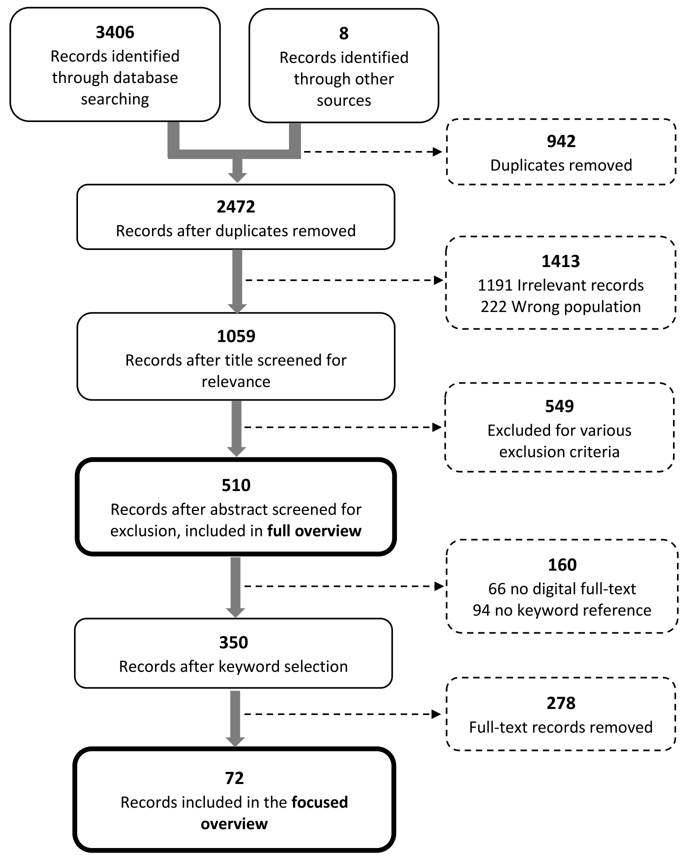

Fig. 1. Flowchart of the study selection.

The following list indicates the number of records excluded per criterion of the 549 excluded records: Controller design (145), non-mechanical design (81), finger design (55), sensor design (51), actuator or mechanism design (47), review paper or clinical trials (47), aerospace application (30), glove design (25), haptic input devices (18), foreign language (18), less than 3 fingers (10), passive devices (10), less than 3 DOFs (7), wrong publication type (3) and not functional (2).

B. Full overview

The 510 papers of the full overview consist of 91 orthoses, 159 prostheses, 234 robot hands and 26 papers of both prostheses and robot hands, indicated as P&R.

1) History of research output: Fig. 2 shows the number of publications for each device category per decade.

2) Actuation: Fig. 3 shows the number of publications reporting various actuation methods such as electric motors, pneumatic actuators, hydraulic actuators, SMAs and TCPMs.

3) Trends in technologies: We searched for the following technologies in the full overview: underactuation, cable transmission and 3D printing. Fig. 4 shows the percentages of the total number of papers reporting these technologies in the title or abstract.

C. *Focused overview*

Tables I, II and III present the results and characteristics of 17 orthoses, 28 prostheses and 27 robot hands of the focused overview, respectively.

IV. Discussion

A. *Full overview*

1) History of research output: Fig. 2 shows the progression of publications over time. Research into hand orthoses is very recent with more than 90% published in the last 10 years, compared to a more gradual increase in publications of prosthetics and robotics.

Active prosthetic hands have a long history of development dating back to the 19th century [7]. The earliest paper in this review is a hand prosthesis, published in 1917. Since 2009, development accelerated in both prosthetics and robotics that benefit from technologies such as 3D printing, lightweight actuators and accessible EMG sensors.

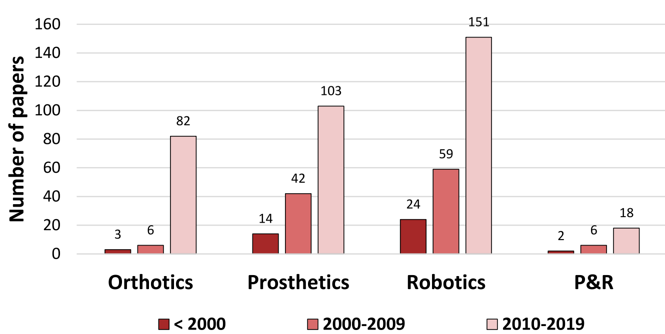

Fig. 2. Number of orthoses, prostheses and robot hand papers published over time.

2) Actuation: Fig. 3 shows the actuation methods per artificial hand category. Electric actuators are the most popular, followed by pneumatic actuators, mainly in robot hands where access to a pneumatic source is possible. Attempts have been made towards implementing small pneumatic artificial muscles (PAMs) [8] or gas-type actuators with a portable fuel cartridge [9] to improve portability.

Hydraulic actuation is not common in artificial hands. However, miniature cylinders that can be applied to hands [10] provide potential for future devices.

Lightweight compliant actuators that deform with heat, such as SMAs [11] and the recently developed TCPMs [12], are not often used. These actuators have drawbacks such as low force, low bandwidth, and the placement of heating elements close to the user. Overcoming these issues may allow these lightweight and inexpensive actuators to improve the design of future artificial hands.

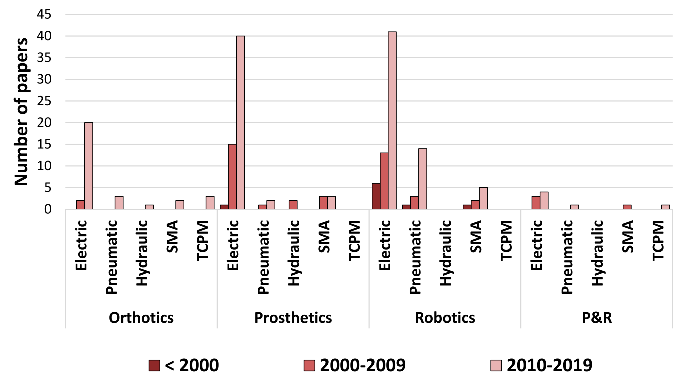

Fig. 3. Number of papers reporting specific actuation methods.

3) Trends in technologies: An underactuated mechanism has more DOFs than actuators [13]. This way, the grasp adapts to the shape of an object. However, there is an inherent loss of controllability that makes precise grip positions hard to achieve. The fewer number of actuators results in a lightweight design and is therefore commonly used, as shown in Fig. 4.

The use of cable transmission is increasing, which can be explained by its simple and lightweight nature. Cables are often called tendons, because they replicate the natural transmission of the human hand.

Although 3D printing has been used for several decades, it became more popular in 2015. In the years leading up to this increase, several key patents of 3D printing technologies expired [14]–[16]. This drastically lowered the cost of 3D printing, and the technology was quickly adopted to produce complex lightweight structures for artificial hands (Fig. 4).

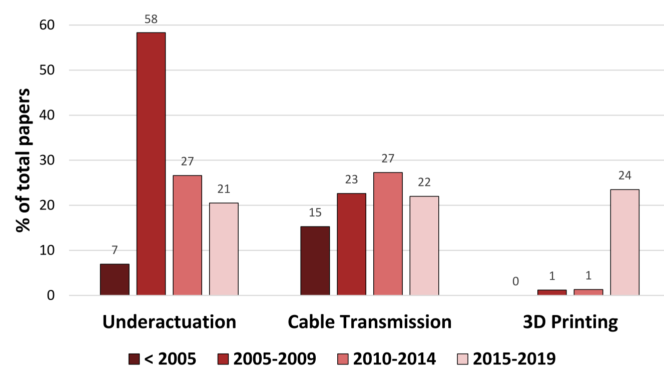

Fig. 4. Percentage of papers from full overview reporting underactuation, cable transmission and 3D printing in the title or abstract.

B. *Qualitative Focused Overview*

1) Actuation: The majority of artificial hands are actuated by electric motors. Many different motor configurations are used, which results in a wide power range. Fig. 5 shows the average values and the range of characteristics of electric actuators. Prosthetic hands are developed for a more specific application with more constraints than robot hands. Orthoses use fewer actuators than prostheses and robots, and therefore need more powerful motors to achieve sufficient grip strength.

The actuation categories are shown in Fig. 6. Electric consists of stepper, servo, AC, brushed DC and BLDC motors. Fluidic actuators are more common in robot hands, SMA and TCPM are used in the remaining orthoses and prostheses.

A notable method is the dual-mode twisted string actuation (TSA) [17], [18], which combines a fast mode, for rapid motion of the fingers, and a force mode that produces a stronger grasp. Other examples of this dual-mode actuation include the flexion (screw and slider) and force-magnification drive (pulley and eccentric cam) [19], joint servo motors and a drive tendon [20], and two pneumatic cylinders with different effective areas [21]. Many devices use a spring-return mechanism, which is useful for underactuated hands to passively extend the fingers.

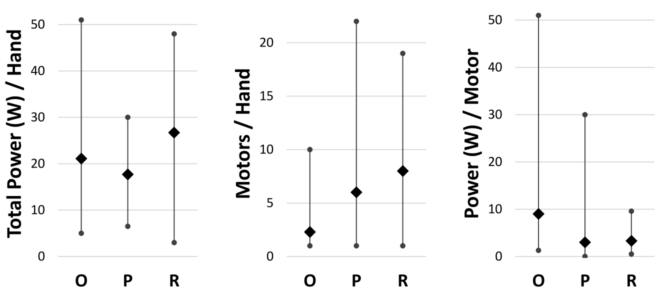

Fig. 5. The average values and range of power (in W) per hand, motors per hand and power (in W) per motor for electric motors of the focused overview for orthoses (O), prostheses (P) and robot hands (R).

2) Transmission: More than half of the devices use a cable transmission instead of rigid linkages (Fig. 6). The cable, or tendon, is attached at the fingertip, runs along the finger and is actuated by a motor-driven pulley. This mechanism is inspired by the tendons of a human hand. Several materials are used for the cable, where steel is the most common, but Spectra Fiber, Dyneema and Kevlar are used for their various properties.

Some notable mechanisms are the electromagnetic (EM) joint locking mechanism [22] and the circuitous joint [23] that can both rotate and translate. Differentials are used to facilitate underactuation and reduction mechanisms to increase output torque. Most devices use bevel or epicyclic gears, but some include harmonic drives, screws, and crank-slider mechanisms.

3) Mechanical structure: Most devices in the focused overview have rigid structures. Orthoses are placed over the human hand and display a wide design range: on one end of the spectrum, rigid dorsal structures that strap around the fingers, on the other end more typical soft structures or gloves, and in between hybrid compliant combinations. In contrast, most prosthetic and robot hands have fully rigid structures. Orthoses mostly use plastic structures, and prostheses and robot hands metallic structures (Fig. 6). Most recent prostheses have 3D-printed structures. Several alternative structures and materials are used: compliant silicone [24], carbon fibre [25] and a 3D-printed steel monocoque [26].

4) Underactuation: To quantify underactuation, we look at the ratio of DOFs per actuators of a device. This underactuation ratio is 1 for fully actuated hands and higher for an underactuated mechanism. These mechanisms could result in a lightweight design because fewer actuators are used.

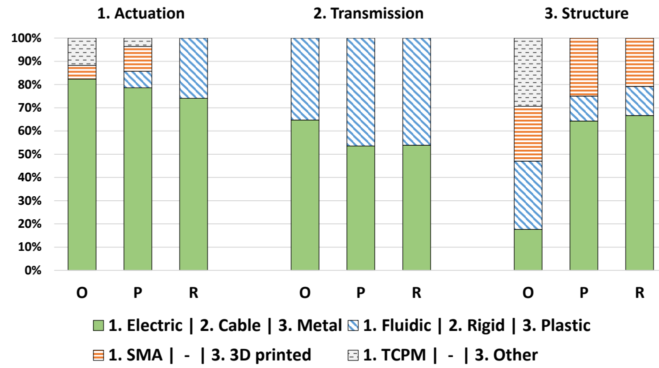

Fig. 6. The distribution of actuation methods, transmission and structures of the artificial hands in the focused overview.

Fig. 7(A) shows that orthoses and prostheses have an average ratio close to 3 and are more frequently underactuated than robot hands, that could be explained by the weight constraints affecting performance and user acceptance. The ratio of orthoses and prostheses is close to a distribution of 1 actuator for each 3-DOF finger.

The most underactuated artificial hand has a ratio of 9 [27] and the most over-actuated hand has a ratio of 0.5 by using 40 actuators for 20 DOFs [28].

5) Grasping and dexterity: A hand's dexterity determines fine movements and precise grasps and is classified in two categories: power and precision grasp [29], [30]. Fig. 7(B) shows the number of devices that feature a thumb or a wrist.

The thumb is fundamental to the stability of both power and precision grasps. It opposes the force of the fingers for a power grasp and allows precision grasps such as the lateral pinch [31]. Therefore, a thumb is present in most prostheses and robot hands but in only 60% of orthoses, which can be explained by the complex movement and location of the thumb on a human hand.

The wrist plays a minor role in grasping objects, but it helps perform certain actions such as writing, eating and opening doors [32]. Few artificial hands have an active wrist which can be explained by their complex design. The mass-DOF ratio is shown in Fig. 7(C).

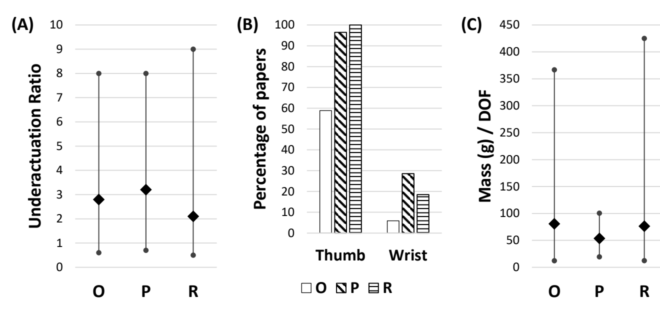

Fig. 7. The average values and range of the underactuation ratio (A), the percentage of papers reporting a thumb or wrist (B) and mass-DOF ratio (C).

C. Quantitative Focused Overview

1) Force: Artificial hands employ a variety of actuation methods that result in a large range of forces, especially in orthoses and robot hands. Electric motors achieve the highest output force in contrast to the low force produced by SMAs, pneumatics and TCPMs. Fig. 8 (A) and (B) shows the average fingertip and grip forces together with the range.

Robotics have a higher range of fingertip force and average grip force compared to prostheses that can be explained by the use of more powerful and remotely placed actuators. Prostheses are limited in weight and usually have smaller, locally-placed actuators. Higher average fingertip forces of orthoses could help to overcome residual forces of the human hand. The grip force of orthoses was generally not reported and is absent in Fig. 8 (B).

To compare these values to the human hand; the highest average grip strength is 347 N for women and 534 N for men [33], resulting in an average grip force of 440 N.

2) Weight: Both orthoses and prostheses have to be lightweight; the comfort of a prosthesis is negatively affected with high weight, and orthosis users often have limited force in the impaired arm. Weight restrictions for robotic arms are less tight. Despite the higher grip force that robot hands often have, Fig. 8 (C) shows that their force-mass ratio is the lowest. This is due to their high mass, shown in Fig. 8 (D).

The average mass of a human hand is 426 g [34] and the average force-mass ratio is above 1000 N/Kg. To define a lightweight orthoses and prostheses design, we use the proposed desirable mass limit for prostheses of 400 g [35]. More than 80% of orthoses and 43% of prostheses in this overview classify as lightweight. Particularly alternative actuation methods such as SMA, TCPM and electrohydraulics appear to enable lightweight solutions.

3) DOF: Fig. 8 (E) shows that robot hands have the highest average DOFs and orthoses the lowest.

4) ROM: The range of motion of a hand depends on the rotational limits of the three finger joints: MCP, PIP and DIP and for the thumb: MCP and IP. The normal ROM of a human hand is 100° (MCP), 105° (PIP) and 85° (DIP) [36]. Most of prostheses and robot hands report a ROM close to the normal ROM. The difficult interaction between a paretic hand and an orthotic structure can lead to a challenging alignment of the joint centers and could explain the lower values of orthoses. Furthermore, orthoses are often designed to achieve functional ROM, which is 73° (MCP), 86° (PIP) and 61° (DIP) [36].

5) Bandwidth: Fig. 8 (F) shows the bandwidth in Hz, which is the frequency of opening and closing the hand. We define the bandwidth to be high if it is more than 1 Hz. All three categories have a high average bandwidth, and the use of electric motors and pneumatic actuators often result in a fast-grasping hand. In contrast, SMAs and TCPMs report low bandwidths that can be explained by their slow heating cycles. Devices with the highest bandwidth use electric motors and a steel cable or rigid transmission [37], [38].

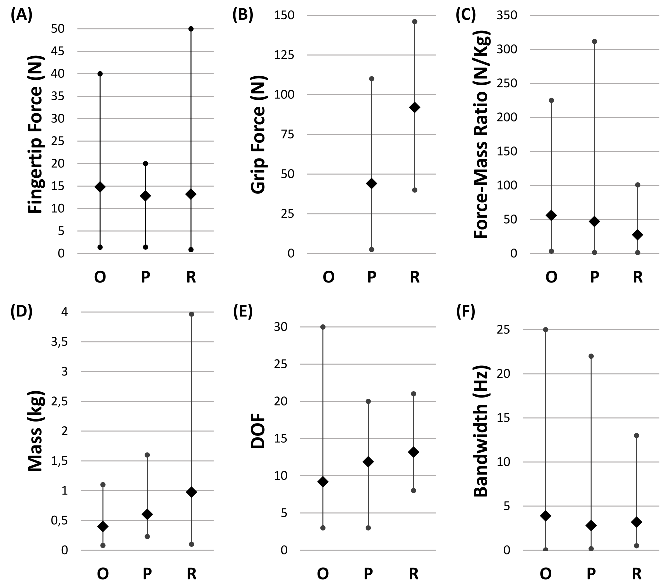

Fig. 8. Average values and range of the fingertip force, grip force, force-mass ratio, mass, DOFs and bandwidth of orthoses (O), prostheses (P) and robot hands (R).

D. Design Recommendations

1) Promising Features: Several technological trends exist that show potential for new types of hands:

A dual-mode actuation that switches between a high-speed mode and a high-force mode is already employed in various mechanisms [17]–[21] and seems to make artificial hands more versatile.

Fluidic actuators such as PAMs and cylinders could lead to a flexible or lightweight design [10], [39]. Compliant actuation, where a spring is placed in series or in parallel with the actuator may also help make artificial hands more compliant and shock-absorbing. Several devices using SMAs and TCPMs are very lightweight and could be effective once their force and bandwidth is improved.

Cable-driven hands, using a motor and pulley, have benefits over traditional linkage transmissions, e.g. they are simple and compact [40]. Several materials with high tensile strength are used (Dyneema, Kevlar), but out of the reported materials only steel cables can both pull and push. These cables are composed of several coiled steel wires that can transmit push forces [41]. Circuitous joints that rotate and translate allow better joint alignment of orthoses [23]. EM joint locking is currently used in robotics and could add functionality to prosthetic hands [22].

Hybrid combinations of materials or 3D-printed structures may be lightweight, strong and customizable. A 3D-printed monocoque protects delicate mechanisms inside and can be used for both prostheses and robot hands [26], [42].

2) Current Challenges: Both orthoses and prostheses have to be lightweight, portable and comfortable, and they need a high grip force to be effective and to be adopted by their users [43]. Furthermore, there is a desire in orthoses for a limited profile, easy donning and doffing, and active thumb assistance. Implementing an active wrist is uncommon and seems challenging for all artificial hands. The complexity of current robot hands limits their use to specialized applications.

3) Future Directions: Orthoses could benefit from soft/hard hybrid mechanical structures to improve comfort, donning and doffing, which are key criteria for adoption. Thus, we recommend pivoting away from glove-based designs towards custom 3D-printed structures. Furthermore, underactuation seems the most promising route for both orthoses and prostheses. Cable-driven designs, which can minimize an orthosis' profile and mimic the human anatomy, seem most effective. While pneumatic actuators are becoming increasingly popular for orthoses, the high forces needed and a desire for limited profile suggests that electric motors with cable transmissions will remain important.

Future prostheses need to reduce weight while increasing grip force. 3D printing could allow for efficient use of material to achieve lightweight yet durable structures. Although micro-motors are common and effective actuators, miniature hydraulics hold potential as well [44]. An active thumb, wrist or joint-locking mechanism, with intuitive control, could substantially improve functionality if not too heavy. Besides promising developments of active prostheses, body-powered systems have other benefits, such as sensory feedback [10], and a future combination of both could be interesting.

Many current robot hands are complex and expensive, with numerous actuators and DOFs. This results in a limited range of applications. It is desirable to simplify the design, while maintaining acceptable dexterity, for use beyond industrial applications, for example in service robots. We recommend designing underactuated systems with lighter actuators, or using cable transmissions to simplify the construction. Furthermore, the use of series elastic actuation or compliant materials could improve future versatility of robot hands.

V. Conclusion

The full overview of 510 papers sheds light on the design history, while the focused overview of 72 papers compares mechanical aspects of hand orthoses, prostheses and robot hands. The full overview shows that these research areas have been growing rapidly over the last decade, but that some trends are only present in one or two of the hand categories, such as employing specific actuation principles.

Also, tight weight constraints especially in prosthetics have led to very lightweight yet dexterous solutions. There may thus be possibilities for transfer between the domains. Emerging technologies like additive manufacturing and lightweight actuators enable improved artificial hands for a wide range of applications. This review can serve as an overview of existing literature to aid the development of future artificial hands.

References

[1] R. Bos, C. Haarman, and T. Stortelder, "A structured overview of trends and technologies used in dynamic hand orthoses," *J NeuroEngineering Rehabil*, vol. 13, no. 62, pp. 240–243, 2016.

[2] R. Clement, K. Bugler, and C. Oliver, "Bionic prosthetic hands: A review of present technology and future aspirations," *The Surgeon*, vol. 9, no. 6, pp. 336 – 340, 2011.

[3] M. Controzzi, C. Cipriani, and M. C. Carrozza, *Design of Artificial Hands: A Review*. Cham: Springer International Publishing, 2014, pp. 219–246.

[4] D. Moher, A. Liberati, J. Tetzlaff, D. G. Altman, and T. P. Group, "Preferred reporting items for systematic reviews and meta-analyses: The prisma statement," *PLOS Medicine*, vol. 6, no. 7, pp. 1–6, 07 2009.

[5] J. Higgins and S. Green, *Cochrane Handbook for Systematic Reviews of Interventions*, version 5.1.0 [updated march 2011] ed. The Cochrane Collaboration, 2011.

[6] M. Ouzzani, H. Hammady, Z. Fedorowicz, and A. Elmagarmid, "Rayyan—a web and mobile app for systematic reviews," *Systematic Reviews*, vol. 5, no. 1, p. 210, 2016.

[7] E. Spellerberg, "Improvement in artificial arms," U.S. Patent 42 515, Apr. 26, 1864.

[8] H. Takeda, N. Tsujiuchi, T. Koizumi, H. Kan, M. Hirano, and Y. Nakamura, "Development of prosthetic arm with pneumatic prosthetic hand and tendon-driven wrist," in *Conf Proc IEEE Eng Med Biol Soc*, Sep. 2009, pp. 5048–5051.

[9] K. B. Fite, T. J. Withrow, X. Shen, K. W. Wait, J. E. Mitchell, and M. Goldfarb, "A gas-actuated anthropomorphic prosthesis for transhumeral amputees," *IEEE Trans Robot*, vol. 24, no. 1, pp. 159–169, Feb 2008.

[10] G. Smit, D. H. Plettenburg, and F. C. T. van der Helm, "The lightweight delft cylinder hand: First multi-articulating hand that meets the basic user requirements," *IEEE Trans Neural Syst Rehabil Eng*, vol. 23, no. 3, pp. 431–440, May 2015.

[11] S. Miyazaki and K. Otsuka, "Development of shape memory alloys," *ISIJ International*, vol. 29, no. 5, pp. 353–377, 1989.

[12] C. S. Haines, M. D. Lima, and N. Li, "Artificial muscles from fishing line and sewing thread," *Science*, vol. 343, no. 6173, pp. 868–872, 2014.

[13] R. Balasubramanian and A. M. Dollar, *Performance of Serial Underactuated Mechanisms: Number of Degrees of Freedom and Actuators*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013, pp. 1–13.

[14] S. R. Abrams, J. U. Korein, V. Srinivasan, and K. Tarabanis, "Method employing sequential two-dimensional geometry for producing shells for fabrication by a rapid prototyping system," U.S. Patent 5 587 913, Dec. 24, 1996.

[15] C. R. Deckard, "Method for producing parts by selective sintering," U.S. Patent 5 639 070, Jun. 17, 1997.

[16] C. M. Childers and C. W. Hull, "Method of making a three-dimensional object by stereolithography," U.S. Patent 5 609 812, Mar. 11, 1997.

[17] Y. J. Shin, Keun-Ho Rew, K. Kim, and S. Kim, "Development of anthropomorphic robot hand with dual-mode twisting actuation and electromagnetic joint locking mechanism," in *2013 IEEE International Conference on Robotics and Automation*, May 2013, pp. 2759–2764.

[18] S. H. Jeong, K. Kim, and S. Kim, "Designing anthropomorphic robot hand with active dual-mode twisted string actuation mechanism and tiny tension sensors," *IEEE Robot Autom Lett*, vol. 2, no. 3, pp. 1571–1578, July 2017.

[19] Y. Takaki and T. omata, "High-performance anthropomorphic robot hand with grasping-force-magnification mechanism," *IEEE/ASME Transactions on Mechatronics*, vol. 16, no. 3, pp. 583–591, 2011.

[20] M. R. Williams and W. Walter, "Development of a prototype overactuated biomimetic prosthetic hand," *PLOS ONE*, vol. 10, pp. 1–15, 03 2015.

[21] K. Kim, S. H. Jeong, P. Kim, and K. Kim, "Design of robot hand with pneumatic dual-mode actuation mechanism powered by chemical gas generation method," *IEEE Robot Autom Lett*, vol. 3, no. 4, pp. 4193–4200, Oct 2018.

[22] Y. J. Shin, S. Kim, and K.-S. Kim, "Design of prosthetic robot hand with high performances based on novel actuation principles," *IFAC Proceedings Volumes*, vol. 46, no. 5, pp. 313–318, 2013.

[23] F. Zhang, L. Hua, Y. Fu, H. Chen, and S. Wang, "Design and development of a hand exoskeleton for rehabilitation of hand injuries," *Mechanism and Machine Theory*, vol. 73, pp. 103–116, 2014.

[24] M. Tian, Y. Xiao, X. Wang, J. Chen, and W. Zhao, "Design and experimental research of pneumatic soft humanoid robot hand," in *Robot Intelligence Technology and Applications 4*, J.-H. Kim, F. Karray, J. Jo, P. Sincak, and H. Myung, Eds. Cham: Springer International Publishing, 2017, pp. 469–478.

[25] L. Zollo, S. Roccella, E. Guglielmelli, M. C. Carrozza, and P. Dario, "Biomechatronic design and control of an anthropomorphic artificial hand for prosthetic and robotic applications," *IEEE/ASME Transactions on Mechatronics*, vol. 12, no. 4, pp. 418–429, Aug 2007.

[26] T. Wiste and M. Goldfarb, "Design of a simplified compliant anthropomorphic robot hand," in *2017 IEEE International Conference on Robotics and Automation (ICRA)*, May 2017, pp. 3433–3438.

[27] H.-K. Ko, C.-H. Cho, H.-C. Kwon, and K.-H. Kim, "Design of an underactuated robot hand based on displacement-force conversion mechanism," *Int J Pr Eng Man*, vol. 13, no. 4, pp. 509–516, Apr 2012.

[28] Z. Xu, V. Kumar, and E. Todorov, "A low-cost and modular, 20-dof anthropomorphic robotic hand: design, actuation and modeling," in *2013 13th IEEE-RAS International Conference on Humanoid Robots (Humanoids)*, Oct 2013, pp. 368–375.

[29] M. R. Cutkosky, "On grasp choice, grasp models, and the design of hands for manufacturing tasks," *IEEE Transactions on Robotics and Automation*, vol. 5, no. 3, pp. 269–279, June 1989.
[30] J. R. Napier, "The prehensile movements of the human hand," *The journal of bone and joint surgery*, vol. 38, no. 4, pp. 902–913, 1956.
[31] D. Dalli and M. A. Saliba, "Towards the development of a minimal anthropomorphic robot hand," in *2014 IEEE-RAS International Conference on Humanoid Robots*, Nov 2014, pp. 413–418.
[32] S. Kestner, "Defining the relationship between prosthetic wrist function and its use in performing work tasks and activities of daily living," *Journal of prosthetics and orthotics*, vol. 18, no. 3, pp. 80–86, 2006.
[33] V. Mathiowetz, N. Kashman, and G. V. et al., "Grip and pinch strength: Normative data for adults," 1985.
[34] C. E. Clauser, J. T. McConville, and J. W. Young, "Weight, volume, and center of mass of segments of the human body," 1969.
[35] J. Pons, E. Rocon, R. Ceres, D. Reynaerts, B. Saro, and S. e. a. Levin, "The manus-hand dextrous robotics upper limb prosthesis: Mechanical and manipulation aspects," *Autonomous Robots*, vol. 16, no. 2, pp. 143–163, Mar 2004.
[36] M. Hume, H. Gellman, H. McKellop, and R. Brumfield, "Functional range of motion of the joints of the hand," *The Journal of Hand Surgery*, vol. 15, no. 2, pp. 240–243, 1990.
[37] S. Roccella, M. C. Carrozza, G. Cappiello, J.-J. Cabibihan, C. Laschi, and P. e. a. Dario, "Design and development of five-fingered hands for a humanoid emotion expression robot," *International Journal of Humanoid Robotics*, vol. 04, no. 01, pp. 181–206, 2007.
[38] H. Kawasaki, H. Shimomura, and Y. Shimizu, "Educational-industrial complex development of an anthropomorphic robot hand 'gifu hand'," *Advanced Robotics*, vol. 15, no. 3, pp. 357–363, 2001.
[39] C. Pylatiuk, S. Mounier, A. Kargov, S. Schulz, and G. Bretthauer, "Progress in the development of a multifunctional hand prosthesis," in *The 26th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, vol. 2, Sep. 2004, pp. 4260–4263.
[40] H. In, K. Cho, and K. Kim, "Jointless structure and under-actuation mechanism for compact hand exoskeleton," in *2011 IEEE International Conference on Rehabilitation Robotics*, June 2011, pp. 1–6.
[41] B. Zeng, S. Fan, L. Jiang, M. Cheng, and H. Liu, "Design and control of an anthropomorphic prosthetic hand with a cosmesis," in *2016 IEEE International Conference on Mechatronics and Automation*, Aug 2016, pp. 926–930.
[42] S. A. Dalley, T. E. Wiste, H. A. Varol, and M. Goldfarb, "A multigrasp hand prosthesis for transradial amputees," in *Int Conf IEEE Eng Med Biol*, Aug 2010, pp. 5062–5065.
[43] F. Cordella, A. L. Ciancio, R. Sacchetti, A. Davalli, A. G. Cutti, and E. e. a. Guglielmelli, "Literature review on needs of upper limb prosthesis users," *Frontiers in Neuroscience*, vol. 10, p. 209, 2016.
[44] S. Schulz, C. Pylatiuk, A. Kargov, R. Oberle, and G. Bretthauer, "Progress in the development of anthropomorphic fluidic hands for a humanoid robot," in *4th IEEE/RAS International Conference on Humanoid Robots, 2004.*, vol. 2, Nov 2004, pp. 566–575.
[45] M. Fontana, A. Dettori, F. Salsedo, and M. Bergamasco, "Mechanical design of a novel hand exoskeleton for accurate force displaying," in *IEEE ICRA*, May 2009, pp. 1704–1709.
[46] J. Arata, K. Ohmoto, R. Gassert, O. Lambercy, H. Fujimoto, and I. Wada, "A new hand exoskeleton device for rehabilitation using a three-layered sliding spring mechanism," in *2013 IEEE International Conference on Robotics and Automation*, May 2013, pp. 3902–3907.
[47] D. Y. Zheng, M. Luo, and S. S. Yang, "Design of a mechanical exoskeleton system for improving hand-gripping force," *Advanced Materials Research*, vol. 663, pp. 708–712, 2013.
[48] Y. Lee, "Design of exoskeleton robotic hand/arm system for upper limbs rehabilitation considering mobility and portability," in *Int Conf URAI*, Nov 2014, pp. 540–544.
[49] B. W. Gasser and M. Goldfarb, "Design and performance characterization of a hand orthosis prototype to aid activities of daily living in a post-stroke population," in *Conf Proc IEEE Eng Med Biol Soc*, Aug 2015, pp. 3877–3880.
[50] I. Jo and J. Bae, "Design and control of a wearable and force-controllable hand exoskeleton system," *Mechatronics*, vol. 41, pp. 90–101, 2017.
[51] C. J. Nycz, T. Bützer, O. Lambercy, J. Arata, G. S. Fischer, and R. Gassert, "Design and characterization of a lightweight and fully portable remote actuation system for use with a hand exoskeleton," *IEEE Robot Autom Lett*, vol. 1, no. 2, pp. 976–983, July 2016.
[52] Y. Park, I. Jo, and J. Bae, "Development of a dual-cable hand exoskeleton system for virtual reality," in *IEEE/RSJ Int Conf IROS*, Oct 2016, pp. 1019–1024.
[53] O. Sandoval-Gonzalez, J. Jacinto-Villegas, I. Herrera-Aguilar, O. Portillo-Rodiguez, P. Tripicchio, and M. H.-R. et al., "Design and development of a hand exoskeleton robot for active and passive rehabilitation," *Int J Adv Robot Syst*, vol. 13, no. 2, p. 66, 2016.
[54] M. Sarac, M. Solazzi, E. Sotgiu, M. Bergamasco, and A. Frisoli, "Design and kinematic optimization of a novel underactuated robotic hand exoskeleton," *Meccanica*, vol. 52, no. 3, pp. 749 – 761, 2017.
[55] B. W. Gasser, D. A. Bennett, C. M. Durrough, and M. Goldfarb, "Design and preliminary assessment of vanderbilt hand exoskeleton," in *2017 International Conference on Rehabilitation Robotics (ICORR)*, July 2017, pp. 1537–1542.
[56] A. Lince, N. Celadon, A. Battezzato, A. Favetto, S. Appendino, and P. A. et al., "Design and testing of an under-actuated surface emg-driven hand exoskeleton," in *2017 International Conference on Rehabilitation Robotics (ICORR)*, July 2017, pp. 670–675.
[57] L. Saharan, M. J. de Andrade, W. Saleem, R. H. Baughman, and Y. Tadesse, "iGrab: hand orthosis powered by twisted and coiled polymer muscles," *Smart Mater Struct*, vol. 26, no. 10, p. 105048, sep 2017.
[58] M. Sarac, M. Solazzi, D. Leonardis, E. Sotgiu, M. Bergamasco, and A. Frisoli, "Design of an underactuated hand exoskeleton with joint estimation," in *Advances in Italian Mechanism Science*, G. Boschetti and A. Gasparetto, Eds. Cham: Springer International Publishing, 2017, pp. 97–105.
[59] A. Sharma, L. Saharan, and Y. Tadesse, "3-d printed orthotic hand with wrist mechanism using twisted and coiled polymeric muscles," *Conf Proc ASME IMECE*, 2017.
[60] M. Xiloyannis, L. Cappello, B. Khanh Dinh, C. W. Antuvan, and L. Masia, "Design and preliminary testing of a soft exosuit for assisting elbow movements and hand grasping," in *Converging Clinical and Engineering Research on Neurorehabilitation II*, J. Ibáñez, J. González-Vargas, J. M. Azorín, M. Akay, and J. L. Pons, Eds. Cham: Springer International Publishing, 2017, pp. 557–561.
[61] C. Light and P. Chappell, "Development of a lightweight and adaptable multiple-axis hand prosthesis," *Medical Engineering & Physics*, vol. 22, no. 10, pp. 679 – 684, 2000.
[62] K. J. Laurentis and C. Mavroidis, "Mechanical design of a shape memory alloy actuated prosthetic hand," *Technology and Health Care*, vol. 10, pp. 91–106, 2002.
[63] F. Sebastiani, S. Roccella, F. Vecchi, M. C. Carrozza, and P. Dario, "Experimental analysis and performance comparison of three different prosthetic hands designed according to a biomechatronic approach," in *Conf Proc IEEE/ASME AIM*, vol. 1, July 2003, pp. 64–69 vol.1.
[64] M. Carrozza, C. Suppo, F. Sebastiani, B. Massa, F. Vecchi, and R. e. a. Lazzarini, "The spring hand: Development of a self-adaptive prosthesis for restoring natural grasping," *Autonomous Robots*, vol. 16, no. 2, pp. 125–141, Mar 2004.
[65] H. Huang, Li Jiang, Y. Liu, L. Hou, H. Cai, and H. Liu, "The mechanical design and experiments of hit/dlr prosthetic hand," in *IEEE ROBIO*, Dec 2006, pp. 896–901.
[66] A. Kargov, C. Pylatiuk, R. Oberle, H. Klosek, T. Werner, and W. R. et al., "Development of a multifunctional cosmetic prosthetic hand," in *IEEE ICORR*, June 2007, pp. 550–553.
[67] K. T. O'Toole and M. M. McGrath, "Mechanical design and theoretical analysis of a four fingered prosthetic hand incorporating embedded sma bundle actuators," *International Journal of Medical and Health Sciences*, vol. 1, no. 7, pp. 430–437, 2007.
[68] N. Li, L. Jiang, D. Yang, X. Wang, S. Fan, and H. Liu, "Development of an anthropomorphic prosthetic hand for man-machine interaction," in *Intelligent Robotics and Applications*, H. Liu, H. Ding, Z. Xiong, and X. Zhu, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 38–46.
[69] M. Hioki, S. Ebisawa, H. Sakaeda, T. Mouri, S. Nakagawa, and Y. U. et al., "Design and control of electromyogram prosthetic hand with high grasping force," in *2011 IEEE International Conference on Robotics and Biomimetics*, Dec 2011, pp. 1128–1133.
[70] H. Huang, Y.-J. Pang, D.-P. Yang, C.-Y. Sun, L. Jiang, and N. e. a. Li, "A bio-mechanical designed prosthetic hand with multi-control strategies," *Int J Hum Robot*, vol. 09, no. 02, p. 1250013, 2012.
[71] M. Polisiero, P. Bifulco, A. Liccardo, M. Cesarelli, M. Romano, and G. D. G. et al., "Design and assessment of a low-cost, electromyographically controlled, prosthetic hand. medical devices," in *Med Devices (Auckl)*, no. 6, 2013, pp. 97–104.
[72] H. Liu, D. Yang, L. Jiang, and S. Fan, "Development of a multi-dof prosthetic hand with intrinsic actuation, intutive control and sensory feedback," *Industrial Robot*, vol. 41, no. 4, pp. 381–392, 2014.

[73] Y.-w. Liu, F. Feng, and Y.-f. Gao, "Hit prosthetic hand based on tendon-driven mechanism," *Journal of Central South University*, vol. 21, no. 5, pp. 1778–1791, May 2014.
[74] K. Andrianesis and A. Tzes, "Development and control of a multifunctional prosthetic hand with shape memory alloy actuators," *J Intell Robot Syst*, vol. 78, pp. 257–289, 2015.
[75] P. Slade, A. Akhtar, M. Nguyen, and T. Bretl, "Tact: Design and performance of an open-source, affordable, myoelectric prosthetic hand," in *IEEE ICRA*, May 2015, pp. 6451–6456.
[76] T. Takaki, K. Shima, N. Mukaidani, T. Tsuji, A. Otsuka, and T. Chin, "Electromyographic prosthetic hand using grasping-force-magnification mechanism with five independently driven fingers," *Advanced Robotics*, vol. 29, no. 24, pp. 1586–1598, 2015.
[77] D. van der Riet, R. Stopforth, G. Bright, and O. Diegel, "The low cost design of a 3d printed multi-fingered myoelectric prosthetic hand," *Mechatronics: Principles, technologies and applications*, pp. 85–117, 2015.
[78] A. Arjun, L. Saharan, and Y. Tadesse, "Design of a 3d printed hand prosthesis actuated by nylon 6-6 polymer based artificial muscles," in *2016 IEEE International Conference on Automation Science and Engineering (CASE)*, Aug 2016, pp. 910–915.
[79] R. Fourie and R. Stopforth, "The mechanical design of a biologically inspired prosthetic hand, the touch hand 3," in *2017 Pattern Recognition Association of South Africa and Robotics and Mechatronics (PRASA-RobMech)*, Nov 2017, pp. 38–43.
[80] P. Wattanasiri, P. Tangpornprasert, and C. Virulsri, "Design of multi-grip patterns prosthetic hand with single actuator," *IEEE T Neur Sys Reh*, vol. 26, no. 6, pp. 1188–1198, June 2018.
[81] T. Zhang, L. Jiang, and H. Liu, "Design and functional evaluation of a dexterous myoelectric hand prosthesis with biomimetic tactile sensor," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 26, no. 7, pp. 1391–1399, July 2018.
[82] H. Hashimoto, H. Ogawa, M. Obama, T. Umeda, K. Tatuno, and T. Furukawa, "Development of a multi-fingered robot hand with fingertip tactile sensors," in *Conf Proc IEEE/RSJ IROS*, vol. 2, July 1993, pp. 875–882 vol.2.
[83] A. Kargov, T. Asfour, C. Pylatiuk, R. Oberle, H. Klosek, and S. S. et al., "Development of an anthropomorphic hand for a mobile assistive robot," in *9th International Conference on Rehabilitation Robotics, 2005. ICORR 2005.*, June 2005, pp. 182–186.
[84] T. Mouri, H. Kawasaki, and K. Umebayashi, "Developments of new anthropomorphic robot hand and its master slave system," in *2005 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Aug 2005, pp. 3225–3230.
[85] M. C. Carrozza, G. Cappiello, S. Micera, B. B. Edin, L. Beccai, and C. Cipriani, "Design of a cybernetic hand for perception and action," *Biological Cybernetics*, vol. 95, no. 6, p. 629, 2006.
[86] W. Fukui, F. Kobayashi, F. Kojima, H. Nakamoto, T. Maeda, and N. I. et al., "Development of multi-fingered universal robot hand with torque limiter mechanism," in *2009 35th Annual Conference of IEEE Industrial Electronics*, Nov 2009, pp. 2205–2210.
[87] H. Kaminaga, J. Ono, Y. Shimoyama, T. Amari, Y. Katayama, and Y. Nakamura, "Anthropomorphic robot hand with hydrostatic cluster actuator and detachable passive wire mechanism," in *2009 IEEE-RAS International Conference on Humanoid Robots*, Dec 2009, pp. 1–6.
[88] S. Lee, S. Noh, Y. Lee, and J. H. Park, "Development of bio-mimetic robot hand using parallel mechanisms," in *2009 IEEE International Conference on Robotics and Biomimetics*, Dec 2009, pp. 550–555.
[89] H. Takeuchi and T. Watanabe, "Development of a multi-fingered robot hand with softness-changeable skin mechanism," in *ISR 2010 (41st International Symposium on Robotics) and ROBOTIK 2010 (6th German Conference on Robotics)*, June 2010, pp. 1–7.
[90] Y. Kurita, Y. Ono, A. Ikeda, and T. Ogasawara, "Human-sized anthropomorphic robot hand with detachable mechanism at the wrist," *Mechanism and Machine Theory*, vol. 46, no. 1, pp. 53–66, 2011.
[91] J. ya Nagase, S. Wakimoto, T. Satoh, N. Saga, and K. Suzumori, "Design of a variable-stiffness robotic hand using pneumatic soft rubber actuators," *Smart Mater Struct*, vol. 20, no. 10, p. 105015, aug 2011.
[92] N. Thayer and S. Priya, "Design and implementation of a dexterous anthropomorphic robotic typing (DART) hand," *Smart Materials and Structures*, vol. 20, no. 3, p. 035010, feb 2011.
[93] J. Bae, S. Park, J. Park, M. Baeg, D. Kim, and S. Oh, "Development of a low cost anthropomorphic robot hand with high capability," in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Oct 2012, pp. 4776–4782.
[94] H. S. Kang and D. H. Shin, "Development of an anthropomorphic robot hand with size and motion range identical to a human hand," *Int J Pr Eng Man*, vol. 14, no. 4, pp. 543–549, Apr 2013.
[95] Y. Hirano, K. Akiyama, and R. Ozawa, "Design of low-cost and easy-assemblable robotic hands with stiff and elastic gear trains," in *IEEE/RSJ Int Conf IROS*, Oct 2016, pp. 864–870.
[96] N. E. Krausz, R. A. L. Rorrer, and R. F. f. Weir, "Design and fabrication of a six degree-of-freedom open source hand," *IEEE T Neur Sys Reh*, vol. 24, no. 5, pp. 562–572, May 2016.
[97] M. Huang and H. Huang, "Innovative human-like dual robotic hand mechatronic design and its chess-playing experiment," *IEEE Access*, vol. 7, pp. 7872–7888, 2019.

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TABLE I
DATA OF THE ORTHOTIC HANDS

First Author	Year	Actuation	Transmission	Structure	Thumb / Wrist	Force	Mass	DOF	ROM	Bandwidth
Fontana [45]	2009	3 motors	Capstan pulley Cable transmission (steel) Double four-bar linkage	Glove	Yes / No	5 N	1100 g	3	N/A	25 Hz
In [40]	2011	1 BLDC motor (5.6 W) Extension springs	Capstan pulleys Differential mechanism Cable transmission	Glove	Yes / No	18 N	80 g	N/A	N/A	1 Hz
Arata [46]	2013	1 Linear DC motor (10 W)	Sliding spring mechanism	Compliant plastic structure	No / No	3 N	256 g (hand) 201 g (act.)	12	MCP: 37° PIP: 67° DIP: 43°	0.1 Hz
Zheng [47]	2013	Shape Memory Alloys (SMA) Titanium-Nickel (3 Amp DC)	Rigid structure	Titanium alloy structure	Yes / No	2 N	100 g	N/A	N/A	17 Hz
Lee [48]	2014	4 Linear motors (1.3 W)	Cable transmission (steel)	Rigid structure	No / No	24.3 N	300 g	9	N/A	N/A
Gasser [49]	2015	2 BLDC motors (9.9 W) Extension springs	Epicyclic gears Pulley and cable transmission (Spectra)	3D printed structure	No / No	12.5 N	414 g	3	N/A	3–5 Hz
Jo [50]	2013-2016	5 Series elastic actuators (SEA) Extension springs	Linkage structure (dorsal)	3D printed structure Glove	Yes / No	3 N	298 g	3	MCP: 93° PIP: 89° DIP: 85°	N/A
Nycz [51]	2016	4 Linear DC motors (3.45 W) (remote)	Bowden cable transmission Sliding spring mechanism	Compliant plastic structure	No / No	3 N	113 g (hand) 754 g (act.)	12	MCP: 37° PIP: 67° DIP: 43°	0.1 Hz
Park [52]	2016	3 DC motors (16.2 W)	Pulley and cable transmission	Rigid plastic structure	Yes / No	10 N	238 g	8	N/A	N/A
Sandoval-Gonzalez [53]	2016	10 DC motors	Worm gear	Rigid plastic structure	Yes / No	10 N	731 g	14	normal ROM	N/A
Sarac [54]	2016	4 Linear actuators (7.8 W)	Linkage structure Rotating and sliding joint	3D printed structure Straps	No / No	40 N	300 g	N/A	MCP: 80° PIP: 90°	N/A
Gasser [55]	2017	2 DC motors	Gearhead Cable transmission	Rigid plastic structure	Yes / No	50 N	400 g	5	N/A	0.8 Hz
Lince [56]	2017	1 Servomotor (51 W)	Epicyclic gears Pulley and cable transmission	Glove	No / No	1.4 N	390 g	8	N/A	N/A
Saharan [57]	2017	Twisted and coiled polymer muscles (TCPMs) (0.6 Amp)	Cable transmission Locking mechanism	3D printed structure Glove Straps	Yes / No	1.5 N	100 g	N/A	MCP: 35° PIP: 80° DIP: 35°	0.033 Hz
Sarac [58]	2017	4 Linear motors	Direct drive	Rigid structure	No / No	40 N	300 g	8	MCP: 80° PIP: 90°	N/A
Sharma [59]	2017	5 TCPMs (0.6 Amp)	Cable transmission	Glove and rigid rings	Yes / Yes	8 N	110 g	9	MCP: 50° PIP: 40° DIP: 15°	0.033 Hz
Xiloyannis [60]	2017	1 DC motor (5 W)	Cable transmission	Glove	Yes / No	2 N m	205 g (hand) 420 g (act.)	9	N/A	8 Hz

TABLE II
DATA OF THE PROSTHETIC HANDS

First Author	Year	Actuation	Transmission	Structure	Thumb / Wrist	Force	Mass (hand, act.)	DOF	ROM (MCP, PIP, DIP)	Bandwidth
Light [61]	2000	6 DC motors	Worm wheel and four-bar linkage	Rigid plastic structure	Yes / No	Grip: 9.2 N	400 g	6	N/A	N/A
Laurentis [62]	2002	5 Shape memory alloys (14.5 W)	Cable transmission	Rigid structure	Yes / No	10 N	1360 g	20	90°	N/A
Sebastiani [63]	2003	RTR3: 1 actuator and springs	Cable transmission and slider	Rigid metal structure	Yes / No	Tip: 10 N	400 g	8	N/A	N/A
Carrozza [64]	2004	1 DC motor	Pulley and cable transmission	Rigid metal structure	Yes / No	Tip: 10 N	400 g	8	90°, 50°, -	N/A
Pons [35]	2004	3 DC motors (5.3 W)	Pulley and cable transmission	Rigid metal structure	Yes / Yes	Grip: 60 N	1200 g	15	N/A	0.8 Hz
Pylatiuk [39]	2004	6 Electrohydraulic actuators	Direct drive	Rigid metal structure	Yes / No	10 N	860 g	8	N/A	N/A
Huang [65]	2006	3 DC motors (3.1 W) Torsion springs	Epicyclic and bevel gears Coupling linkage	Rigid metal structure	Yes / No	Tip: 10 N	500 g	13	N/A	N/A
Kargov [66]	2007	1 Electrohydraulic actuator	Direct drive	Rigid metal structure	Yes / No	Grip: 110 N	353 g	7	N/A	1 Hz
O'Toole [67]	2007	Shape memory alloys (SMAs)	Linear sliding mechanism Pulley and cable transmission	Rigid polymer structure	No / Yes	16.6 N	400 g	12	90°	N/A
Roccella [37]	2007	6 DC motors (4.5 W)	Worm and cable transmission	Rigid metal structure	Yes / No	Grip: 35 N	320 g	16	90°	22 Hz
Zollo [25]	2007	4 DC motors (2 W) Torsion springs	Gears and screw Cable transmission	Aluminium alloy structure Carbon fibre shell	Yes / No	Tip: 15 N Grip: 35 N	850 g	10	90°	0.17 Hz
Dalley [42]	2009	5 Brushed DC servomotors (6 W) Torsion springs	Epicyclic gears Cable transmission (Spectra)	3D printed monocoque Nickel coated thermoplast	Yes / Yes	Tip: 20 N Grip: 80 N	580 g	16	N/A	4 Hz
Li [68]	2010	5 DC motors	Direct drive, Coupling linkage	Rigid metal structure	Yes / No	1 N m	420 g	15	N/A	N/A
Hioki [69]	2011	6 stepper motors (0.02 W) SEA 3 AC motors (7.5 W) (thumb/wrist)	Differential reduction gears (wrist) Worm gear (fingers)	3D printed structure Integrated motors	Yes / Yes	Grip: 20 N	336 g	8	N/A	0.4 Hz
Huang [70]	2012	3 Stepper motors	Epicyclic and bevel gears Coupling linkage	Rigid metal structure	Yes / No	10 N	500 g	15	115°	N/A
Polisiero [71]	2013	1 DC motor (18 W)	Linear transmission and gears	Rigid aluminium structure	Yes / No	Grip: 54 N	230 g	3	N/A	N/A
Liu [72]	2014	5 DC motors (1.3 W)	Epicyclic and bevel gears Four-bar linkage	Rigid metal structure	Yes / No	Tip: 10 N	420 g	N/A	87°	0.7 Hz
Liu [73]	2014	4 DC motors	Gear head Cable transmission	Rigid plastic structure	Yes / No	16 N	350 g	15	90°	N/A
Andrianesis [74]	2015	9 SMAs (50 W, 140 W peak)	Cable transmission	3D printed structure	Yes / No	11 N	350 g	15	100°, 75°, 25°	0.2 Hz
Slade [75]	2015	6 DC motors (3.6 W)	Cable transmission, Coupling link	3D printed structure	Yes / No	Tip: 4.21 N	350 g	11	90°	2.8 Hz
Takaki [76]	2015	5 DC motors (0.75 W) (fingers) 2 DC motors (3 W) (thumb/wrist)	Spur and epicyclic gears Feed screw and eccentric cam	Rigid metal structure	Yes / Yes	Tip: 20 N	398 g	14	90	2 Hz
van der Riet [77]	2015	6 DC motors (1.3 W)	Worm gears	3D printed structure	Yes / Yes	Grip: 2.5 N	1600 g	16	Normal ROM	N/A
Williams [20]	2015	22 DC motors (1 W)	Cable transmission	Rigid metal structure	Yes / Yes	21.2 N	1048 g	16	80°, 100°, -	N/A
Arjun [78]	2016	5 TCPMs	Cable transmission	3D printed structure	Yes / No	1.44 N	290 g	15	85°	N/A
Zeng [41]	2016	6 DC motors Torsion spring	Epicyclic gears, Worm drive Cable transmission (steel)	Rigid metal structure	Yes / No	Tip: 12 N	450 g	11	90°	0.5 Hz
Fourie [79]	2017	5 DC motors (3.3 W)	Linkage transmission	3D printed structure	Yes / Yes	18 N	513 g, 593 g	11	N/A	N/A
Wattanasiri [80]	2018	1 BLDC motor (30 W)	Crank-slider, four-bar mechanism and harmonic drive	Aluminium alloy links ABS plastic cover	Yes / No	Grip: 34.5 N	980 g	10	N/A	0.6 Hz
Zhang [81]	2018	6 Brushed DC motors (3.4 W)	Epicyclic and worm gears Cable transmission	Rigid metal structure	N/A	Tip: 12 N	450 g	6	100°	0.67 Hz

TABLE III
DATA OF THE ROBOT HANDS

First Author	Year	Actuation	Transmission	Structure	Thumb / Wrist	Force	Mass (hand, act.)	DOF	ROM (MCP, PIP, DIP)	Bandwidth
Hashimoto [82]	1993	16 DC motors	Gears, pulley and cable	4 fingers, 4 DOFs each	Yes / Yes	Tip: 8.8 N	1710 g	16	N/A	N/A
Kawasaki [38]	2001	16 DC servomotors	Epicyclic and worm gears Four-bar linkage	Rigid metal structure 5 fingers	Yes / No	1.1 N (finger) 8.8 N (thumb)	1400 g	20	N/A	13 Hz
Schulz [44]	2004	8 Flexible fluidic actuators Extension springs	N/A	Aluminium frame 5 fingers	Yes / No	Tip: 7.8 N	383 g	13-15	80°	N/A
Kargov [83]	2005	1 Flexible fluidic actuator	Direct drive	Rigid metal structure	Yes / No	Tip: 1 N	490 g	8	N/A	0.64 Hz
Mouri [84]	2005	15 DC motors	Gearbox	Rigid structure	Yes / No	Tip: 0.86 N	655 g	15	90°	N/A
Carrozza [85]	2006	6 DC motors (5.3 W)	Pulley and cable transmission	Carbon fiber structure	Yes / No	Grip: 70 N	360 g, 1440 g	16	90°	0.5 Hz
Fukui [86]	2009	DC motors	Torque limiter mechanism	Rigid metal structure	Yes / No	Tip: 3.3 N	1323 g	16	110°, 95°, 95°	N/A
Kaminaga [87]	2009	3 Fluidic actuators	Direct drive	Rigid metal structure	Yes / No	Tip: 10 N	3400 g	8	90°	N/A
Lee [88]	2009	8 DC motors	Screw and guide	Rigid metal structure	Yes / No	Grip: 40 N	740 g	9	85°	0.88 Hz
Takeuchi [89]	2010	12 DC motors (8x 3.5 W, 4x 0.5 W)	Differential and rigid links	Rigid metal structure	Yes / No	Tip: 7 N	1500 g	12	N/A	N/A
Kurita [90]	2011	16 Actuators (remote)	Pulley and cable transmission Wrist gear and joint coupling	Aluminium plate structure Stainless steel joint shafts	Yes / Yes	Tip: 10 N	665 g, 3300 g	21	MCP: 90°	N/A
Nagase [91]	2011	3 Pneumatic actuators	Cable transmission	ABS-Kevlar composite	Yes / No	0.14 N m	270 g	8	75°	N/A
Takaki [19]	2011	6 DC motors (1x 3 W, 5x 1.2 W)	Feed screw and eccentric cam Pulley and cable transmission	Rigid metal structure	Yes / No	Tip: 20 N	328 g	14	90°	2.1 Hz
Thayer [92]	2011	19 Servomotors (2 W, 1.44 W)	Cables and four-bar links	Rigid structure	Yes / Yes	Tip: 15 N	90 g, 960 g	19	70°, 90°, 90°	2.9 Hz
Bae [93]	2012	16 DC motors	Gearbox	Rigid structure	Yes / No	Tip: 50 N	900 g	16	N/A	N/A
Ko [27]	2012	1 DC motor (3 W) Extension springs	Feed drive (screw-nut-spring) Cable transmission Force conversion mechanism	3 fingers	Yes / Yes	18 N	N/A	9	45°	N/A
Kang [94]	2013	8 Linear and 2 DC motors (0.61 W)	Lead screw	Rigid structure	Yes / No	0.36 N m	670 g	10	Normal ROM	1.16 Hz
Shin [17]	2013	6 Dual-mode twisting actuation with electric motors (8 W) Extension springs	Reduction gears Four-bar linkage EM joint locking mechanism	5 fingers	Yes / No	Tip: 36.5 N	362.1 g	10	N/A	4 Hz
Xu [28]	2013	36 Pneumatic cylinders (hand) 4 cylinders (wrist)	Cable transmission	3D printed structure	Yes / Yes	Tip: 7 N Grip: 75 N	660 g w/o act.	20	90°	3 Hz
Dalli [31]	2014	8 Linear actuators (remote)	Cable transmission	3D printed structure 2 fingers and a thumb	Yes / No	Tip: 2.6 N	100 g w/o act.	8	45°	N/A
Hirano [95]	2016	6 Micro servomotors	Gears and rigid links	3D printed structure	Yes / No	5 N	458 g	15	N/A	N/A
Krausz [96]	2016	6 DC motors (6 W)	Gears and belt drive	3D printed structure	Yes / No	Tip: 4.12 N	5.84 g	10	N/A	N/A
Jeong [18]	2017	4x Active dual-mode twisted string act. (8 W, 1.5 W), 2 thumb motors	Cable transmission (Spectra) Four-bar linkage	Rigid metal structure Plastic covers, 5 fingers	Yes / No	Tip: 31.3 N Grip: 128 N	380 g	11	N/A	2 Hz
Tian [24]	2017	8 Pneumatic actuators	Direct	Soft silicone structure	Yes / No	7 N	380 g	8	N/A	N/A
Wiste [26]	2017	5 BLDC motors (9.6 W) SEA Torsion springs	Harmonic drive reducer Bidirectional one-way clutch Cable transmission (Dyneema)	Monocoque (steel 3D printed) Shock absorbers	Yes / No	Tip: 35–44 N Grip: 146 N	437 g	11	N/A	2.6 Hz
Kim [21]	2018	3x Pneumatic dual-mode actuation mechanism 1 Single-acting piston Torsion spring	Differential pulley mechanism Rack and pinion clutch Cable transmission (Kevlar) Four-bar linkage	Rigid metal structure 5 fingers	Yes / No	Tip: 29.1 N	420 g	N/A	N/A	5.2 Hz
Huang [97]	2019	12 DC motors (1.2 W) SEA	Cable transmission	Rigid metal structure	Yes / No	6 N	1065 g	19	N/A	N/A