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.

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? OR Orthotic OR Prosthes? 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*]

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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 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.

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.

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.

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. 2. Number of orthoses, prostheses and robot hand papers published over time.](image)

![Fig. 3. Number of papers reporting specific actuation methods.](image)

![Fig. 4. Percentage of papers from full overview reporting underactuation, cable transmission and 3D printing in the title or abstract.](image)

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.

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.

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).
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].

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 recom-
mand 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

[28] Z. Xu, Y. Kumar, and E. Todorov, “A low-cost and modular 20-


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<table>
<thead>
<tr>
<th>First Author</th>
<th>Year</th>
<th>Actuation</th>
<th>Transmission</th>
<th>Structure</th>
<th>Thumb / Wrist</th>
<th>Force</th>
<th>Mass</th>
<th>DOF</th>
<th>ROM</th>
<th>Bandwidth</th>
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<td>Fontana [45]</td>
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<td>3 motors</td>
<td>Capstan pulley Cable transmission (steel) Double four-bar linkage</td>
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<td>No / No</td>
<td>3 N</td>
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<td>Bowden cable transmission Sliding spring mechanism</td>
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<td>No / No</td>
<td>3 N</td>
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<td>40 N</td>
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<td>Epicyclic gears Pulley and cable transmission</td>
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<td>Glove and rigid rings</td>
<td>Yes / Yes</td>
<td>8 N</td>
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<td>1 DC motor (5 W)</td>
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<td>Glove</td>
<td>Yes / No</td>
<td>2 N m</td>
<td>205 g (hand) 420 g (act.)</td>
<td>9</td>
<td>N/A</td>
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<td>Light [61]</td>
<td>2003</td>
<td>6 DC motors</td>
<td>Worm shaft and bell-crank</td>
<td>Rigid plastic</td>
<td>Yes / No</td>
<td>2000</td>
<td>100°</td>
<td>6</td>
<td>30°</td>
<td>NA</td>
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<tr>
<td>Lemos [62]</td>
<td>2003</td>
<td>5 Shape memory alloys (14,5 W)</td>
<td>Cable transmission</td>
<td>Rigid structure</td>
<td>Yes / No</td>
<td>1500</td>
<td>90°</td>
<td>7</td>
<td>90°</td>
<td>NA</td>
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<tr>
<td>Cannizzaro [63]</td>
<td>2004</td>
<td>1 DC motor</td>
<td>Polyaxial transmission</td>
<td>Rigid structure</td>
<td>Yes / No</td>
<td>400</td>
<td>90°</td>
<td>8</td>
<td>90°</td>
<td>NA</td>
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<tr>
<td>Pylatiuk [39]</td>
<td>2004</td>
<td>6 Electrohydraulic actuators</td>
<td>Direct drive</td>
<td>Rigid structure</td>
<td>Yes / No</td>
<td>860</td>
<td>80°</td>
<td>8</td>
<td>90°</td>
<td>NA</td>
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<tr>
<td>Huang [65]</td>
<td>2006</td>
<td>3 DC motors (3.1 W)</td>
<td>Torsion springs</td>
<td>Gears and screw</td>
<td>Yes / No</td>
<td>500</td>
<td>130°</td>
<td>10</td>
<td>90°</td>
<td>NA</td>
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<tr>
<td>Kargov [66]</td>
<td>2007</td>
<td>1 Electrohydraulic actuator</td>
<td>Direct drive</td>
<td>Rigid structure</td>
<td>Yes / No</td>
<td>353</td>
<td>70°</td>
<td>11</td>
<td>90°</td>
<td>NA</td>
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<td>O’Toole [67]</td>
<td>2007</td>
<td>Shape memory alloys (SMAs)</td>
<td>Linear sliding mechanism</td>
<td>Rigid structure</td>
<td>Yes / Yes</td>
<td>400</td>
<td>120°</td>
<td>12</td>
<td>90°</td>
<td>NA</td>
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<tr>
<td>Polisiero [71]</td>
<td>2013</td>
<td>1 DC motor (18 W)</td>
<td>Gear head</td>
<td>Rigid aluminium</td>
<td>Yes / No</td>
<td>230</td>
<td>30°</td>
<td>15</td>
<td>90°</td>
<td>NA</td>
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<td>Liu [72]</td>
<td>2014</td>
<td>5 DC motors (1.3 W)</td>
<td>Epicyclic and bevel gears</td>
<td>Four-bar linkage</td>
<td>Yes / No</td>
<td>420</td>
<td>87°</td>
<td>11</td>
<td>90°</td>
<td>NA</td>
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<td>Liu [73]</td>
<td>2014</td>
<td>4 DC motors</td>
<td>Cable transmission</td>
<td>Rigid plastic</td>
<td>Yes / No</td>
<td>350</td>
<td>150°</td>
<td>16</td>
<td>90°</td>
<td>NA</td>
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<tr>
<td>Andrianesis [74]</td>
<td>2015</td>
<td>9 SMA (5.8, 140 W peak)</td>
<td>Differential reduction gears (worm)</td>
<td>Rigid structure</td>
<td>Yes / Yes</td>
<td>150</td>
<td>90°</td>
<td>15</td>
<td>90°</td>
<td>NA</td>
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<tr>
<td>Slade [75]</td>
<td>2015</td>
<td>6 DC motors (6.3 W)</td>
<td>3A motors (7.5 W) (thumb)</td>
<td>Rigid structure</td>
<td>Yes / Yes</td>
<td>144</td>
<td>100°</td>
<td>15</td>
<td>90°</td>
<td>NA</td>
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<tr>
<td>van der Riet [77]</td>
<td>2015</td>
<td>6 DC motors (1.3 W)</td>
<td>Worm gears</td>
<td>Rigid structure</td>
<td>Yes / Yes</td>
<td>2.5</td>
<td>90°</td>
<td>16</td>
<td>90°</td>
<td>NA</td>
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<tr>
<td>Slade [76]</td>
<td>2015</td>
<td>5 DC motors (0.75 W)</td>
<td>2 DC motors (3 W) (thumb)</td>
<td>Spur and epicyclic gears (worm)</td>
<td>Yes / Yes</td>
<td>20</td>
<td>90°</td>
<td>14</td>
<td>90°</td>
<td>NA</td>
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<td>Zeng [41]</td>
<td>2016</td>
<td>6 DC motors (3.4 W)</td>
<td>Epicyclic and worm gears</td>
<td>Rigid structure</td>
<td>Yes / Yes</td>
<td>12</td>
<td>75°</td>
<td>6</td>
<td>100°</td>
<td>NA</td>
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<tr>
<td>First Author</td>
<td>Year</td>
<td>Actuation</td>
<td>Transmission</td>
<td>Structure</td>
<td>Thumb / Wrist</td>
<td>Force</td>
<td>Mass (hand, act.)</td>
<td>DOF</td>
<td>ROM (MCP, PIP, DIP)</td>
<td>Bandwidth</td>
</tr>
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<tr>
<td>Hashimoto [82]</td>
<td>1993</td>
<td>16 DC motors</td>
<td>Gears, pulley and cable</td>
<td>4 fingers, 4 DOFs each</td>
<td>Yes / Yes</td>
<td>Tip: 8.8 N</td>
<td>1710 g</td>
<td>16</td>
<td>N/A</td>
<td>N/A</td>
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<td>Kawasaki [38]</td>
<td>2001</td>
<td>16 DC servomotors</td>
<td>Epicyclic and worm gears Four-bar linkage</td>
<td>Rigid metal structure 5 fingers</td>
<td>Yes / No</td>
<td>Tip: 8.8 N (finger) 8.8 N (thumb)</td>
<td>1400 g</td>
<td>20</td>
<td>N/A</td>
<td>13 Hz</td>
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<td>Schulz [44]</td>
<td>2004</td>
<td>8 Flexible fluidic actuators</td>
<td>Extension springs</td>
<td>Aluminium frame 5 fingers</td>
<td>Yes / No</td>
<td>Tip: 7.8 N</td>
<td>383 g</td>
<td>13-15</td>
<td>80°</td>
<td>N/A</td>
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<tr>
<td>Kargov [83]</td>
<td>2005</td>
<td>1 Flexible fluidic actuator</td>
<td>Direct drive</td>
<td>Rigid metal structure</td>
<td>Yes / No</td>
<td>Tip: 1 N</td>
<td>490 g</td>
<td>8</td>
<td>N/A</td>
<td>0.64 Hz</td>
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<tr>
<td>Mouri [84]</td>
<td>2005</td>
<td>15 DC motors</td>
<td>Gearbox</td>
<td>Rigid structure</td>
<td>Yes / No</td>
<td>Tip: 0.86 N</td>
<td>655 g</td>
<td>15</td>
<td>90°</td>
<td>N/A</td>
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<tr>
<td>Carrozza [85]</td>
<td>2006</td>
<td>6 DC motors (5.3 W)</td>
<td>Pulley and cable transmission</td>
<td>Carbon fiber structure</td>
<td>Yes / No</td>
<td>1.1 N (finger) 8.8 N (thumb)</td>
<td>740 g</td>
<td>9</td>
<td>85°</td>
<td>0.88 Hz</td>
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<tr>
<td>Fukai [86]</td>
<td>2009</td>
<td>DC motors</td>
<td>Torque limiter mechanism</td>
<td>Rigid metal structure</td>
<td>Yes / No</td>
<td>Tip: 3.3 N</td>
<td>1323 g</td>
<td>15</td>
<td>90°, 95°, 95°</td>
<td>N/A</td>
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<tr>
<td>Kaminaga [47]</td>
<td>2009</td>
<td>3 Fluidic actuators</td>
<td>Direct drive</td>
<td>Rigid metal structure</td>
<td>Yes / No</td>
<td>Tip: 10 N</td>
<td>3400 g</td>
<td>8</td>
<td>90°</td>
<td>N/A</td>
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<tr>
<td>Lee [88]</td>
<td>2009</td>
<td>8 DC motors</td>
<td>Screw and guide</td>
<td>Rigid metal structure</td>
<td>Yes / No</td>
<td>Grip: 40 N</td>
<td>9</td>
<td>9</td>
<td>28°</td>
<td>0.88 Hz</td>
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<tr>
<td>Takeuchi [89]</td>
<td>2010</td>
<td>12 DC motors (8x 3.5 W, 4x 0.5 W)</td>
<td>Differential and rigid links</td>
<td>Rigid metal structure</td>
<td>Yes / No</td>
<td>Tip: 7 N</td>
<td>1500 g</td>
<td>12</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>Kurita [90]</td>
<td>2011</td>
<td>16 Actuators (remote)</td>
<td>Pulley and cable transmission</td>
<td>Aluminium plate structure</td>
<td>Yes / Yes</td>
<td>Tip: 10 N</td>
<td>665 g, 3300 g</td>
<td>21</td>
<td>MCP: 90°</td>
<td>N/A</td>
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<td>Nogame [91]</td>
<td>2011</td>
<td>3 Pneumatic actuators</td>
<td>Cable transmission</td>
<td>ABS-Kevalar composite</td>
<td>Yes / No</td>
<td>0.14 N m</td>
<td>270 g</td>
<td>8</td>
<td>75°</td>
<td>N/A</td>
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<tr>
<td>Takaki [19]</td>
<td>2011</td>
<td>6 DC motors (1x 3 W, 5x 1.2 W)</td>
<td>Feed screw and eccentric cam</td>
<td>Rigid metal structure</td>
<td>Yes / No</td>
<td>Tip: 20 N</td>
<td>328 g</td>
<td>14</td>
<td>90°</td>
<td>2.1 Hz</td>
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<td>Thayer [92]</td>
<td>2011</td>
<td>19 Servomotors (2 W, 1.44 W)</td>
<td>Cables and four-bar links</td>
<td>Rigid structure</td>
<td>Yes / No</td>
<td>Tip: 15 N</td>
<td>90 g, 960 g</td>
<td>19</td>
<td>70°, 90°, 90°</td>
<td>2.9 Hz</td>
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<td>Bae [93]</td>
<td>2012</td>
<td>16 DC motors</td>
<td>Gearbox</td>
<td>Rigid structure</td>
<td>Yes / No</td>
<td>Tip: 50 N</td>
<td>900 g</td>
<td>16</td>
<td>N/A</td>
<td>N/A</td>
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<td>Ko [27]</td>
<td>2012</td>
<td>1 DC motor (3 W)</td>
<td>Feed drive (screw-nut-spring)</td>
<td>Cable transmission</td>
<td>3 fingers</td>
<td>Force conversion mechanism</td>
<td>18 N</td>
<td>N/A</td>
<td>9</td>
<td>45°</td>
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<td>Kang [94]</td>
<td>2013</td>
<td>8 Linear and 2 DC motors (0.61 W)</td>
<td>Lead screw</td>
<td>Rigid structure</td>
<td>Yes / No</td>
<td>0.36 N m</td>
<td>670 g</td>
<td>10</td>
<td>Normal ROM</td>
<td>1.16 Hz</td>
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<td>Shin [17]</td>
<td>2013</td>
<td>6 Dual-mode twisting actuation with electric motors (8 W)</td>
<td>Reduction gears Four-bar linkage EM joint locking mechanism</td>
<td>Rigid structure</td>
<td>Yes / No</td>
<td>Tip: 36.5 N</td>
<td>362.1 g</td>
<td>10</td>
<td>N/A</td>
<td>4 Hz</td>
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<tr>
<td>Xu [28]</td>
<td>2013</td>
<td>36 Pneumatic cylinders (hand) 4 cylinders (wrist)</td>
<td>Cable transmission</td>
<td>3D printed structure</td>
<td>Yes / Yes</td>
<td>Tip: 7 N Grap: 75 N</td>
<td>660 g w/o act.</td>
<td>20</td>
<td>90°</td>
<td>3 Hz</td>
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<tr>
<td>Dalli [31]</td>
<td>2014</td>
<td>8 Linear actuators (remote)</td>
<td>Cable transmission</td>
<td>3D printed structure 2 fingers and a thumb</td>
<td>Yes / No</td>
<td>Tip: 2.6 N</td>
<td>100 g w/o act.</td>
<td>8</td>
<td>45°</td>
<td>N/A</td>
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<tr>
<td>Hirano [95]</td>
<td>2016</td>
<td>6 Micro servomotors</td>
<td>Gears and rigid links</td>
<td>Rigid structure</td>
<td>Yes / No</td>
<td>Tip: 5 N</td>
<td>458 g</td>
<td>15</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>Krausz [96]</td>
<td>2016</td>
<td>6 DC motors (6 W)</td>
<td>Gears and belt drive</td>
<td>3D printed structure</td>
<td>Yes / No</td>
<td>Tip: 14.12 N</td>
<td>584 g</td>
<td>10</td>
<td>N/A</td>
<td>N/A</td>
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<td>Jeong [18]</td>
<td>2017</td>
<td>4x Active dual-mode twisted string act. (8 W, 1.5 W), 2 thumb motors</td>
<td>Cable transmission (Spectra) Four-bar linkage</td>
<td>Rigid metal structure Plastic covers, 5 fingers</td>
<td>Yes / No</td>
<td>Tip: 31.3 N Grap: 128 N</td>
<td>380 g</td>
<td>11</td>
<td>N/A</td>
<td>2 Hz</td>
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<td>Tian [24]</td>
<td>2017</td>
<td>8 Pneumatic actuators</td>
<td>Direct</td>
<td>Soft silicone structure</td>
<td>Yes / No</td>
<td>Tip: 7 N</td>
<td>380 g</td>
<td>8</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>Wiste [26]</td>
<td>2017</td>
<td>5 BLDC motors (9.6 W) SEA Torsion springs</td>
<td>Harmonic drive reducer Bidirectional one-way clutch Cable transmission (Dyneema)</td>
<td>Monocoulo (steel 3D printed) Shock absorbers</td>
<td>Yes / No</td>
<td>Tip: 35–44 N Grap: 146 N</td>
<td>437 g</td>
<td>11</td>
<td>N/A</td>
<td>2.6 Hz</td>
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<td>Kim [21]</td>
<td>2018</td>
<td>3x Pneumatic dual-mode actuation mechanism 1 Single-acting piston Torsion spring</td>
<td>Differential pulley mechanism Rack and pinion clutch Cable transmission (Kevlar) Four-bar linkage</td>
<td>Rigid metal structure 5 fingers</td>
<td>Yes / No</td>
<td>Tip: 29.1 N</td>
<td>420 g</td>
<td>N/A</td>
<td>N/A</td>
<td>5.2 Hz</td>
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<tr>
<td>Huang [97]</td>
<td>2019</td>
<td>12 DC motors (1.2 W) SEA</td>
<td>Cable transmission</td>
<td>Rigid metal structure</td>
<td>Yes / No</td>
<td>Tip: 6 N</td>
<td>1065 g</td>
<td>19</td>
<td>N/A</td>
<td>N/A</td>
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