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A comparative review

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

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***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, in this article, 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*—Dexterity, hands, orthotics, prosthetics, robotics.**

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 as follows.

1) Device types.
   a) Include: Hand orthoses, prosthetic, and robot hands.
   b) Exclude: Gloves and nonanthropomorphic grippers.
2) Device purpose.
   a) Include: Medical, rehabilitation, assistive, and research devices.
   b) Exclude: Military, aerospace, and haptic input devices.
3) Mechanical domain criteria.
   a) Include: Actuation, transmission, and structure.
   b) Exclude: Energy source, sensors and control, human–machine interaction, and nonstructural cosmetics.

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4) Publication criteria.
   a) Include: Digital journal and conference papers that describe the mechanical design of active devices.
   b) 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 nondigitized 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 as follows:

[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 ineligible 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.

1) Number of publications per year.
2) Electric, Pneumatic, Hydraulic, Shape memory alloy (SMA), and Twisted and coiled polymer muscle (TCPM).
3) Underactuation, cable transmission (tendon, wire)
4) Three-dimensional (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.

1) Device information (author, date).
2) Actuation, transmission, mechanical structure.
3) Thumb and wrist, force, weight, DOF, ROM.
4) 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 noneligible 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.

The following list indicates the number of records excluded per criterion of the 549 excluded records: Controller design (145), nonmechanical 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 three 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–III present the results and characteristics of 17 orthoses, 28 prostheses, and 27 robot hands of the focused overview, respectively.

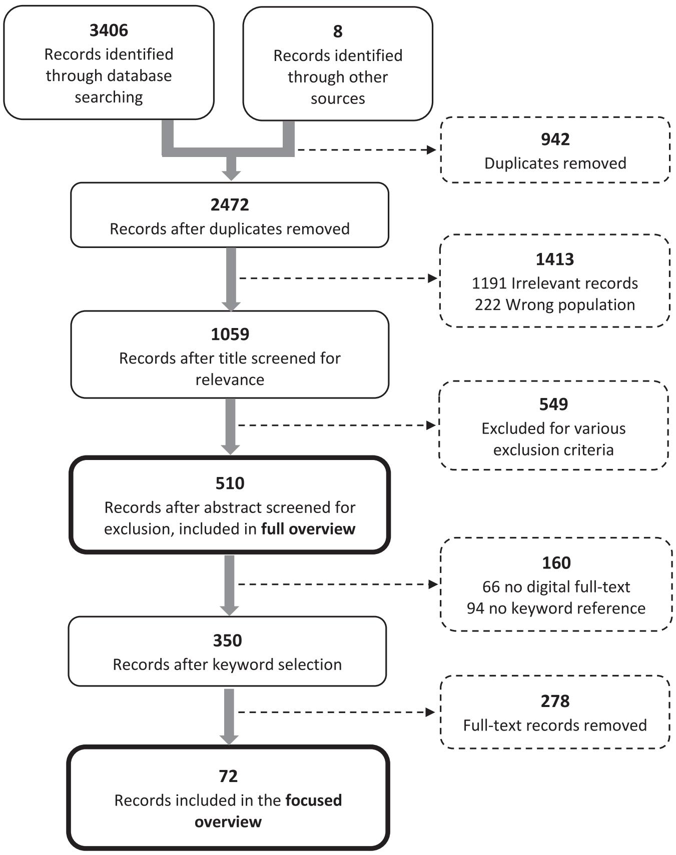

Fig. 1. Flowchart of the study selection.

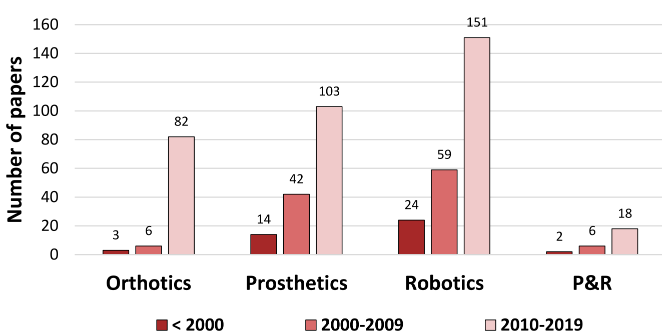

Fig. 2. Number of orthoses, prostheses, and robot hand papers published over time.

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.

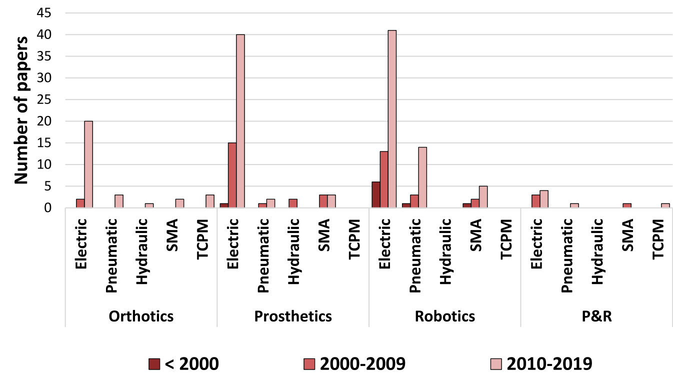

Fig. 3. Number of papers reporting specific actuation methods.

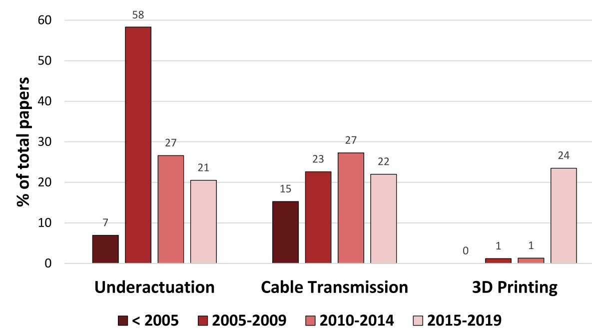

Fig. 4. Percentage of papers from full overview reporting underactuation, cable transmission, and 3D printing in the title or abstract.

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 toward 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

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

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 (see Fig. 4).

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 (see 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 (see 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].

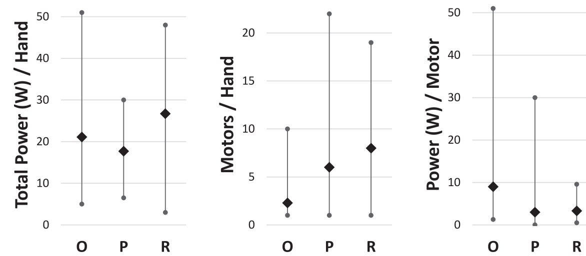

Fig. 5. Average values and range of power (in W) per hand, motors per hand and power (in W) per motor for electric motors of the focused overview for orthoses (O), prostheses (P), and robot hands (R).

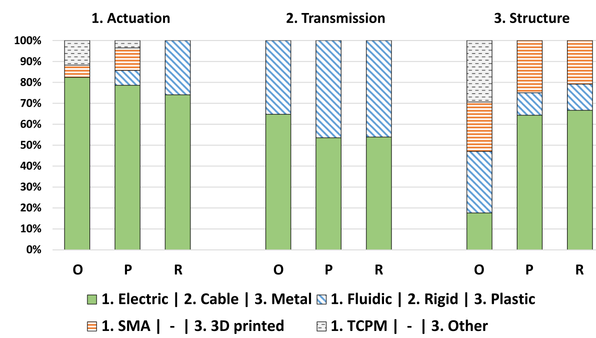

Fig. 6. Distribution of actuation methods, transmission, and structures of the artificial hands in the focused overview.

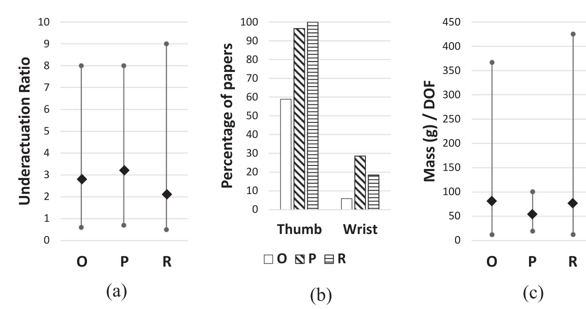

Fig. 7. Average values and range of the underactuation ratio (a), the percentage of papers reporting a thumb or wrist (b) and mass-DOF ratio (c).

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. 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 overactuated 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).

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 ROM 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

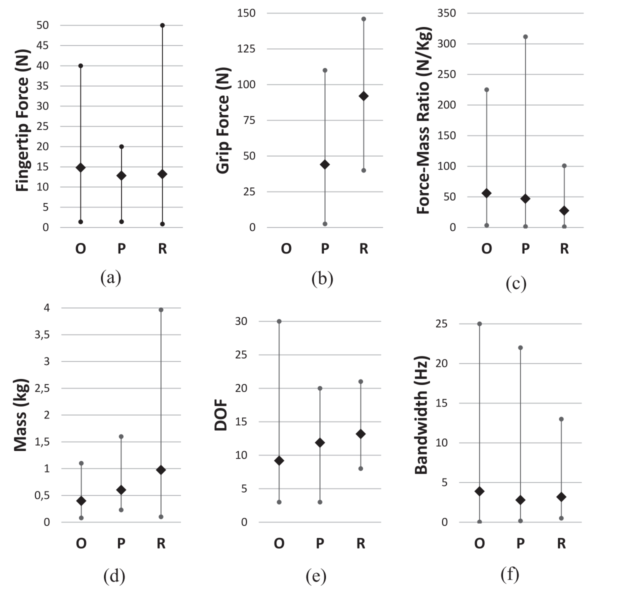

Fig. 8. Average values and range of the fingertip force, grip force, force-mass ratio, mass, DOFs and bandwidth of orthoses (O), prostheses (P), and robot hands (R).

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 hertz, 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 recommend pivoting away from glove-based designs toward 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 micromotors 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.

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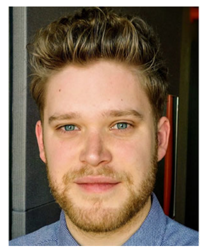

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