



Review

The Library of Approaches: A systematic mapping of approaches for the mechanical design of tendon-driven, rigid-sequential anthropomorphic robot hands

Daniel Gossen^a ,^{*} Tianyi Jin^a, Sebastian Polzin^a, Mark Witte^a, Eugen Schustermann^a, Ana Laura Urzua^a, Clément Gosselin^b, Mathias Hüsing^a, Burkhard Corves^a

^a RWTH Aachen University, Institute of Mechanism Theory, Machine Dynamics and Robotics, Aachen, 52062, Germany

^b Université Laval, Robotics Laboratory, Québec, G1V0A6, Canada

ARTICLE INFO

Keywords:

Design
Principal solutions
Anthropomorphic
Robot hand
Review
Tendon-driven

ABSTRACT

The mechanical design of anthropomorphic robot hands is complex and comprehensive and accessing relevant information remains challenging. Existing reviews provide valuable insights but lack a structured overview of the mechanical design approaches for robot hands. This work addresses this gap by introducing the Library of Approaches (LoA), a collection of mechanical design approaches for tendon-driven, rigid-sequential anthropomorphic robot hands, organized in morphological boxes. In a systematic mapping following the PRISMA guideline, joint-related design approaches are collected and used to synthesize initially undocumented principal solutions (PSs) for fields of interest (Fols). Literature references are then categorized into the established PSs and assigned to different morphological boxes. To comprehensively capture the state of the art, five separate search strategies are conducted, resulting in the analysis of 147 publications, including 87 robot hands and 110 authors. In total, 92 Fols and 177 PSs are identified. The main objective is to provide a convenient initial source of references for the early mechanical design of anthropomorphic robot hands, without claim of completeness. The study concludes with a discussion of current limitations and potential future work.

Contents

1.	Introduction	2
2.	Methodology	3
2.1.	Data structure	3
2.2.	Naming convention	3
2.3.	Review systematic	4
2.4.	Related work	8
3.	Library of Approaches excerpts	8
3.1.	Group “Thumb”	8
3.2.	Group “Finger”	15
3.3.	Group “Transmission”	17
3.4.	Group “Covering”	22

^{*} Corresponding author.

E-mail address: gossen@igmr.rwth-aachen.de (D. Gossen).

3.5. Group “Kinematic Base Chain”	23
4. Conclusion	25
CRediT authorship contribution statement	26
Declaration of competing interest	26
Acknowledgments	26
Appendix A. LoA examples	26
Appendix B. LoA tables	35
Data availability	38
References	38

1. Introduction

The mechanical design of anthropomorphic robot hands is a comprehensive and complex field of study. The comprehensiveness arises from the diverse components involved, including the fingers, thumb, palm, and other sections, each of which can be considered a distinct field of study. For each component, literature provides much information and considerations, resulting in numerous important aspects to address and possible design solutions to consider. In addition to the quantity of information, the complexity stems from the range of mechanical engineering disciplines required, such as kinematic and dynamic analysis, mechanism design for underactuation and couplings, and hands-on prototyping. Together, these elements contribute to the multifaceted nature of mechanical robot hand design.

The nature of robot hand design poses a challenge for roboticists in finding relevant information during the early design phase. The large amount of information available can be overwhelming, making it nearly impossible for roboticists to be aware of all existing design approaches. Those new to the field often require significant time to acquire the necessary knowledge for effective design. This is one reason why the design process is often highly iterative, with important aspects becoming clear only after building and testing prototypes. Even experienced roboticists face challenges in this field. Consequently, many focus on specific areas, such as underactuation, kinematic design, or impact resistance. A centralized source of information could provide key knowledge and make it easier for newcomers to enter the field.

After more than a century of robot hand research [1], many excellent surveys are available, offering summarized sources of information. Concise examples are major reviews by Bicchi [2] and Piazza et al. [1] or by Controzzi et al. [3] and Biagiotti et al. [4], among others. These reviews focus on different aspects for the analysis of the state of the art and thus provide a good overview.

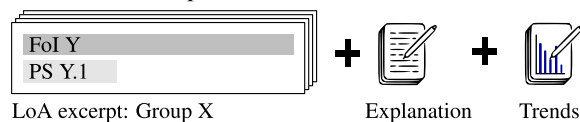
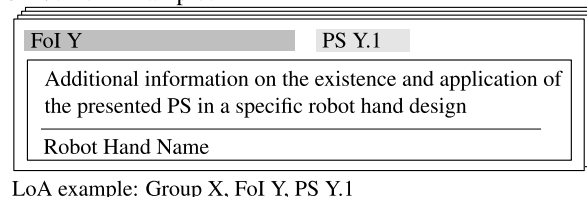
Still, no review paper has yet provided a clear overview of the different approaches used for designing anthropomorphic robot hands. No structured summary exists that presents the approaches for the mechanical design of robot hands found in the literature, with corresponding references to the sources. These approaches may concern which degrees of freedom (DOF) have been applied, which type of underactuated mechanisms have been used, and where has it been applied, among other factors.

This is particularly important today, given the significant rise in interest in developing advanced control and sensory technologies over contributions to the mechanical design. The number of publications focusing on control and sensor development has been continuously increasing, potentially correlating with recent progress in artificial intelligence. However, the importance of mechanical design should not be overlooked. It forms the foundation upon which control techniques are developed and enables the robot's mechanical movements for any sensory measurements. An appropriate mechanical basis is therefore essential and currently represents a barrier to entry for research on control, either due to the high cost of commercial options or the expertise required for custom designs. A summary of existing approaches for the mechanical design would therefore provide substantial value for both mechanical design and control design engineers. For the former, it could facilitate entry into the field for newcomers and guide both newcomers and experts to relevant work, streamlining the identification of existing research. For the latter, it could accelerate the mechanical design phase of custom designs for subsequent research.

This work addresses the gap by systematically mapping existing knowledge for the mechanical design into morphological boxes, following the PRISMA guideline [5]. In a first step, literature is systematically collected, to adequately represent the existing knowledge in a manageable set. The global systematic employs five search strategies, screening existing literature for holistic review paper, a set of here defined “significant robot hands”, thumb and finger design, interfinger underactuation and covering. In a second step, the gathered knowledge is used to synthesize *Fields of Interest* (Fols) and *Principal Solutions* (PSs) in morphological boxes (MBs) and categorize respective works. Five MBs are created for the major components of robot hands “Thumb”, “Finger”, “Kinematic Base Chain” (KBC), “Transmission”, and “Housing”. Thereby, the KBC covers the aspects for the connection of the fingers, such as the palm. All MBs together form the *Library of Approaches* (LoA). In this work, we present the LoA, refraining from providing recommendations and focusing instead on the neutral presentation of the current state of research.

The authors explicitly do not claim completeness. Rather than presenting the full range of design approaches for anthropomorphic robot hands, this study aims to provide an overview on approaches for the early design of rigid-sequential anthropomorphic robot hands. To this end, beside the MB for housing, the work concentrates on joint-related approaches, including joint configuration, coordination, allocation and design. The approaches are derived from studying tendon-driven robot hands only, in order to limit the scope of this work. However, the joint-related insights are expected to be transferable to other rigid-sequential designs.

The paper is structured as follows. In Section II, this paper's methodology is described, covering the search systematic, applied structuring, and chosen terminologies. Differences from other review papers and related works are also discussed. Section III presents the LoA following a defined pattern illustrated in Fig. 1. This section is organized into LoA Groups, showing excerpts of the full tables

Section III: LoA Excerpts**Section IV: Discussion and Conclusion****Section V: LoA Examples****Section VI: LoA Full Tables**

Library of Approaches. Group: X				
FoI Y	PS Y1	PS Y2	PS Y3	PS Y4

Fig. 1. Illustration of the structure of the paper.

with explanations, and potential trend analyses. Additional examples for the presented excerpts related to robot hand designs are provided as index cards at the end of this work in Section V for better readability. Similarly, the complete LoA tables are included in Section VI. A discussion and outlook is given in Section IV.

2. Methodology

The creation of the *Library of Approaches* requires three essential aspects: the collection of information, the structure of the gathered information and a naming convention within the structure. The systematics for the collection of paper are presented in Section 2.3. The structure, into which gathered information is captured, is presented in Section 2.1. The naming convention that is applied for the gathered information within the structure is presented in Section 2.2.

2.1. Data structure

The goal of the structure is to enable a concise presentation of existing approaches for the mechanical design of anthropomorphic robot hands and to allow differentiation between them. Therefore, a structuring into MBs was chosen. Categories on the left hand side of a MB are defined as FoIs. These FoIs abstractly capture the research or application objectives. For a given FoI, PSs are identified that describe how these objectives can be realized. The principal solutions are also high-level and generic, not tied to specific design solutions. Specific design solutions can be found in the relevant literature linked to a particular PS.

The structuring process is illustrated in Fig. 2. At the top of the figure are the collected papers that provide the information that is structured. The systematic way in which this information has been collected is presented in Section 2.3. Relevant information from a paper is then either used to create a FoI and PS, or assigned to an already established FoI and PS, as shown in the center of the figure as highlighted cards. Thereby, multiple works can contribute to the creation of a certain FoI, while being attributed to distinct PSs (illustrated in blue and green in the figure). Finally, the established FoIs and PSs are assigned to the relevant MBs, as shown at the bottom of the figure. Five MBs have been created to promote concise links to relevant literature. One MB represents one Group, containing multiple FoIs and PSs. A Group is created for every major component of an anthropomorphic robot hand: “Thumb”, “Finger”, “Covering”, “Transmission” and “Kinematic Base Chain” (KBC). The KBC contains important aspects of global connection of the individual components.

2.2. Naming convention

The structuring of data into FoIs and PS requires the definition of some ground rules to reduce the level of arbitrariness. Storing design approaches in the form of FoIs and PSs without any further naming convention lead to very different results in the different systematic mappings. For this reason, basic rules were defined to enable the merging of results. First and foremost, the naming of

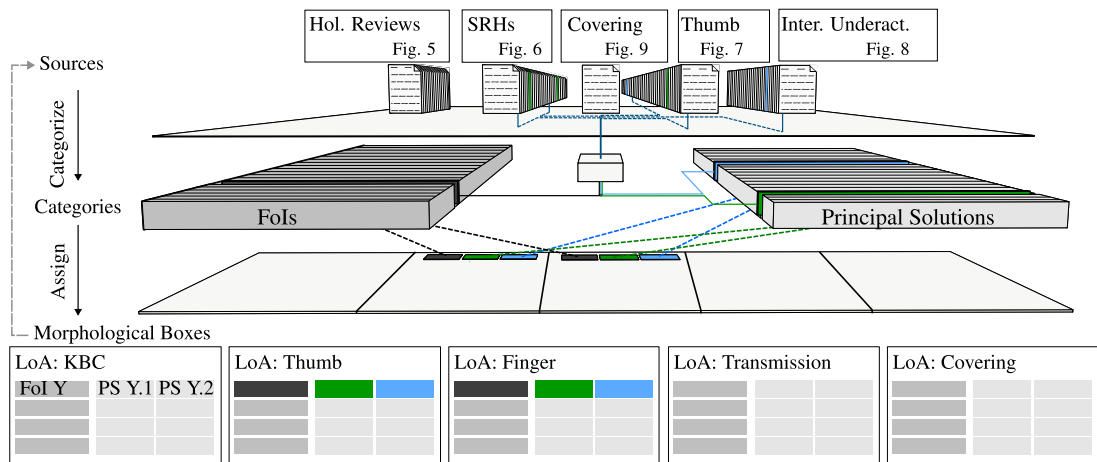


Fig. 2. Illustration of the applied systematic mapping process.

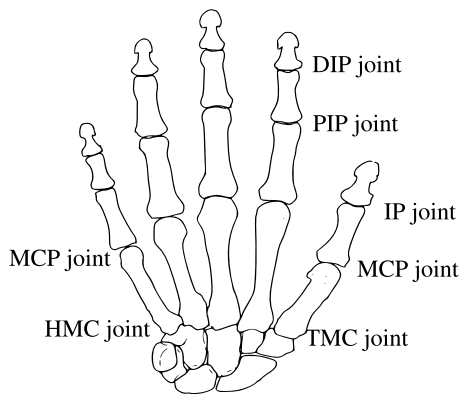


Fig. 3. Anthropomorphic joint terminology (re-drawn from Kasper et al. [6]).

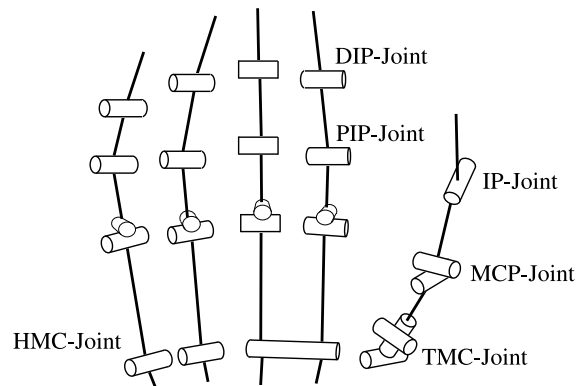


Fig. 4. For reference defined joint configuration [7].

FoIs and PSs is kept generic and does not directly refer to a specific design. Instead, references to the literature are used for this purpose. Furthermore, the data should be structured in such a way that the PSs of a FoI are understood as OR solutions of the FoI. This has led to renaming and restructuring of the identified FoIs and PSs during the merging process. Similarly, FoIs should be understood as AND or OR solutions among one another. This approach helps reduce arbitrariness in naming while primarily aiming to enable the automated use of identified FoIs and PSs in future design synthesis studies.

Furthermore, anthropomorphic joint terminology and an initially defined joint configuration are used to reduce ambiguity in the naming of FoIs and PSs. A universally standardized naming convention cannot be established, as the categorization into Groups, FoIs, and PSs remains somewhat subjective. To address this, anthropomorphic joint terminology and a predefined joint configuration serve as the foundation for naming and structuring. The anthropomorphic joint terminology, presented in Fig. 3, ensures a clear assignment of FoIs and PSs to specific joints. Additionally, the predefined joint configuration, shown in Fig. 4, enables the classification based on the number of DOF. For instance, the FoI “Eliminating Two DOF TMC Joint” includes a PS “Eliminating TMC F-E & P-S DOF”, which refers to studies implementing a thumb TMC joint with only a single A-A DOF.

The joint configuration is adopted from a previous study [7], which captures the joints implemented in successful robotic hand designs from the literature. This configuration was derived through anatomical analysis and comparison with existing robotic hands, making it a suitable reference for naming conventions in this work. However, in principle, any configuration could serve as a basis for naming the approaches, provided that the naming remains consistent.

Lastly, clarification on terminologies is necessary. Therefore, we distinguish in this study between the degree of actuation (DOA), as a design parameter, and underactuated mechanisms (UMs), as physical solutions to reduce the DOA.

2.3. Review systematic

For the intended data structuring, a systematic for capturing literature needed to be defined to adequately cover the state of the art in the mechanical design of anthropomorphic robotic hands. Since no PSs or FoIs had been defined at the time of literature

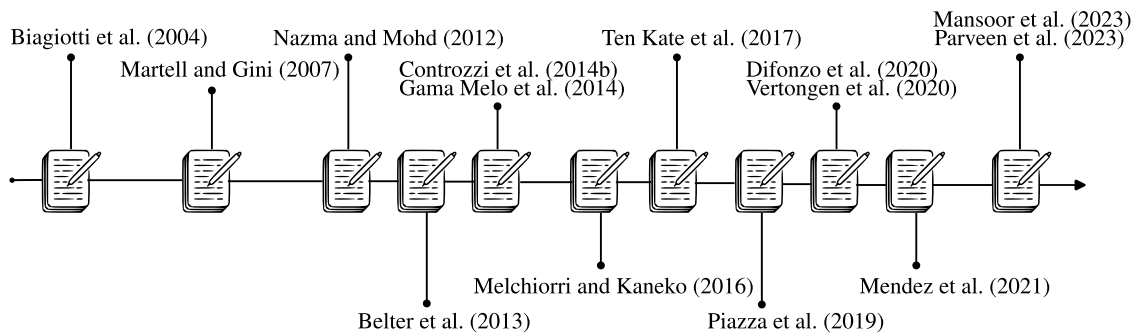


Fig. 5. Illustration of time line of collected holistic reviews (see [1,3,4,8–18]).

collection, it was not possible to explicitly screen the literature based on these criteria. Therefore, the primary objective was to gather an adequate set of literature with various focal points within the domain of mechanical design.

Five independent systematic approaches were applied to collect relevant literature with different focal points. In a first step, review papers were gathered that holistically examine the research, developments, and trends in robotic hands. This chosen methodology is based on the assumption that, after approximately 150 years of research on robotic hands [1], much of the relevant information has already been published and reviewed. In the second step, an analysis of existing robotic hands was conducted to identify additional Fols and PS. The scope of this analysis is defined by a set of Significant Robot Hands (SRHs), which we extracted from the review papers. To further address the particularly relevant fields of thumb design and underactuation, additional robotic hands were identified with corresponding focus. Lastly, a separate review was conducted to identify PS for the development of coverings. This was not motivated by its prominence in existing literature but rather by the lack of information found, despite its evident importance in the design of robotic hands. The execution of all five systematic approaches was completed by end of May 2023.

The following search strategy is applied for the identification of holistic review papers. The keywords “robotic hands” OR “anthropomorphic gripper” are combined with “review” OR “overview” to conduct a literature search on Google Scholar. The search was limited to the first ten pages of results and publications after the year 2000. This search resulted in 213 studies, of which 16 were published on or before the year 2000. For the remaining 197 studies, only those that were freely accessible through RWTH Aachen University and that investigated robotic hands holistically by reflecting on a collection of robotic hands were considered. Therefore, reviews were excluded if they, firstly, focused primarily on single aspects, such as sensors; secondly, investigated contributions to a specific field of application, such as agriculture; and lastly, exclusively examined industrial grippers. In total, 15 papers were identified and summarized in a timeline, as depicted in Fig. 5.

The set of SRHs is defined through an analysis of the holistic review papers as those mentioned at least twice. A single mention results in a total of 135 robotic hands. The threshold was chosen to create a more manageable set of frequently discussed designs. The set of SRHs comprises 24 robotic hands, analyzed across 31 studies covering different iterations of their designs. The complete collection of SRHs is presented in a timeline in Fig. 6. We emphasize that the chosen terminology does not imply the insignificance of other robotic hands but serves solely as a defined systematic approach due to the lack of alternatives.

For the identification of robotic hands with thumb design contribution, two search strategies are applied. In a first step, a backwards-snowballing approach is applied. The review by Nanayakkara et al. [101] is chosen as the starting point for its matching focus, as it provides an extensive literature overview of anthropomorphic robotic hands with a focus on the mechanical realizations of their thumbs. Additionally, the review has been very successful in comparison to other reviews on the subject. For the backwards-snowballing approach, all references cited in that work are reviewed and presented robot hand designs are captured. For thoroughness, former and past iterations of that robot hand are further identified in literature. The approach resulted in 183 studies. Based on an analysis of the title and abstract, 82 of the 183 studies are chosen for detailed analysis. After a detailed analysis of the studies, 61 out of the 82 studies are identified with an actual matching focus, including any predecessor or successor versions of a robot hand. In a second step, a keyword-based search is performed to identify those relevant robot hand designs published after the work by Nanayakkara et al. [101]. A search on ResearchGate using the keywords “anthropomorphic robotic thumb” OR “robotic thumb” was conducted. The search revealed 40 studies, considering the first two pages, respectively. Based on an analysis of the title and abstract if a contribution to mechanical thumb design is addressed, nine potentially interesting studies are chosen for further analysis. Out of these, six further studies are identified. Thus, in total, 67 studies are chosen for the identification of PSs, addressing the development of robot hand designs in multiple iterations. The resulting 34 robot hand designs are given in Fig. 7 in a timeline.

For the identification of robot hands focusing on interfinger underactuation, a keyword-based search strategy is performed. The keywords “between fingers” AND “robotic hands” AND “underactuated” OR “underactuation”, AND “wire-driven” OR “tendon-driven” are used on Google Scholar. The keyword “between fingers” was added to filter out studies predominantly focused on underactuated mechanisms within fingers. As we consider these design approaches part of finger design, we aimed to capture those PSs through thumb design studies. The keyword “anthropomorphic” was deliberately left out to broaden the range of potential

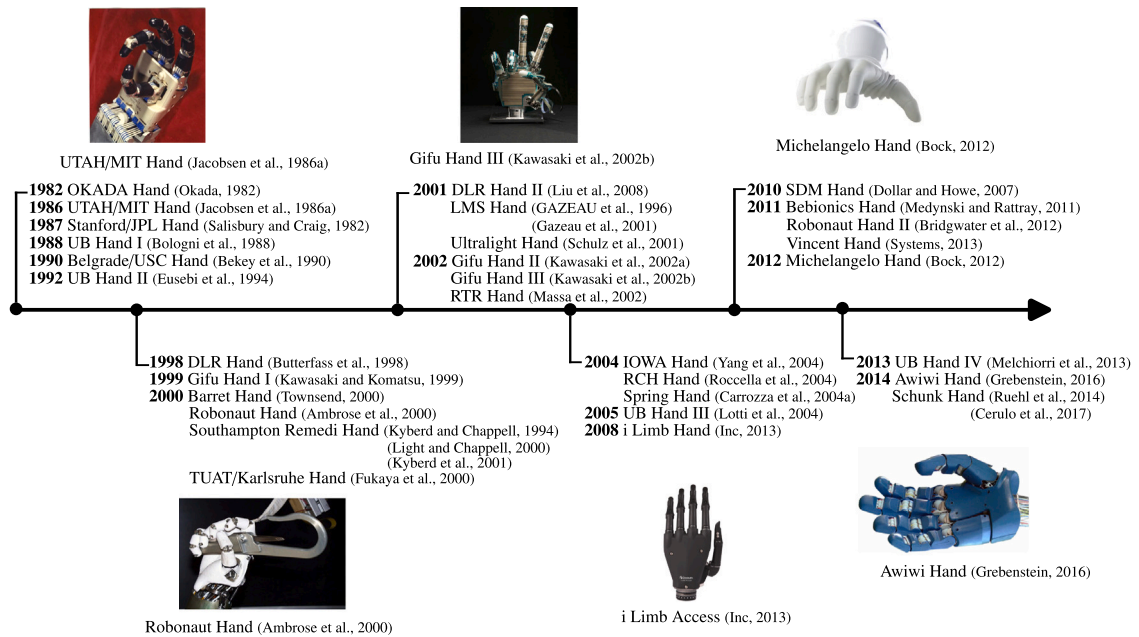


Fig. 6. Illustration of time line of collected significant robot hands (see [19–28,28–53]).

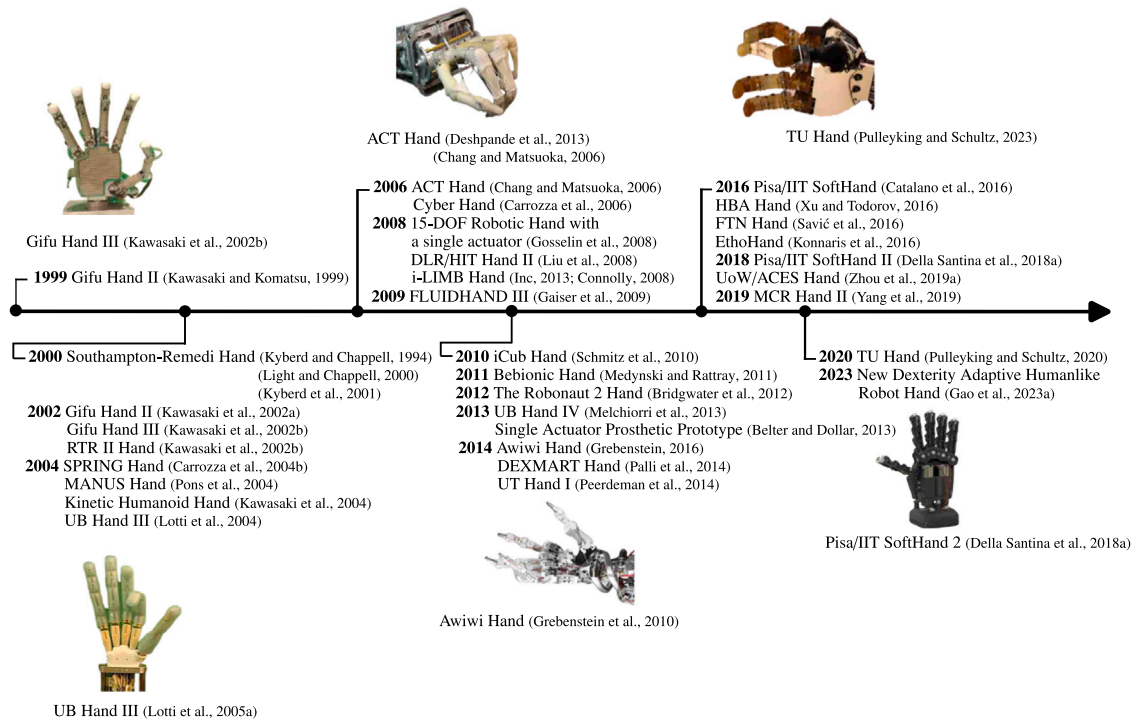


Fig. 7. Robot hands analyzed for thumb literature review (see [26,29,31–34,38,42–44,46,47,50,51,54–73,73–77]).

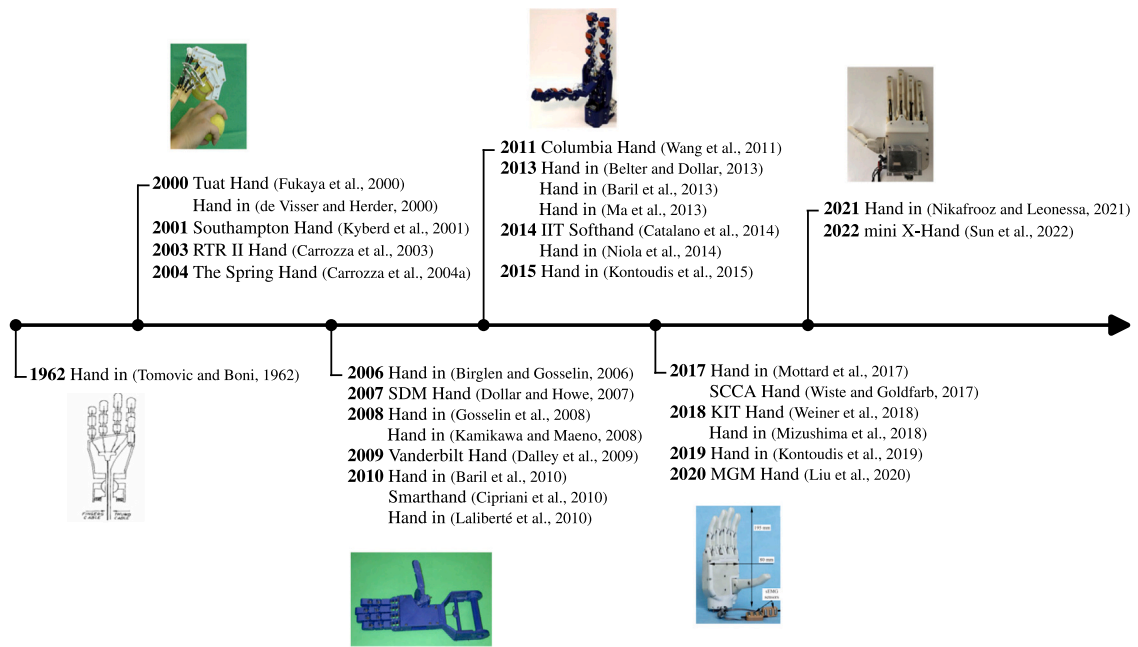


Fig. 8. Robot hands analyzed for application of interfinger underactuation (see [30,32,42,45,60,64,78–100]).

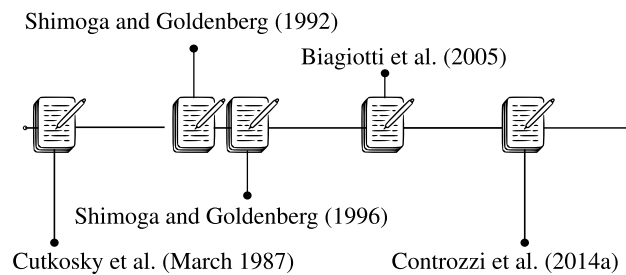


Fig. 9. Illustration of time line of Paper analyzed the covering (see [103–107]).

studies. The search was limited to the first three pages, yielding 58 studies. These studies were evaluated based on their titles and abstracts to determine whether they investigated tendon-driven mechanisms for interfinger underactuation. As a result, 16 studies were selected for detailed analysis. Notably, the book *Underactuated Robotic Hands* by Birglen et al. [102] emerged as a frequently cited and influential source in the field, considered the pioneering work exclusively focused on underactuated hands. To identify relevant robotic hands, the sources of the 16 studies were further examined. Ultimately, a total of 29 robot hands were identified for the analysis of approaches towards interfinger underactuation, illustrated in a timeline in Fig. 8.

For the covering, the search strategy resulted in only five papers in which covering was explicitly examined in detail. Combinations of the keywords “robot hand” AND “finger pads” OR “contact material” OR “covering” OR “skin” OR “soft fingertip” were used on Google Scholar. Only the first page of results was evaluated due to the limited number of relevant matches. The search revealed a total of 42 potential studies. These 42 studies were evaluated based on their titles and abstracts to determine whether they truly implemented, analyzed, or evaluated covering materials. As a result, studies focusing on sensors or control modeling were excluded. From these 42 studies, 10 were selected for further analysis. After closer examination, another five were excluded. The remaining five studies are illustrated in a timeline in Fig. 9. Besides the identified sources, additional implicit information on covering approaches was obtained from the SRHs and other robotic hands. However, in many cases, rubber is used generically as a contact material without further investigation into its influence.

This study applies a number of limitations for the identification of PS within the LoA. It focuses exclusively on anthropomorphic robot hand designs, specifically addressing only the mechanical aspects of these designs. The scope is further limited to tendon actuation, although many of the identified approaches can be applied to other actuation principles as well. Furthermore, some mechanical design aspects are not examined in detail. This includes research on the design of the wrist, forearm, or drive units.

2.4. Related work

The proposed review distinguishes itself from the identified holistic review papers in three key aspects: (1) the goal, (2) the applied search strategies, and (3) the outcome. All three aspects are discussed in more detail in the following.

Firstly, the goal of the proposed review is to emphasize the structured organization of mechanical design approaches as PSs in MBs. It aims to address the need for a structured source of existing knowledge while also providing a framework that supports continuous structuring and updating of data over time. By employing a systematic approach to defining and organizing mechanical design approaches into MBs, this work directly supports researchers and designers in understanding and navigating the field. In contrast, other reviews focus on specific components, design trends, evaluation metrics, or related aspects. In contrast, the proposed review emphasizes the identification of overall valid, robot-hand-unspecific principal design solutions, with references to specific robot hands provided for further context. Summarizing, while other reviews offer comprehensive and valuable overviews, none share the same objective as the proposed review.

Secondly, the applied search strategy sets the proposed review apart from other review papers. As mentioned above, it is based on the assumption that, after approximately 150 years of research on robot hands [1], most relevant information has already been published and reviewed. Thus, the goal is to summarize the content of those review paper in an appropriate structure. This approach does not necessarily aim to generate new findings but rather serves the purpose of summarizing and organizing the content of previous (review) studies.

Finally, this review is distinguished by its outcome. The outcome of this review is the LoA, a comprehensive resource that organizes research fields of interest and PSs for anthropomorphic robot hand design into MBs, each linked to relevant literature and accessible via a digital interface. The LoA enhances accessibility and usability, enabling efficient exploration of design approaches for both novice and experienced designers. Similar approaches can be found in the literature. For example, in the review by Piazza et al. [1], a large databases can be downloaded in a pdf format. It contains a large collection of knowledge with information on robot hands, their degree of actuation, degrees of freedom and other key data. It is thus a collection of hands with information regarding the form, feature and performance. However, we present a collection of information regarding the design in form of principal solutions, referring to robot hands. No database could be found in literature that pursues the same goal as proposed in this work.

3. Library of Approaches excerpts

In this section, the LoA is presented in detail. For improved readability, this section is divided into the LoA Groups. Furthermore, the FoIs and PSs are presented in smaller excerpts of a LoA Group, allowing to scan conveniently this study for additional information on a specific FoI and/or PS. In each excerpt, the FoIs are presented centered and bold, to distinguish them from the associated PSs. In some excerpts, additional references are given if their number exceeds the examples given in the text.

3.1. Group “Thumb”

In this section, the FoIs and PSs identified in the review are examined in more detail. All FoIs and PSs of the Group “Thumb” are shown in Table 56.

Due to the number of results identified, the FoIs and PSs are presented in categories. The first category deals with approaches for the alteration of joint configuration. The second category deals with the structural design of the applied joints. The third category reflects on the application of intrafinger underactuation. The fourth category deals with approaches for the design implementation and the last category deals with approaches for dimensioning.

Joint Configurations

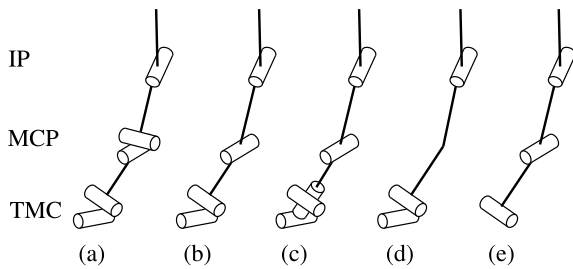
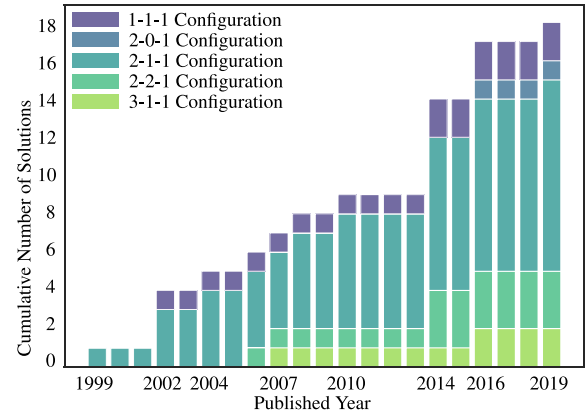
In this category, approaches for simplifying the DOF of individual joints are presented. For thumb design, two primary modifications to the MCP and TMC joints are identified, respectively. For the MCP joint, the first approach involves eliminating the Adduction/Abduction (A-A) DOF, thereby limiting the MCP joint to a single Flexion/Extension (F-E) DOF. As a second approach, the literature also describes the complete removal of the MCP joint, where a fixed angle is implemented in its place. For the TMC joint, the first option eliminates only the Pronation/Supination (P-S) DOF, allowing the TMC joint to retain two remaining DOFs. Thereby, the eliminated P-S DOF is often passively compensated for through skillful choice of inclination and twist angles between the remaining joints [51]. The second option further eliminates the F-E DOF, resulting in a TMC joint with only a single A-A DOF (see Table 1).

To provide examples from the literature, a combination of the DOF elimination approaches are presented as joint configurations. Five different joint configurations for the thumb are identified in the literature, each representing a combination of proposed DOF eliminations. For the configurations, we adopt the terminology introduced by Wang et al. [112], denoting them as X-Y-Z configurations, where X, Y and Z indicate the number of DOFs in the MCP, DIP and PIP joints, respectively. These joint configurations found in the literature are visualized in Fig. 10. They allow a maximum of five DOFs for the thumb, achieved by 3-1-1 and 2-2-1 configurations. The minimum of three DOFs is achieved by 2-0-1 and 1-1-1 configurations. Finally, intermediate 4 DOF 2-1-1 configurations are also identified. Each configuration has been successfully applied in robotic hand designs, demonstrating functional dexterity. However, this work does not compare levels of dexterity or success between configurations, as the literature uses different metrics and defines different objectives. However, it is safe to assume that the dexterity of a 3 DOF configuration is significantly lower than the dexterity of a 5 DOF configuration. Examples for each configuration are given in the appendix in Appendix A. A

Table 1

LoA excerpt: FoIs and PSs for thumb joint configuration.

Elim. 1 MCP Joint DOF	
Elim. MCP A–A DOF	(see [26,33,34,38,39,43,51,55,56,63,65,66,71,72,75,108–110])
Elim. 2 MCP Joint DOF	
Elim. MCP Joint	(see [68,76,111])
Elim. 1 TMC Joint DOF	
Elim. TMC P–S DOF	(see [26,33,34,38,43,51,55–58,63,65,68,71,75,76,108,109,111–114])
Elim. 2 TMC Joint DOF	
Elim. TMC P–S and F–E	(see [39,66])

**Fig. 10.** Illustration of identified thumb joint configurations: (a) 2–2–1, (b) 2–1–1, (c) 3–1–1, (d) 2–0–1, and (e) 1–1–1 configurations.**Fig. 11.** Cumulative illustration of thumb configuration frequencies.

comparison of the frequencies of the individual configurations is shown in the cumulative representation in Fig. 11. As shown in the examples, a relative frequency of the 2–1–1 configuration is evident and continues to increase. However, in recent years, there has also been an increase in more complex configurations, such as the 3–1–1 or 2–2–1 configurations. This may be due to advances in control techniques or a recent desire for more dexterous robot hands. On the other hand, there is also an increase in comparatively simpler configurations, such as the 1–1–1 or 2–0–1 configurations. On the one hand, this can be attributed to the desire for simpler control. On the other hand, configurations such as the 2–0–1 configuration can be understood as a correlation with improvements in the medical domain.

Structural Joint Design

Another category of FoIs and PSs addresses the structural design of joints, largely inspired by the work of Wang et al. [112]. Structural design refers to the number of axes in a given joint and their relative arrangement. In the work by Wang et al. different robot thumb structure configurations are defined, as shown in Fig. 12, and analyzed. Robot hands are assigned to the configurations (e.g. Shadow Hand [113] and CEA Dexterous Hand [114] with 2–2–1 structures as configuration (h)). Additionally, metrics are introduced to evaluate thumb performance based on the chosen structural design, proving the influence on robot hand performance. In this paper, structural designs for individual joints are defined as PSs based on a previous conceptual definition of these. To identify PSs in the literature, the conceptual options are first established. By drafting various conceptual designs of joint structures, a range of options is defined and illustrated in Fig. 13. For a two-DOF design, there are in essence two options: either the two axes intersect at a central point, or they do not (see rows in Fig. 13). Each of these two options can further be divided into configurations where the A–A axis is positioned above or below the F–E axis, resulting in a total of four possibilities. Additionally, each of the four configurations can be designed with either orthogonal axes or axes with an angle, such as an inclination or twist angle (see columns in Fig. 13), yielding a total of eight options. While identifying structures with specific inclination and/or twist angles would be valuable, such details are rarely explicitly documented in the literature. Therefore, these structures are generally referred to as “non-orthogonal”. The 2-DOF TMC joint has eight additional options, compared to the derived structures for the MCP joint. In the TMC joint, for each presented MCP joint structure, a P–S DOF can replace either the F–E DOF or the A–A DOF. For the 3-DOF TMC joint, multiple options can be derived from a single TMC 2-DOF design: a third DOF can be added either above or below the structure, intersecting or non-intersecting, and orthogonal or non-orthogonal. The resulting options are not illustrated in Fig. 13, due to the large quantity of options and the limited need to define them, as 3-DOF designs are barely available in literature. The structural joint design PSs identified in literature are given in Table 2. A detailed list of examples is not provided here for the sake of conciseness. However,

Table 2		
LoA excerpt: Fols and PSs for thumb structural joint design.		
MCP Joint Struc. Design (2 DOF)		
2 axis not orth./non-intersecting – Add./Abd. below (e.g. [57])	2 axis orth./non-intersecting – others (e.g. [118])	
TMC Joint Struc. Design (2 DOF)		
2 axis orth./non-intersecting – Add./Abd. below (e.g. [19,47,51,65,108,115,116])	2 axis orth./non-intersecting – Add./Abd. at top (e.g. [25,117])	2 axis orth./non-intersecting – others (e.g. [3,119])
2 axis not orth./non-intersecting – Add./Abd. below (e.g. [57])	2 axis not orth./non-intersecting – others (e.g. [71,77])	2 axis orth./intersecting – Add./Abd. at top (e.g. [30,34])
2 axis orth./intersecting – Add./Abd. below (e.g. [26,33,38,120,121])		

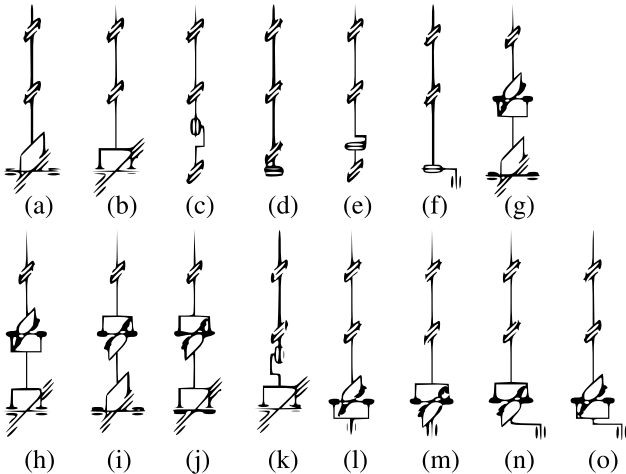


Fig. 12. Thumb structural joint configurations (redrawn from [112]): (a)–(f) 2–1–1, (g)–(k) 2–2–1, and (l)–(o) 3–1–1 configuration with different axis arrangements.

		intersecting				not intersecting				
TMC 2DOF										
										orthogonal
MCP 2DOF										orthogonal
										not orthogonal

Fig. 13. Conceptual definition of structural joint configurations, derived from [112].

reference is made to the works by [115] and [116] for the structural joint design with 2 axis orth. / non-intersecting - Add./Abd. below and to the work by [117] for Add./Abd. at top.

Table 3

LoA excerpt: FoIs and PSs for thumb DOA reduction.

Elim. 1 DOA MCP–IP Joints		
Tendon coupling of two joints (e.g. [25,66])	Linkage coupling of two joints (e.g. [34,109])	Linkage UA of two joints (e.g. [123,124])
Elim. 2 DOA TMC–MCP–IP Joints		
Linkage UA of three joints (e.g. [71,74,125–127])	Tendon UA of three joints (e.g. [60,128,129])	Linkage coupling of three joints (e.g. [130])
Elim. 3 DOA TMC–MCP–IP Joints		
Linkage UA of three joints [131]		

Intrafinger Underactuation/Coupling

The PSs collected in this category include methods for connecting joints rather than eliminating them. For this reason, the elimination of DOAs is chosen as the naming for the FoIs. For the elimination of a DOA, UMs or couplings are applicable. Even though the latter also eliminates a DOF, the PSs are not considered within the FoIs “Elim. DOF”, as no joint is eliminated.

Prior presentation of distinct PSs for the connection of joints, the differences between UM and couplings are highlighted. The definition of UMs is discussed in detail in numerous works. For a more detailed definition, the reader is referred to the work by Birglen et al. [102]. From a practical perspective, an intra-finger UM is a mechanism that allows more than one phalanx of a finger to be deflected by a single actuator, and also allows the deflection to continue even when one phalanx is in contact with an object. Thus, intra-finger UMs allow robotic fingers to passively adapt to object shapes [102], requiring fewer actuators and reducing the need for active control [122]. On the one hand, this simplifies the robotic hands, resulting in lighter, more compact and affordable designs [102]. On the other hand, a conjunction of joints is generally associated with a limitation of dexterity, compared to full actuation. Therefore, when designing robotic hands, a balance for the application of UMs must be carefully considered. Coupling within a finger allows a similar reduction in the number of DOAs, but at the same time reduces the number of DOFs. Furthermore, coupling does not allow the finger to passively adapt to the grasped geometry. Instead, all coupled joints deflect in a predefined proportion to each other, and all phalanges are blocked as soon as one of them makes contact with the object. However, couplings are not unpopular because of their comparatively easy design, which reduces design effort and cost.

The defined PSs for connection of joints are given in Table 3. A distinction is made between the elimination of a single DOA, two DOAs and three DOAs. Within these FoIs, the PSs differ with respect to the application of an underactuation or coupling and with respect to the application of tendons or linkages. The FoIs and their corresponding PSs are described in more detail below. The identified PSs for the conjunction of joints are conceptually illustrated in Fig. 14. In the given illustration, for the application of linkages, the respective joints are colored in red. For the application of tendons, the joints are colored in green. Furthermore, for the application of UMs, the joints are striped. It is important to note, the illustrated joints are not necessarily applied in the robot hands that are mentioned. Here, we solely refer to the applied conjunction of joints. Further PSs for the elimination of DOF can be applied. Example cases from the literature are provided in the index cards in Appendix A.

The identified PSs for the reduction of one DOA in the thumb all refer to the conjunction of the MCP and IP joints, as given in Table 3. First, the tendon coupling of MCP and IP joints (see Fig. 14(c)) could be identified in the literature. Second the linkage coupling (see Fig. 14 (a); e.g. [132,133]), and third a linkage underactuation could be identified (see Fig. 14 (b); e.g. [124]). For a tendon actuated robot hand, the tendon coupling is comparably easy to implement. As a result, this is a common choice, referring to the conjunction of MCP and IP joints in human thumbs [134]. For tendon coupling of MCP and IP joints, examples from the literature are given in Table 30. Examples for the linkage coupling are given in Table 31.

The identified PSs for the reduction of two DOA in the thumb refer to the conjunction of the TMC, MCP and IP joints, as given in Table 3. Three different options to eliminate two DOAs in a thumb design are identified: First, a linkage coupling of three joints (see Fig. 14 (e)); second, a linkage underactuation of the three joints (see Fig. 14 (f); e.g. [126,127]); and last, a tendon underactuation of the three joints (see Fig. 14 (d); [128,129]). For the last, a detailed example from the literature is given in Table 32.

For the elimination of three DOAs in thumb design, only a single solution could be identified in the literature. In the work by [131], a spherical five-bar mechanism and two underactuated four-bar linkages are applied. The applied mechanism allows the connection of IP F–E, MCP F–E and TMC F–E and A–A DOFs, as illustrated in figure (see Fig. 14(g)).

Mechanical Joint Design

Within the LoA, many FoIs capture the efforts made towards the mechanical design of joints. It is possible to argue towards the comparably lower urgency of these research fields for the design of anthropomorphic robot hands. However, joint design is an always present necessity in a design. Therefore, we collected the information from the literature to provide guidance and sources for comparison, as the general goal of the LoA. In the following, the different collected FoIs and PSs for 1-DOF joint designs are presented in Table 4, 2-DOF joint designs in Table 5 and 3-DOF joint designs in Table 6.

For the PSs under 1 DOF joint design, four different joint types are identified, following the suggestion in the work of Piazza et al. [1]: A closed hinge joint, an open hinge joint, a compliant joint and a rolling contact joint. In our case, the open hinge joint corresponds to the “dislocatable joint” from Piazza’s work in order to make the naming less function-based and more implementation-based. The closed hinge joint is the most common and intuitive joint type. It is a compressed representation of all fully enclosed joint design, e.g. revolute joints and pin joints. Examples are given in Table 33. The open hinge joint is characterized by its ability to dislocate under high external forces. This feature increases the impact resilience of the thumb and the entire robot hand, as dislocation prevents structural damage to the robot hand. To function properly, the drive tendons must be pre-tensioned

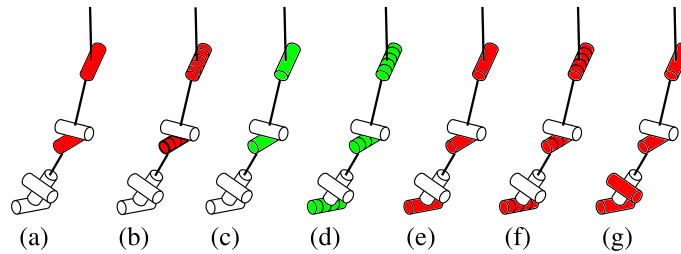


Fig. 14. Illustration of thumb joint conjunctions on a 3–2–1 configuration (red: linkages; green: tendons; striped: underactuated; unstriped: coupled): (a)–(c) DIP–PIP F–E, (d)–(f) MCP–DIP–PIP F–E, and (g) MCP A–A combined with MCP–DIP–PIP F–E conjunction.

Table 4

LoA excerpt: FoIs and PSs for 1 DOF joint design.

IP & MCP Joint Mech. Design (1 DOF)		
Closed hinge Joint (e.g. [57,63,65,71,75–77,108,109])	Open hinge joint (e.g. [51])	Compliant joint (e.g. [45,56,74])
Rolling-contact Joint (e.g. [69,135,136])		
TMC Joint Mech. Design (1 DOF)		
Closed hinge Joint (e.g. [39,66])		

Table 5

LoA excerpt: FoIs and PSs for 2 DOF joint design.

MCP Joint Mech. Design (2 DOF)		
Closed hinge Joint (e.g. [57])		
TMC Joint Mech. Design (2 DOF)		
Closed hinge Joint (e.g. [25,137,138])	Open hinge Joint (e.g. [51])	Compliant Joint (e.g. [43,56,74])
Rolling-contact Joint (e.g. [76,139])	Ball Joint (e.g. [140,141])	Combined closed– and open hinge joint (e.g. [50,65])

Table 6

LoA excerpt: FoI and PSs for 3 DOF joint design.

MCP Joint Mech. Design (3 DOF)
Ball joint (e.g. [72])

to allow the use of an open wrist. An important example of a dislocatable open hinge joint is given in Table 44, with reference to the work of Grebenstein [51]. The wording “open hinge joint” is a compressed representation of all partially enclosed joints, which includes a convex surface of one phalanx link that articulates with a concave surface of the other. Open hinge joint could also be referred to as condyloid joint and saddle joint. The rolling contact joint consists of two cylinders in rolling contact with each other. Again, some means of fixing the two cylinders is required. Apart from this additional mechanical design effort, the design has certain advantages, as suggested in the work of Catalano et al. [136] and Catalano et al. [69]: firstly, the mechanical design allows easy modification of the characteristic diameters, which in turn modifies the transmission ratio of the joint and consequently the transmitted force. In addition, the use of a suitable tendon guide makes it possible to achieve zero torque; secondly, despite the absence of bearings, the joint exhibits minimal friction and negligible abrasive wear; thirdly, the absence of mechanical connection elements such as screws and bolts means a significant reduction in the number of components required for assembly. More detailed examples are given in Tables 34 and 39. For the mechanical design of 2 DOF joints, only MCP and TMC joints are investigated. In addition to the previously identified four different joint designs, a ball joint (e.g. [141]) could be identified in literature for the implementation of 2 DOFs. The closed hinge joint encompasses both Flexion–Extension (F–E) and Abduction–Adduction (A–A) movement and compresses similar rigid, enclosed joint designs to one attribute, such as universal joints, Cardan joints and double pin joint. Compared to the closed hinge joint, an open hinge joint with 2 DOFs encompasses designs like saddle joint: a type of synovial joint characterized by interlocking convex and concave articulating surfaces, while resembling two saddles opposed to one another [142]. 2 DOFs compliant joints and rolling-contact joints (e.g. [139]) are based on two 1 DOF designs with their rotational axis respectively on F–E and A–A. Two DOF ball joint designs lock one rotational axis in order to keep only F–E and A–A movement. Lastly, an additional design option for TMC joints has been identified as a combination of closed and open hinges. The F–E movement is realized by a closed hinge and the A–A movement by an open hinge. The design thus takes advantage of the comparatively more compact design of a closed hinge joint, which is an important design factor considering the limited space in anthropomorphic robotic fingers. Examples can be found in the works of Melchiorri et al. [50], Palli et al. [65].

Only one approach using a 3 DOF joint at TMC joint mechanical design is found through a literature search, which is the thumb TMC joint of the EthoHand [72]. The thumb base is composed of two distinct components: the ball joint, which is the TMC joint, and

Table 7

LoA excerpt: FoIs and PSs for Thumb Design Implementation.

Finger Structure		
Rigid-sequential (e.g. [28,51,72])		Flexible (e.g. [24,45,56])
Phalanx Design		
Exoskeleton (e.g. [26,33,34,38,39,66,72])		Endoskeleton (e.g. [51,56,57,65,70])
Resetting		
Torsional spring	Rubber band	Antagonistic actuation

Table 8

LoA excerpt: FoIs and PSs for thumb dimensioning aspects.

Joint ROM	
Anthropomorphic	
Finger Size	
Anthropomorphic relations	
Phalanx Length	
Anthropomorphic relations	
Improving Opposition	
Inclination of IP Joint	Twist between IP and MCP Joint

the socket, which is attached to the palm. The ball joint exhibits three rotational degrees of freedom. Two degrees of freedom define a directional axis, thereby enabling planar movements. The third degree of freedom permits rotation around the aforementioned directional axis.

Design Implementation This section records the PSs identified for aspects of the implementation of the designs. The FoIs cover options for the structure of the finger, the design of the phalanx, and methods for resetting the finger. Each FoI is discussed individually below and presented in Table 7. The first FoI includes two derived PSs for finger structures. The finger can be either rigid sequential or flexible. References are given in the full LoA Table 56.

The second FoI explores options for thumb phalanx design, broadly classified into two main variants: exoskeleton and endoskeleton. In the exoskeleton model, the supporting frame forms a hollow structure characterized by closed profiles and a favorable stiffness-to-weight ratio. However, this conventional design underutilizes the internal thumb space, which is largely occupied by joints, gears, and actuators [50]. Many robotic hands, such as the UB Hand II [143] and DLR/HIT Hand I [110], have been inspired by this approach. The endoskeleton model, inspired by the human hand, distinguishes between an inner rigid frame and an outer flexible layer. This design reduces the part count and provides space for components like drive tendons, sensors, electronics, and soft pads, arranged around the frame rather than inside it [50], [51].

One of the main differences between the two models is the application of covering material. In exoskeleton designs, adding substantial malleable material around the finger structure is challenging without exceeding acceptable finger size limits [56]. As a result, only a thin rubber layer is typically applied to enhance contact friction [144]. In contrast, the endoskeleton design accommodates malleable pads between the internal bone structure and external surfaces, improving grip quality and ensuring more uniform load distribution [51]. Examples of endoskeleton-based hands include the Awiwi Hand by Grebenstein [51] and UB Hand III by Lotti et al. [43,56].

The final FoI addresses PSs for implementing resetting mechanisms. In addition to the obvious approach of antagonistic tendon actuation for active resetting, two passive options have been identified. The most common passive solution is the use of torsional springs, which are well-documented, commercially available, and offer a range of stiffness options. Alternatively, rubber bands can be employed, benefiting from lower space requirements. However, our prototypes revealed challenges in selecting suitable rubber bands to coordinate sequential phalanx movements within a single finger.

Dimensioning

This section records the PSs identified for dimensioning aspects. Dimensioning includes options for finger length, phalanx length within a finger, the positioning of the first finger joint, and any potential twist and inclination angles within a finger. Each FoI related to the thumb is discussed individually below and presented in Table 8. Corresponding considerations for the fingers are discussed in their respective section. The positioning of the TMC joint is not addressed here, as this section focuses solely on the FoIs and PSs for thumb design. Instead, thumb positioning, as well as the positioning of the first joint for all fingers, is discussed in the “Kinematic Base Chain” Group, which includes PSs for the shared kinematic foundation of all fingers.

Before presenting the individual PSs, the relevance of anthropomorphic proportions for dimensioning in robot hand design is discussed. Beyond applications like prosthetics, where anthropomorphic proportions are sought for aesthetic reasons, various studies have demonstrated the functional importance of anthropomorphic proportions. For example, research on the iCub robot hand highlights the value of human-like proportions. An earlier iteration of the iCub hand, featuring an additional thumb phalanx, exhibited impaired functionality; the longer thumb constrained the practical range of other fingers and led to unnatural postures during gripping. By reducing the thumb's length to match human proportions, the robot achieved a more natural structure and

improved dexterity [108]. Further studies emphasize that a robot hand with human-like size and geometry enhances dexterous manipulation, reflecting the efficiency and adaptability of human hand kinematics [51,145]. Thereby, the importance of proportional ratios rather than individual lengths is emphasized. This principle can also be found in surgical procedures, such as “pollicisation”, used to reconstruct a lost thumb out of the index finger. Achieving the appropriate thumb length is considered critical for generating sufficient opposition force and avoiding weak grips caused by excessive thumb length [146].

Anthropomorphic dimensions are often taken from one’s own hand, but can also be found well documented in the literature. The standard DIN 33402-2 [147] contains many relevant dimensions of the human hand. For each measurement, the gender and age groups are specified. A total of 21 dimensions of the human hand are categorized, including the finger width and length as well as the thickness and length of the palm. Only the thicknesses of the individual fingers are not specified. Alternatively, a detailed description of anthropomorphic dimensions can be found in the study by Vergara et al. [148]. In this study, a total of 99 dimensions of the hand were measured in 134 test subjects. In comparison to the DIN standard, the length, width and thickness of each phalanx were measured. In addition, the thickness of the palm is determined at nine positions. The mean values of the dimensions are reported both separately for each gender and combined. Other works can be found in the literature, such as that of Jee et al. [149]. Overall, however, the work by Vergara et al. [148] offers the most measurement points and covers all the necessary dimensions.

The first FoI in Table 8 deals with the joint ROM values. A large number of sources for anthropomorphic dimensions can be found in the literature [150–158]. A summary of the given values is presented in Table 9. However, the given values are ambiguous. Further, the movements of the thumb and information of the considered joints vary and, thus, a unique assignment is difficult. In the past, for our own prototypes, we have therefore combined the ROM values from different studies. The ROM values for the fingers were taken from the work of Cobos et al. [153], the ROM values for HMC joints from the work of El-Shennawy et al. [152] and the ROM values for the thumb from the work of Peña-Pitarch et al. [156].

The phalanx lengths have been identified to follow certain ratios. Chalon et al. [146] argue towards the existence of a consistent ratio between phalanges in humans and its requirement in robot hands. The ratios are found to be highly consistent across different individuals. It is recommended to apply the identified ratios to ensure maximum contact surface during the grasp. Further studies by van der Hulst et al. [159] and Peña-Pitarch et al. [156] identified ratios for the phalanx lengths in dependency of the hand length. Van der Hulst et al. present phalanx lengths of each finger as percentage of full hand length, which are used as DH-parameters calculation. According to the proximal, medial and distal phalanges, the index finger phalanx lengths are given as 21.8%, 14.1%, 8.6% of hand length, with middle finger as 24.5%, 15.8%, 9.8%, ring finger as 22.2%, 15.3%, 9.7%, little finger as 17.7%, 10.8%, 8.6%, thumb as 17.1%, 12.1% [159]. The metacarpal segment length between CMC and MCP Joint is not assigned as a fixed value. Apart from the phalanx length formula Peña-Pitarch et al. presents the formula for metacarpal length of each finger, where the thumb metacarpal length is given as 25.1% of hand length, with index finger given as the distance of 37.4% of hand length and 12.6% of hand breadth, middle finger as 37.3% of hand length, ring finger as the distance of 33.6% of hand length and 7.7% of hand breadth, little finger as the distance of 29.5% of hand length and 17.9% of hand breadth [156].

For the improvement of opposition of the thumb to the other fingers, Inclination and Twist angles within the thumb have been proposed, which is considered as a solution to compensate the pronation/supination movement of natural human thumb. Inclination is the angle between the axis of movement of the joint and the vertical position. The inclination of the joint axis allows the fingers to be parallel to each other at rest and to tilt towards the sagittal plane during flexion [67]. In this way, the fingers have a common vanishing point on the palm when flexed [160]. Twist is the deviation of the joint axis around the longitudinal axis. The twist between thumb MCP and IP Joints allows the inward rotation of the thumb to flexion, supporting key grasps and pinch grasps for contact improvement [51].

Grebenstein conducted an experimental analysis to evaluate the benefit of inclination and/or twist angles. Initially, an appropriate thumb TMC joint pose was identified. Thereafter, the Kapandji test and a series of gripping tests, including the key and power grasp, were employed with four different thumb configurations: (1) Thumb IP without twist and inclination, (2) Thumb IP with twist, (3) Thumb IP with inclination, and (4) Thumb IP with twist and inclination.

The experimental findings indicate the necessity of fine-tuning of inclination and twist angles. In some instances, a superior performance of the thumb was observed in the absence of inclination and twist angles. For instance, the MCP joint of the index finger was more naturally reached in the Kapandji test without application of twist and inclination. Additionally, the thumb’s position in the key grasp was better when an inclination and twist angle was not applied, resulting in a better tip contact. However, inclination and twist angles were found to be more effective when grasping large cylindrical objects. In the absence of any twist or inclination of the thumb, the angle between the pad of the thumb and the object is not optimal, which is important for stable power grasps. Additionally, considering the key grasp, the observed offset angle with applied inclination and twist is sufficiently minor to be counterbalanced by the malleable tip of the thumb.

The following guidelines for tuning twist and inclination angles are derived in the work by Grebenstein [51]: (1) Given the superior functionality of the power grasp, which is far more prevalent in robotic applications than the key grasp, corresponding twist and inclination should be applied. (2) To enhance contact during key-grasp, the IP joint should be twisted in an outward direction from the palm of the hand. (3) To enhance contact during grasping of large surfaces, the IP joint should be twisted inwards. (4) To enhance the power-grasp capability for smaller objects, it is necessary to fine-tune the inclination of the IP joint to achieve optimal opposition. Regarding approximate ranges, the inclination and twist angle of the thumb between 0°–5° and 0°–9° are specified. [51]

Table 9

ROM values from literature for different finger, with sources (1) Becker and Thakor [150], (2) Hume et al. [151], (3) El-Shennawy et al. [152], (4) Cobos et al. [153], (5) Barakat et al. [154], (6) Ngeo et al. [155], (7) Bain et al. [157], (8) Lee and Jung [158], (9) Peña-Pitarch et al. [156].

Digit	Joint	Movement	ROM values [°]															
			(1)		(2)		(3)		(4)		(5)		(6)		(7)		(8)	
Thumb	TMC	Pa. A-A	-	-	-	-	-	-	90	15	61.2	31	amb.	-	-	amb.	60	0
		Ra. A-A	-	-	-	-	-	-	60	-	62.9	10.2	-	-	-	-	25	35
	MCP	A-A	-	-	-	-	-	-	-	-	-	-	-	-	-	-	60	0
		F-E	-	-	0	56	-	0	80	8.1	60	10	55	-	-	0	61	10
	IP	F-E	-	-	-5	73	-	-	10	80	12	90	15	80	-	0	81	15
Index finger	HMC	F-E	-	-	-	-	-	3	0	5	-	-	-	-	-	-	-	-
	MCP	A-A	-	-	-	-	-	-	-	60	-	-	-	-	-	-	-	13
		F-E	-	70.83	0	100	-	-	40	90	-	-	45	90	19	90	-	80
	PIP	F-E	-	103.87	0	105	-	-	0	110	-	-	0	100	7	101	-	104
	DIP	F-E	-	61.17	0	85	-	-	5	90	-	-	0	80	6	84	-	68
Middle finger	HMC	F-E	-	-	-	-	-	3	0	5	-	-	-	-	-	-	-	-
	MCP	A-A	-	-	-	-	-	-	-	60	-	-	-	-	-	-	-	8
		F-E	-	85.3	0	100	-	-	40	90	-	-	45	90	19	90	-	85
	PIP	F-E	-	103.98	0	105	-	-	0	110	-	-	0	100	7	101	-	107
	DIP	F-E	-	61.17	0	85	-	-	5	90	-	-	0	80	6	84	-	70
Ring finger	HMC	F-E	-	-	-	-	-	15	0	10	-	-	-	-	-	-	-	-
	MCP	A-A	-	-	-	-	-	-	-	45	-	-	-	-	-	-	-	14
		F-E	-	85.09	0	100	-	-	40	90	-	-	45	90	19	90	-	87
	PIP	F-E	-	107.15	0	105	-	-	0	120	-	-	0	100	7	101	-	107
	DIP	F-E	-	66.96	0	85	-	-	5	90	-	-	0	80	6	84	-	66
Little finger	HMC	F-E	-	-	-	-	-	30	0	15	-	-	-	-	-	-	-	-
	MCP	A-A	-	-	-	-	-	-	-	50	-	-	-	-	-	-	-	19
		F-E	-	85.58	0	100	-	-	40	90	-	-	45	90	19	90	-	86
	PIP	F-E	-	98.95	0	105	-	-	0	135	-	-	0	100	7	101	-	104
	DIP	F-E	-	70.79	0	85	-	-	5	90	-	-	0	80	6	84	-	69

Pa.: palmar, Ra.: radial, amb.: ambiguous in source.

Table 10

LoA excerpt: FoIs and PSs for finger dimensioning (partial).

Improving Opposition	
Inclination of MCP Joint	Inclination of IP Joint

Table 11

LoA excerpt: FoIs and PSs for finger 1 DOF joint design (partial).

DIP Joint Mech. Design (1 DOF)
Passive hyperextension

3.2. Group “Finger”

In this section, the FoIs and PSs of the Finger Group are presented. Within the LoA, the fingers are assigned an individual Group separated to the thumb, even though some FoIs and PSs are identical. This decision has been made because the references and specific details of the PSs may differ and are relevant to emphasize. These differences are presented in the following. The full LoA table is given in Table 57.

Not all FoIs and PSs of the “Finger” Group are presented in detail due to their similarities to the “Thumb” Group. Regarding these similarities, it is noted that minor naming differences exist between the “Finger” and “Thumb” Groups. For instance, the PSs of the thumb TMC joint design are partially identical to those of the finger–MCP joint design, as the MCP joint serves as the base joint of the finger. For this Group, selected FoIs and PSs that are particularly distinct from the “Thumb” Group are presented.

In Table 11, a partial LoA excerpt with FoIs and PSs for 1 DOF finger joint design is given. Specifically, the mechanical design of DIP joints implementing hyperextension is presented. The implementation of passive hyperextension presents a notable difference to the mechanical design of thumb joints. In the thumb, the implementation of passive hyperextension could not be identified. For the DIP joints in the fingers, an extra designed DIP joint allows the passive hyperextension in grasps, to improve the contact conditions and thus the grasp. This design approach is uncommon in tendon-driven robot hands, yet can enhance performance in pinching and touching tasks. An example is given in Table 55.

In Table 10, a partial LoA excerpt with FoIs and PSs for finger dimensioning is given. Specifically, the application of inclination angles to improve finger opposition is presented. Grebenstein [51] proposes inclination angle of IP joint for the ring finger, little finger and index finger to improve opposition performance of robot hands. In the Awiwi Hand, these IP joints have inclination angles to improve opposition and power grasp of spherical objects. Too much inclination angle would cause finger overlapping and should be avoided [161]. The inclination angle of each finger is different and subject to optimization and depends on many aspects, such as thumb positioning, finger lengths and palm dimensions. For fine-tuning the inclination angles, Grebenstein [51] suggests starting with large inclination angles, balancing between overlapping issue and opposition improvement, and starting from index finger to little finger. The final adjustment should be made on the physical prototype to account for opposition compensation through the finger pad. Regarding approximate ranges, the inclination angle in the middle finger is negligibly small [67]. For the ring and little finger, inclination angles between 5°–9° and 10°–14° are specified. [51]

In Table 12, the FoIs and PSs for index finger joint configuration are presented. First, the elimination of MCP joint A–A DOF could be identified in the literature. Notably, this elimination is controversially discussed in the literature. For successful grasping,

Table 12

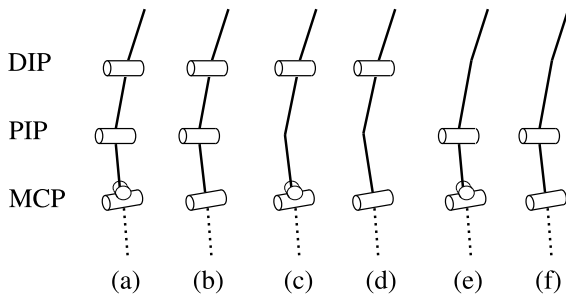
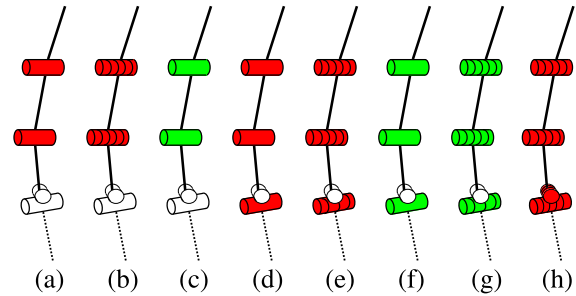
LoA excerpt: FoIs and PSs for finger joint configuration.

Elim. 1 MCP Joint DOF		
Elim. MCP Add./Abd. DOF (e.g. [26,33,34,38,39,43,51,55,56,63,65,66,71,72,75,108–110,112])		
Elim. 1 IP Joint DOF		
Elim. PIP/DIP Joint (e.g. [26,33,34,38,43,51,55–58,63,65,68,71,75,76,108,109,111–114,162])		

Table 13

LoA excerpt: FoIs and PSs for finger DOA reduction.

Elim. 1 DOA DIP-PIP Joints		
Tendon coupling of two joints (e.g. [25])	Linkage coupling of two joints (e.g. [47,66,109,164])	Linkage UA of two joints (e.g. [123,124])
Elim. 1 DOA MCP-PIP Joints		
Tendon coupling of two joints (e.g. [66])	Linkage coupling of two joints (e.g. [132,133,165])	Linkage UA of two joints (e.g. [123])
Elim. 2 DOA MCP-PIP-DIP Joints		
Linkage UA of three joints e.g. [71,74,125–127])	Tendon UA of three joints (e.g. [60,128,129])	Linkage coupling of three joints (e.g. [130])
Tendon coupling of three joints (e.g. [54])		
Elim. 3 DOA MCP-PIP-DIP Joints		
Linkage UA of three joints (e.g. [131])		

**Fig. 15.** Illustration of identified finger joint configurations: (a) 2–1–1, (b) 1–1–1, (c) 2–0–1, (d) 1–0–1, (e) 2–1–0, and (f) 1–1–0 configurations.**Fig. 16.** Illustration of identified finger joint conjunctions on a 2–1–1 configuration (red: linkages; green: tendons; striped: underactuated; unstripped: coupled): (a)–(c) DIP-PIP F–E, (d)–(g) MCP-DIP-PIP F–E, and (h) MCP A–A combined with MCP-DIP-PIP F–E conjunction.

many robot hand designs implement A–A in all fingers but middle finger [e.g. 163]. However, the complete elimination of all A–A DOF is comparably frequent in robot hand designs. Second, the elimination of DIP or PIP joint can be identified. In such instances, the joint is replaced with a constant angle between the two adjacent phalanges. An Example can be found, for instance, in the Mia Hand from Prensilia®.

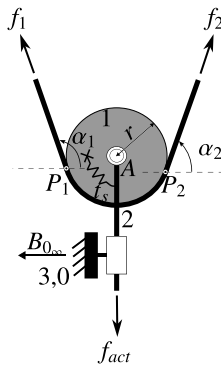
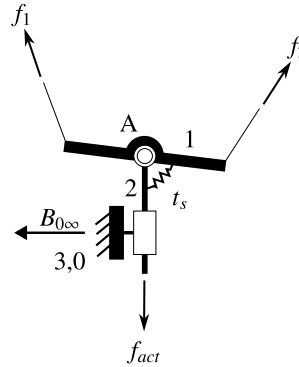
The combinations of the above identified PSs for finger joint configuration are given in Fig. 15. As illustrated, six different combinations are depicted. The setup ranges from configurations with four DOF to configurations with only two DOF. Examples from the literature can be found in the corresponding PSs of the LoA, such as [162] for configuration (f), or [72] for configuration (b). For configurations (c) and (d), no sources are captured in the LoA. However, they are illustrated for the sake of completeness, as we interpret the lack of sources as a limitation of this work rather than an indication of the absence of such finger joint configurations.

In Table 13, the FoIs and PSs for the reduction of DOA are presented. Even though the PSs are identical to those from the “Thumb” Group for reduction of DOA, the location of application is different and thus worth to mention. For the reduction of one DOA, two main principles can be found. Either the DIP and PIP joint (e.g. linkage UA [124] and linkage coupling [164]), or the MCP and PIP joint (e.g. linkage UA [124] and linkage coupling [132,133]) are connected. The former is a comparably common choice, imitating human physiology. The latter is usually combined with the elimination of the DIP joint, as presented above as a PS. For the elimination of two DOA, a tendon or linkage UA or coupling can be found in the literature, similar to those for the thumb. Further, an elimination of three DOA in finger design could be found in the literature. In the work by Tae-uk and Yonghwan [131], a spherical five-bar mechanism is proposed for a finger operation in space rather than in a plane. Thus, the A–A movement is included in the UA.

Table 14

LoA excerpt: FoI and PSs for types of underactuated interfinger mechanisms.

Type of Underactuation			
Moveable Pulley	Seesaw Bar	CDC	Hybrid

**Fig. 17.** Mechanical linkage of the underactuated mechanism movable pulley.**Fig. 18.** Mechanical linkage of the underactuated mechanism seesaw bar.

An illustration of applied DOA reduction strategies from literature are given in Fig. 16. A prominent design choice is to neither couple nor underactuate the A–A DOF in the MCP joint. Only one out of eight cases includes this DOF for a conjunction. For this one case, examples in literature are rare. Besides, four out of the eight cases involve coupling or underactuation of the F–E DOF of the MCP joint, achieved through either tendons or linkages. The remaining options focus on connecting only the DIP and PIP joints, mimicking human physiology while creating additional workspace by independently actuating the MCP joint. Examples for the given DOA reduction strategies are (from left to right) the work by Kawasaki et al. [33], Yang et al. [123], Davis et al. [138], Kyberd et al. [32], Laliberté and Gosselin [125] and Azlan and Yamaura [126] and Licheng et al. [127], Pons et al. [54], Gosselin et al. [60] and Esposito et al. [128], Ceccarelli and Zottola [129], and Tae-uk and Yonghwan [131], respectively.

3.3. Group “Transmission”

In this section, transmission related FoIs and PSs with a major focus on interfinger underactuation are presented. The previous Section 3.1 already presented the general definition of UMs and their application for joint conjunctions within a finger (intrafinger UMs). This section solely focuses on the reduction of DOAs using UMs to transmit the actuation force to different fingers (interfinger UMs). For more information on UMs and detailed calculations, it is referred to the book by Birglen et al. [102] that has been established as the main reference on that matter. To complement the work by Birglen et al. we focus in this work on the definition of PSs with reference to the literature, and the analysis of trends. All FoIs and PSs of the “Transmission” Group are shown in Table 58.

In Table 14, the different types of UMs for interfinger underactuation are presented as PSs. Based on the literature search, three PSs were identified for UMs: “Moveable Pulley”, “Seesaw Bar”, and “CDC”. All these mechanisms demonstrate promising potential in achieving interfinger underactuation and enhancing the capabilities of tendon-driven anthropomorphic robotic hands [84,102,166]. In the literature, some robotic hands incorporate a combination of UMs, specifically, of seesaw bar and movable pulley. In this review these combinations of UMs are called hybrids.

The UM movable pulley is depicted in Fig. 17. It consists of a pulley (link 1) with the radius r and a rotary joint A , around which a wire is placed connecting it to one finger on each end. The pulley is connected to a bar (link 2), which travels through a prismatic joint ($E_{0\infty}$) fastened to the frame (link 3,0). This system, therefore, has three links and two joints, resulting in two DOFs. One DOF permits translation along the prismatic joint and the other DOF enables rotation of the pulley around its pivot point. The actuator force exclusively controls the translational motion of the mechanical system. The remaining rotational DOF is constrained by integrating a spring into the pulley. When the actuator pulls down the pulley, both wire ends and consequently the fingers are pulled. However, if one of the fingers encounters an object and its movement is blocked, the respective wire’s end stops moving. Meanwhile, the other finger can continue its downward motion due to the pulleys rotational movement, allowing the wire to run along it.

The UM seesaw bar is depicted in Fig. 18. It consists of a bar (link 1) mounted on a revolute joint (A) with two wires attached to it at both ends. The revolute joint is additionally connected to a second bar (link 2) which travels through a prismatic joint $B_{0\infty}$ attached to the frame (link 3). This system has therefore three links and two joints, resulting in two DOFs. One DOF permits translation along the vertical axis and the other DOF enables rotation of the seesaw bar around its pivot point. The actuator force

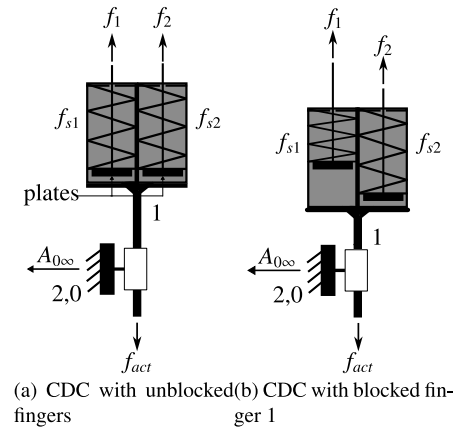


Fig. 19. Mechanical linkage of underactuated mechanism compliant differential coupling.

exclusively controls the translational motion of the mechanical system. The remaining rotational DOF is constrained by integrating a spring into the pulley. When the actuator pulls down the seesaw bar, the ends of both wires and consequently the fingers are pulled downward. However, if, for example, finger 1 encounters an object, its movement is blocked. Meanwhile, finger 2 can continue its downward motion due to the rotation of the bar. This allows the right end of the bar to move downward while the left end rotates upward in response to an applied force.

Fig. 19 illustrates the CDC mechanism presented by Massa et al. [39] in an unblocked (a) and blocked (b) configuration. It depicts a slider (link 1) which travels through a prismatic joint ($A_{0\infty}$) affixed to the frame (link 2,0). The slider consists of a solid volume containing two compression springs featured by the two spring forces f_{s1} and f_{s2} . A movable plate is attached at the bottom of each spring. The wires transmitting the respective forces to each finger, are fastened to the corresponding plate. The calculation of the DOFs reveals that a CDC mechanism has one DOF and one actuator ($n_{act} = 1$). This indicates a coupled mechanism. Nonetheless, if one finger becomes obstructed, the slider can still travel further down. This is due to the compression of the corresponding spring, as depicted in Fig. 19(b). Despite the theoretical coupling of a CDC mechanism ($n_{DOF} = n_{act}$), the inclusion of springs introduces compliance to the coupling, facilitating differential movement. This compliant characteristic enables the actuation of multiple fingers using a single actuator.

In the course of trend analysis, the frequency of occurrence is investigated. The pi-chart in Fig. 20 illustrates the percentile distribution of the number of UMs among the 29 evaluated tendon-driven robot hands. It becomes evident that the most widely used UM is the seesaw bar, accounting for 41% of the total. Following closely, the movable pulley covers 28% of the UMs, the CDC constitutes 17% and 14% utilize hybrid mechanisms (see Fig. 20).

In addition to the total frequency, the temporal accumulation is examined and illustrated in Fig. 23. Within the investigated set of robot hands, the first two interfinger UM to emerge were the CDC and seesaw bar mechanisms. In 2004, the first movable pulley mechanism was introduced. Subsequently, the development of tendon-driven robot hands incorporating one of the three UMs continued to increase over the years. The first hybrid mechanism was published in 2013. Besides the first appearances, a notable trend towards seesaw bar mechanisms is visible, with a consistent increase in publications since 2014. On the contrary, the publication of robotic hands featuring the movable pulley mechanism and CDC mechanism stagnated: The last reported instance for a moveable pulley was in 2014, and the last robotic hand with a CDC and hybrid mechanism was published in 2018. This cumulative calculation of the UM trends clearly highlights the growing preference for seesaw bar mechanisms in the design of robotic hands over the years.

One of the primary advantages of UMs is their potential to reduce the weight of robotic hands by requiring fewer actuators. Therefore, information on the involved weight depending on the applied UM is investigated. Among the 29 evaluated publications, 12 provided data on the weight of the constructed hand could be identified. Out of these, six incorporated a seesaw bar mechanism, three utilized a movable pulley mechanism, and three adopted a CDC mechanism. The weights of these hands are presented in a box plot shown in Fig. 21. Notably, the box plot for the seesaw bar mechanism indicates a maximum weight of 730 g. This substantial difference in weight can be attributed to a specific robotic hand [82], constructed using aluminum, while most other hands were predominantly 3D-printed. Additionally, it can be observed that the mean weight of robotic hands with a movable pulley mechanism is the highest. However, due to limited data and variations in reporting, a meaningful evaluation is challenging. Many reports did not provide detailed information on the components included in the weight calculation [e.g. 83,92,94]. Some reports included the motor and battery weight in their measurements [42,98], while others specifically excluded batteries and control components [64,167].

The grip force was also recorded and analyzed in the course of collecting information. 14 out of the 29 analyzed robotic hands state a measurement of grasp force. Fig. 22 illustrates a column diagram showing the grasp force for each hand, categorized by the corresponding UM. However, a conclusive comparison is not possible. It is evident that the grasp forces vary significantly for each mechanisms and robotic hands with CDC mechanisms are too few to draw conclusions. The wide variation in grasp force can be attributed to the absence of a standardized test procedure [168], the diversity of grasp types and the way grasp force is measured.

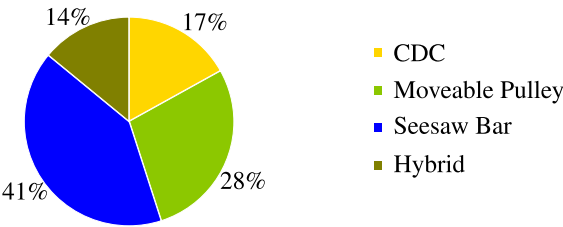


Fig. 20. Percentile distribution of underactuated mechanisms among the 29 evaluated tendon-driven robotic hands.

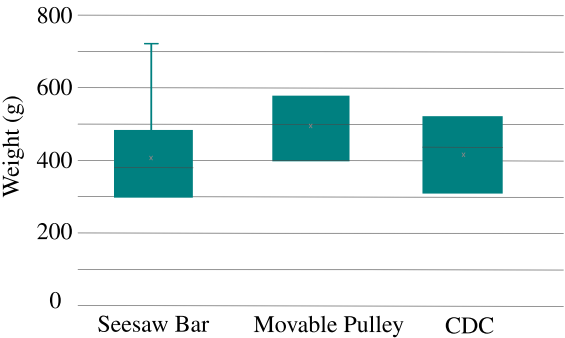


Fig. 21. Box plot illustrating the weight distribution in grams on the y-axis for the three underactuated mechanisms: seesaw bar, movable pulley, and compliant differential coupling.

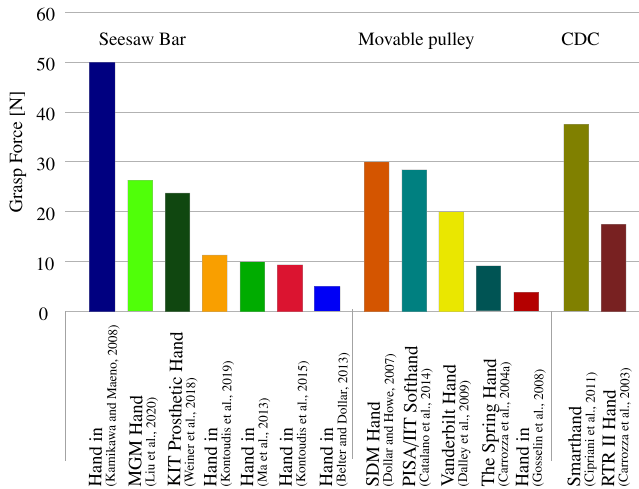


Fig. 22. Grasp force of various underactuated robot hands, categorized by applied underactuated mechanism. The data are aggregated from the literature under non-standardized test conditions, and the results should therefore be interpreted qualitatively (see [42,45,60,64,80,82,83,89,90,92,95,97,98,167]).

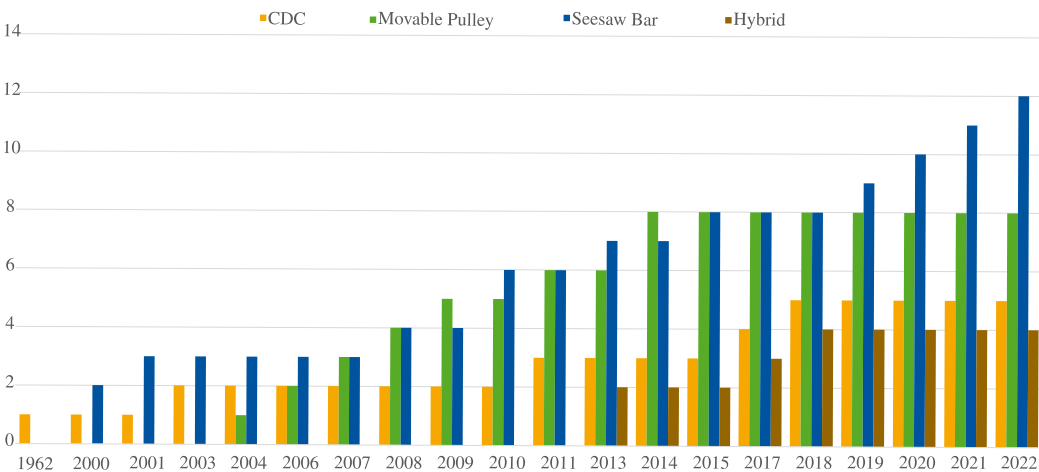


Fig. 23. Cumulative Development of Underactuated Mechanisms from 1962 to 2022.

Table 15

LoA excerpt: FoIs and PSs for elimination of DOAs in transmission.

Eliminating 1 DOA		
Tendon Underactuation F-E LF-RF	Tendon Underactuation F-E MF-IF	
Eliminating 2 DOA		
Tendon Underactuation F-E LF-RF-MF	Tendon Underactuation F-E RF-MF-IF	Tendon Coupling A-A LF-RF-IF
Eliminating 3 DOA		
Tendon Underactuation F-E LF-RF-MF-IF		
Eliminating 4 DOA		
Tendon Underactuation F-E LF-RF-MF-IF-Tb	Tendon Underactuation/Coupling F-E LF-RF-MF-IF-Tb	Tendon Underactuation A-A LF-RF-MF-IF-Tb

Furthermore, the grasp force and therefore output force of the transmission system is a function of the input actuator force [102], which is often not given [89,95].

The number of eliminated DOA is used interchangeably with the number of underactuated fingers in this work. Specifically, the underactuation of n fingers corresponds to a reduction of $n - 1$ DOAs. Therefore, it is assumed that the application of a single UM allows two outputs with a single input and thus reduces one DOA, regardless of the nature of the output (A–A, F–E). In case of F–E, most often, the respective finger applies intrafinger underactuation and has, thus, a single tendon for the complete finger F–E. However, this is no requirement for the application of interfinger underactuation and, therefore, the reason for the separate consideration of inter- and intrafinger underactuation.

In Table 15, the PSs and FoIs for the elimination of DOA are presented. An interesting observation includes the differences in number of finger and chosen finger. This is in particular the case for the elimination of one and two DOA. All FoIs are given in more detail in the following.

The elimination of one DOA involves the conjunction of two fingers. The decision to underactuate two fingers in certain robotic hands is driven by specific goals. For example, Dalley et al. [83] aimed to achieve maximum continuous grasp force, while Wiste and Goldfarb [94] sought to simplify control and mechanical structure. The RTR II hand by Massa et al. [39] was designed with a total of three fingers, including the thumb. Therefore, in this design, the two fingers, apart from the thumb, were underactuated to enhance the hand's adaptability to the shape of objects.

The elimination of two DOAs involves the conjunction of three fingers. Two different combinations could be found for the underactuation of three fingers. In the work by Cipriani et al. [85], the conjunction of LF, RF and MF is argued based on a statistical investigation of the human hand. The study by Ingram et al. [169] revealed that the thumb is the most independent finger, followed by the index finger, which led to the decision of underactuating the middle, ring, and little fingers. This approach was also supported by Kyberd et al. [32], who provided a similar rationale for underactuating these particular fingers (the ability to pick up small objects with the index finger and thumb). Besides underactuation, a tendon coupling could also be identified in the literature.

The elimination of three DOAs is the most common choice and involves an underactuation of all fingers but the thumb. In this configuration, an additional actuator is dedicated to the thumb [78,92,100]. Possibly, further actuators are considered in the robot hand to enable A–A movements, enhancing dexterity [97].

The elimination of four DOAs incorporates the thumb in the conjunction. All captured robot hands with four underactuated fingers did not include the thumb in the underactuation but coupled it directly to the actuator, enabling the use of a single actuator to control all five fingers. This design approach aims to achieve a simpler and lighter robotic hand [45,60,81,84]. However, other designs exist that apply an underactuation that incorporates the thumb for F–E [69] or A–A [73]. In every case, the thumb requires particular attention in terms of its force. Since the thumb functions as a counterpart to the other fingers, it should be capable of generating a force equal to the sum of the forces of the rest of the fingers [60].

To date, there is no defined standard for a correct number of underactuated fingers for a robotic hand. Therefore, an analysis is performed to understand common choices and trends. The number of underactuated fingers and therefore decreased number of actuators is a balance between performance, complexity and therefore cost [83]. In Fig. 24, a piechart illustration of the distribution of the number of underactuated fingers is given. It is apparent that 55% of the 29 evaluated hands feature four underactuated fingers. Additionally, 17% of the hands have five underactuated fingers, while 14% have three, and another 14% have two underactuated fingers. Another analysis of the implemented UM in dependency of the number of underactuated fingers is given in Fig. 25. The distribution of UMs is depicted across various numbers of underactuated fingers in the evaluated robotic hands. Among the hands with five underactuated fingers 40% utilized a seesaw bar mechanism, another 40% employed a movable pulley mechanism and 20% used a combination of both which in review are called hybrids. For the hands with four underactuated fingers 50% opted for a seesaw bar mechanism, while 19% utilized movable pulleys, another 19% used hybrids and 13% incorporated a CDC mechanism. Among the hands underactuating three fingers, half implemented a seesaw bar mechanism, and the remaining two quarters were divided between movable pulleys and CDC mechanisms. Lastly, for the hands with two underactuated fingers, half integrated a CDC mechanism, and the other half utilized a movable pulley mechanism. This graph allows to observe the variations in UMs chosen for different numbers of underactuated fingers in the evaluated robotic hands but also clearly demonstrates the dominance of the seesaw bar mechanism.

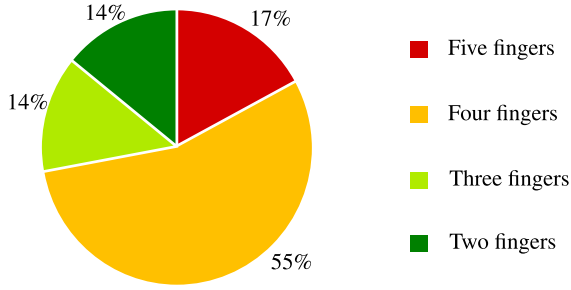


Fig. 24. Percentile distribution of the number of underactuated fingers among the 29 evaluated tendon-driven robotic hands.

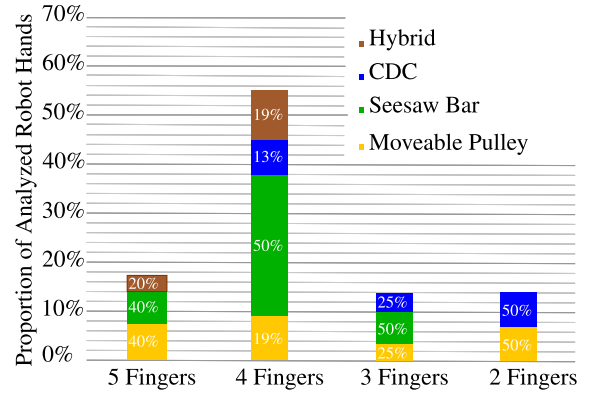


Fig. 25. Quantity of underactuated number of fingers in [%] including the distribution of underactuated mechanisms.

Table 16

LoA excerpt: FoI and PSs for transmission architecture for interfinger UM.

Transmission Tree

Parallel	Serial	Hybrid
----------	--------	--------

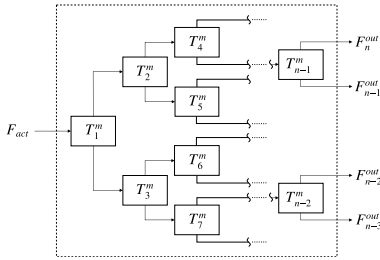


Fig. 26. Strictly parallel force transmission tree.

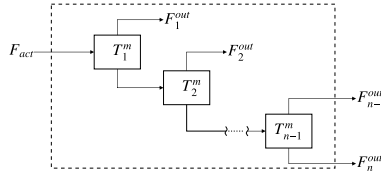


Fig. 27. Strictly serial force transmission tree.

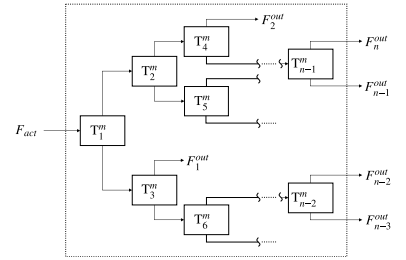


Fig. 28. Force transmission tree combining serial and parallel layouts.

The FoI “Transmission tree” includes different PSs for the architecture of multiple UMs for underactuation of multiple fingers. In order to generate n outputs, two different types of transmission trees are possible: Parallel transmission trees or serial transmission trees [102]. Alternatively, a combination of both can be applied, labeled here as a hybrid transmission tree. The different architectures are generally applied for movable pulleys and seesaw bars. The CDC mechanism can be easily resized, by adding further springs, to underactuate a greater number of fingers and does not require such a transmission architecture. These architectures are illustrated through force transmission trees in , respectively. The transmission architectures are explained in more detail in the following (see Table 16).

A parallel transmission tree consists of several UMs arranged in parallel stages. Each UM is defined by a corresponding force transmission matrix T_n^m . The superscript m describes the general consideration of UMs. (The UM specific definitions of transmission matrices are presented in the work of Birglen et al. [102]). Each UM generates two output forces which are transmitted to the next UM. The output forces crossing the system boundary are marked with the upper index *out* and represent the forces transmitted to the fingers of a robotic hand. n output forces require $n - 1$ UMs.

A serial transmission tree consists of several UMs arranged in serial stages. Each UM generates two output forces: one that crosses the system boundaries, marked with the upper index *out* and another that is transmitted to the subsequent UM. This leads to the fact that if the UM in the first stage evenly distributes the input force to both output forces, the output force F_1^{out} equals the sum of the rest of the output forces. Just like for parallel transmission trees, in order to achieve n output forces, $n - 1$ UMs are required.

The choice of transmission tree layout in robotic hands depends on multiple factors, including the number of fingers to be underactuated and requirements on force distribution. A strictly symmetrical parallel transmission tree enables force isotropy [102]. Conversely, force isotropy is not achievable with a serial layout. However, a serial layout becomes suitable when one of the output forces F_1^{out} must equal the sum of the remaining output forces, which is usually the case for the thumb. A combination of both transmission types (see Fig. 28) is thus a common choice to combine both characteristics.

Table 17

LoA excerpt: FoI and PSs for adaptation.

Adaptation		
Soft Tissue/Pads	Filled Pads	None

Table 18

LoA excerpt: FoI and PSs for contact material.

Contact Material		
Silicon	Polyurethane	Vinyl

Table 19

LoA excerpt: FoIs and PSs for proportion of covered area.

Proportion of Covered Area		
Full Finger cover	Gloves	Partial Cover
Fingertips		

Table 20

LoA excerpt: FoI and PSs for surface textures.

Surface Texture		
Fingerprints	Hexagonal Pillars	Flat

3.4. Group “Covering”

This section takes a closer look at the Group “Covering” and presents the FoIs and their PSs. The results are summarized in [Table 59](#). As already mentioned in Section 2, only a few studies could be found that explicitly investigated coverings for robotic hands. In most studies, the contact surface is only briefly mentioned or not mentioned at all.

Adaptation

The FoI “Adaptation” includes PSs for the level of flexibility and adaption of the contact material (see [Table 17](#)). The PS “none” does not imply the complete absence of covering, but the application of a thin layer of material that does not allow adaptation. It is often used to increase friction [118]. Further, for covering pads that allow adaptation, it is distinguished between pads made of one material and filled pads. Filled pads have the advantage that the contact material can be selected according to friction properties and the filling material according to compliance properties. This type of covering was investigated in the work of Shimoga and Goldenberg [104] and later in the work by Controzzi et al. [107]. For pads made of one material, the selected material must have a suitable coefficient of friction as well as good compliance. These pads can be found in the work of Grebenstein [51], the UB-Hand by Lotti et al. [170] and in the work by Biagiotti et al. [106].

Contact material

The FoI “Contact Material” refers to the selected material used for the covering (see [Table 18](#)). Construction materials such as rigid plastics and metals are not taken into account, but only those that are explicitly used as housing to improve contact properties by adding extra layer. In the literature, it is often unspecifically referred to “rubber”. If explicitly mentioned, specified materials are Polyurethanes (PU) [51,170], silicones [171,172], or vinyl [173]. PU and silicone are elastomers and can be cast in molds for production and are available in several strength levels (Shore hardness). A specification of which hardness was used could not be found.

Proportion of covered area

The FoI “Proportion of covered area” includes which areas are additionally covered with such a contact material (see [Table 19](#)). In some works, such as the one by Grebenstein [51], a glove is applied over the hand, thereby covering the entire hand. For the UB-Hand by [170], on the other hand, only the fingers are covered with PU. Further, in other works, such as by Butterfass et al. [120], only individual areas of the hand are provided with pads. Last, a PS is identified for the sole covering of the fingertips [e.g. 3,106,137].

Surface Texture

The FoI “Surface Texture” includes PSs for the application of textures on an applied covering (see [Table 20](#)). Studies could be found for the influence of textures on covering layers. For example, in dry conditions, it is established that smooth surfaces without textures benefit the holding force better than textured surfaces. However, in wet conditions, a textured surface has a strong advantage, as the liquid can be forced into the gaps of the textures to maintain direct contact, comparable to the tread of a car tire [174].

The Group “Covering” reveals a problem with implicit knowledge, as many works lack clear information on that aspect. This makes it hard to draw precise conclusions about the effects of different PSs. For example, while textured surfaces are known to perform better than smooth surfaces under wet conditions, not enough information could be collected that allow a comparison of materials, such as PU and silicone, or strategies, such as filled or flat pads.

Table 21

LoA excerpt: FoIs and PSs for KBC joint configuration.

Eliminating 1 HMC Joint DOF		
Eliminating RF HMC joint (e.g. [51])	Implementing joined LF–RF HMC joint (e.g. [109,118])	Eliminating joined IF–MF HMC joint (e.g. [163,175])

Table 22

LoA excerpt: FoIs and PSs for KBC underactuation and coupling.

Eliminating 1 DOA HMC Joint		
Linkage Underactuation HMC–MCP Joints (e.g. [118,120])	Linkage Coupling HMC–MCP Joints (e.g. [72])	Linkage Coupling Grebenstein [51]

3.5. Group “Kinematic Base Chain”

In this section, the FoIs and PSs of the Group “Kinematic Base Chain” are presented. The complete Group is summarized in Table 60. This Group is established to highlight FoIs and PSs towards the synergy and allocation of the individual components. Further, it involves FoIs and PSs for the palm design, as the common basis of a robot hand.

Joint Configurations

In Table 21, the FoIs and PSs for the elimination of HMC joints are presented for the KBC Group. HMC joints can be argued to belong to the respective finger and should thus be considered in the respective Group of the LoA. However, in this work, they are considered in the KBC Group as they are located in the palm, can be assigned to more than one finger and are frequently considered for the cupping movement of the palm.

The general relevance of HMC joints is discussed in multiple works. Konnaris et al. [72] propose two additional HMC joints for ring- and little finger to achieve palm-arch capabilities. Similarly, Grebenstein [51] propose a LF HMC joint for the Awiwi Hand to improve the grasp of small spherical objects. Including an HMC joint, the workspace is turned inward and, thus, the opposition with the thumb is improved. The considered HMC joints, as introduced in Fig. 4, represent the options found in literature.

The identified PSs for the elimination of 1 HMC joint DOF include three options. The first PS describes the elimination of the joined IF–MF HMC joint. This is the most common choice, considering the low number of robot hands that apply HMC joints for IF and MF. In the course of this study, no robot hand with individual HMC joints for IF and MF could be identified. However, examples such as the MSR Hand by Lee et al. [176] performed successfully all Feix grasps and the Kapandji test with a joined IF–MF HMC joint. The second PS describes application of a joined LF–RF HMC joint, found in MSR Hand or in the MCR Hand II [109]. The third PS describes an elimination of RF HMC joint, as found in examples such as the Awiwi Hand [51]. Similarly, Yang et al. [109] and Zhang et al. [118] propose a palm design split into two parts using a single joint at HMC base between ring- and middle finger. No consideration of HMC joints (elimination of three HMC joint DOFs) is the most common choice in robot hand designs. Examples include the iCub Hand Serie [108,138], ACB Hand [175] or ISR Alpha Hand [177].

Underactuation/Coupling

In Table 22, PSs are presented for the elimination of DOAs through underactuation or coupling. Three PSs are collected for eliminating 1 DOA at HMC joints: First, a linkage underactuation of the HMC with the corresponding MCP joints is identified in literature. For example, in the work by Ambrose et al. [28], the underactuated palm is able to cup in a human-like way without the fingers colliding. Similarly, Zhang et al. [118] apply an underactuated DOF at the palm that relies on ring and little fingers' flexion. Second, a linkage coupling of the HMC joint with the corresponding MCP joint could be identified. Konnaris et al. [72] propose two HMC joints of ring- and little finger in the dorsal region of the palm. Both of them are directly coupled with the Flexion/Extension MCP joint. And last, a special linkage coupling is identified in the work by Grebenstein [51]. In that work, the authors propose a linkage coupling where the mechanism connect the little finger with the ring finger at HMC joint position. The mechanism enables a nonlinearly coupled inward rotation of the little finger by avoiding collision of the little finger with the ring finger. The classification of this PS can be argued. On the one hand, the mechanism does not reduce a DOA of the HMC joint and could thus be understood as a mechanical joint design instead of a coupling. On the other side, the mechanism establishes a dependency of one movement with another, which is a crucial characteristic of a coupling and/or underactuation.

Mechanical Design

The mechanical design includes the HMC joint design and the palm design (see Table 23). The mechanical design of HMC joint can be categorized into open hinge joint and closed hinge joint with the same definition as introduced in Section 3.1. Examples for open and closed hinge HMC joints can be found in the work by Konnaris et al. [72] and Zhang et al. [118], respectively. The mechanical design of the palm includes a single PS, which is collected for the sake of completeness. Throughout this paper, only rigid flat palms could be identified. On the one hand, this is an obvious solution. On the other hand, for a designer seeking orientation in the FoIs and PSs of the LoA, it is valuable to note that no designs implementing a (partly) flexible palm in tendon-driven robot hands for the cupping movement could be identified. Although some works contribute to this result, they are not considered here in the palm design, as it is not specifically intended. For example, the implementation of HMC joints represents one such contribution. Additionally, there are mechanical palm designs with rigidly implemented cupping. For instance, the DLR-HIT-Hand II by Liu et al. [34] features a design with a thenar that mimics a cupped hand. However, this feature results from a strategic implementation of the TMC joint to eliminate one avoidable DOF in that specific configuration.

Table 23

LoA excerpt: FoIs and PSs for KBC mechanical joint design.

Mechanical HMC (CMC) Joint Design

Closed hinge joint	Open hinge joint
Mechanical Palm Design	
Flat Rigid Surface	Bent Rigid Surface

Table 24

LoA excerpt: FoIs and PSs for KBC dimensioning design.

HMC/MCP Joint Position

Anthropomorphic relations		
TMC Joint Position		
Isobe	Euler-angle	Angled towards palm and finger
Opposing to fingers	Variable positioning	Grebenstein et al.
Anthropomorphic position		

Dimensioning

For dimensioning in palm design, the positioning of the HMC, MCP, and TMC joint(s) are important FoIs. It can be concluded that no unique values could be identified in the course of this study for the positioning of HMC, MCP and TMC joints. In contrast to the lengths of the phalanges, as discussed in Section 3.1, the positioning of the base joints is not generally described in the literature. The required dimensions are either not labeled, or not further specified or not parametrically defined. While relationships between the lengths of the phalanges and the hand length already exist, such data for the positioning of the base joints could not be identified. Therefore, roboticists use various methods to identify or approximate these positions.

For HMC and MCP joint positioning, the information given in publications provide initial indications for optimizations. Often, existing dimensions from other robot hands or the own hand dimensions are adapted and optimized through prototyping iterations. Alternatively, the MRI-based models by van der Smagt and Stillfried [178] (also 2009,2010,2014) allow precise localization of joint positions, offering the advantage of avoiding soft tissue displacement during measurements. However, these models lack parametrized data, and their descriptions are insufficient for direct technical application. Additionally, they are based on 50–100 scans of a single hand, limiting their generalizability. Further, van der Hulst et al. [159] developed a comprehensive model including relevant HMC joints, described using Denavit–Hartenberg matrices. While this approach allows for parametrized adaptation to different hand sizes, key parameters for joint positioning remain undefined. Last, Peña-Pitarch et al. [156] also present a model incorporating 25 DOFs, with detailed parametrization for distances. However, similarly, important vector lengths remain undefined. The parametric definition of these positions remains a challenge in robot hand design.

For TMC joint positioning, various approaches are proposed in the literature to identify a suitable position. The identified approaches are given as PSs in Table 24. The approaches vary from guidance to practical instructions. They are described in more detail in the following.

The first PS is identified in the work by Kawasaki et al. [38]. In 1985, Y. Isobe made two observations based on the human hand that can be used to infer a possible placement of the thumb for robotic hands [145]: The first observation is that if all fingers and the thumb are spread out, all fingertips are on the circumference of a circle. The radius of the circle is proportional to the length of the middle finger. Secondly, the vertical axis of the palm represents the center line of the middle finger. A line extending from the MCP joint of the index finger to the MCP joint of the little finger intersects the vertical axis at an angle of 75 degrees. An application example can be found in Table 50.

The PS “Euler-angle” is identified in the work by Wang et al. [112] and Wang et al. [182]. In their work, the authors propose a method for determining the position of the thumb on the palm through the Euler Theorem on the Finite Rotation of a Rigid Body. They assume that most typical grasps related to the thumb could be accomplished through two sorts of postures: One is for Tip, Palmar and Lateral grasp, the other is for Cylindrical and Spherical grasp. Based on Euler’s Theorem on the Finite Rotation of a Rigid Body, any arbitrary finite rotation of a rigid body about a fixed point O can be achieved by a finite rotation about a specific axis passing through O . Similarly, the transition between posture 1 and posture 2 of the thumb can be accomplished by a finite rotation about a determined axis. A detailed description on design and its application on revised DLR/HIT Hand II are explained in Table 51.

The PS “Angled towards palm and finger” is identified in multiple works [66,71]. This refers to the positioning of the thumb at specific pre-defined angles relative to the other fingers and the plane of the palm to facilitate opposition movement. Examples with data are detailed in Table 52.

The PS “Various positioning” refers to a set of working solutions. These TMC joint positions cannot be uniquely defined due to design varieties but show successful anthropomorphic performance [46,61,77]. In Table 53, two examples of each research-based robotic hand and commercial prosthetic hand will be discussed.

The PS “Grebenstein et al.” refers to a practical method to identify a suitable TMC pose. The method proposes the creation of a preliminary kinematic paper model for functional understanding. The paper model is then evaluated using a defined set of grasps

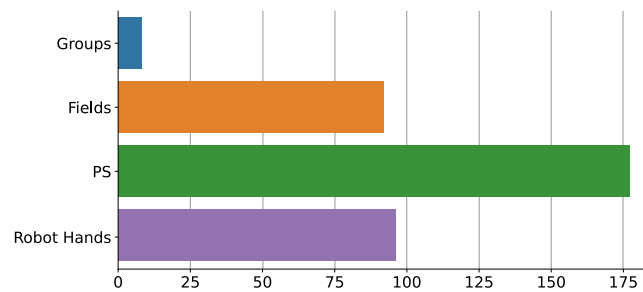


Fig. 29. Quantitative numbers for the Library of Approaches.

and iteratively improved until the performance is satisfying. Given the pivotal role of the thumb in human hands, the position and arrangement of the TMC joint axes are tested in a series of combinations: (1) Thumb base joint located within the palm, (2) Thumb base in front of the palm, (3) Thumb axes of TMC orthogonal, (4) Thumb axes of TMC non-orthogonal. The Kapandji test [183] is deployed for evaluating opposition performance of different TMC joint positioning. Observations and results are discussed in Table 54.

The PS “Anthropomorphic position” refers to the application of human-like dimensions. This approach is typically based on the goal of designing a robotic hand that resembles the geometry of a human hand [145]. It is argued that developing a definitive kinematic structure is challenging and that, in reality, no optimal solution exists. Using this approach, roboticists use the average dimensions of an adult human hand for positioning the fingers and thumb. For instance, the Kinematic Humanoid Hand [55], the EthoHand [72], the ACT Hand [57], the HBA Hand [70], and the UoW/ACES Hand [74] initially base the positioning and orientation of the thumb on average values, which are then experimentally adjusted to meet specific requirements.

4. Conclusion

The main objective of this article is to provide a convenient initial source of references for the early mechanical design of anthropomorphic robot hands. For that purpose, a systematic mapping is applied to capture approaches for the mechanical design in form of PSs, without claiming any completeness. The information is structured in morphological boxes for intuitive illustration, allowing an interested reader to conveniently screen this study for relevant information. We hope that prospective designers will find the presented information and reference to original work useful.

No equivalent database could be found in literature, although similar approaches can be found. For example, in the review by Piazza et al. [1], a large database can be downloaded in a pdf format. It contains a large collection of robot hands, their DOAs, their DOFs and other key data. However, no database could be found that pursues the same goal and is available online, interactively accessible and extensible.

In the course of this review, a large number of different robot hands, assemblies and research fields of interest for anthropomorphic tendon-driven robot hands were analyzed. To limit the scope of this work, only anthropomorphic tendon-driven robot hands were analyzed. Furthermore, only the mechanical design of the robot hand is considered, resulting in the exclusion of any electro-mechanical aspects and software-related information. Therefore, sensors, actuators and control aspects are not part of the evaluation. Additionally, the mechanical design of the wrist and the design of a forearm or any form of external drive-unit are not considered either. In Fig. 29, the total numbers of identified categories is illustrated: 87 robot hands, 8 Groups, 92 Fols, 110 authors with 147 references and 177 PS.

To keep this study concise, we refrain from providing a detailed comparative analysis of thumb and finger joint configurations. While such an analysis would be highly valuable, it exceeds the scope of this work and warrants dedicated studies of its own. Previous work has already demonstrated this need, for example Wang et al. [112] for thumb configurations. In a previous study [7], we compared the joint configurations of successfully evaluated robot hands. Since we found substantial differences even among qualitatively equally evaluated hands, we concluded that dedicated quantitative comparative evaluations are required. We hope that the present neutral overview of existing thumb configurations will support such future work.

Due to the focused nature of our systematic approach, certain gaps in the identified PSs are inevitable. At the beginning of this study, it was established that identifying the totality of approaches for mechanical design within a single study is unlikely. Instead, the aim was to collect a representative selection of literature covering various foci. However, the targeted search for robotic hands with a specific focus or contribution inevitably results in certain foci being omitted, if they have not been addressed in previous iterations of a robotic hand. For example, the authors observed that PSs for intrafinger underactuation are missing. While this aspect was conceptually covered, no detailed PSs for underactuated mechanisms were documented. This observation should be understood both as a limitation of the study and as a reinforcing argument for our efforts to structure the data in an extendable manner. Once again, we encourage readers to contact us with potential extensions in the form of additional sources, PSs, and Fols.

The identified PS can be utilized in various ways for future work. Primarily, the collection of PS, along with links to the respective references, presents a convenient guidance for future designers. The LoA allows them to quickly and easily identify key aspects of mechanical design and access relevant literature to deepen their understanding. Besides, future work can use the presented

results for a systematic review. Within such, literature can be sought regarding certain PS, and the PS can be both qualitatively and quantitatively assessed and compared. Third, the derived PS can be used to classify for the first time robot hand designs regarding their design. Currently, popular choices for comparison of robot hand designs include aspects related to the form (e.g. size, weight, number of finger), features (e.g. implemented sensors) or performance (e.g. number of successful grasps from the taxonomy by Feix et al. [184]). [185] Last, we work on an automated task-based design assistance system using the LoA. With a defined compatibility matrix, feasible conceptual designs are created through the automated combination of PSs with the defined joint configuration in Fig. 4. Simultaneously, each PS is evaluated regarding a set of defined criteria, leading to a certain score for each of the derived conceptual designs. Based on a user input, the scores are modified and the assistance system selects the most suitable design.

Analyzing the collected information, several open challenges in the mechanical design of anthropomorphic robot hands can be identified. Firstly, the neutral presentation of different joint configurations found in literature illustrates the variety of options. It is evident that no unique solution exists for the joint configuration of the robot hand. In particular, multiple solutions for the design of the thumb can be found in the literature, often yielding similar results in evaluations of grasping performance. Quantitative measures are necessary to differentiate these similar outcomes, as the prevalent use of the Kapandji Test and Feix or Cutkosky Taxonomy currently relies on qualitative evaluations. However, works such as that by Wang et al. [112] provide a solid foundation for future research. For the application of HMC joints, however, such analyses are notably absent. Second, no definitive rule for the application of underactuation or coupling could be identified. While intrafinger underactuation is commonly adopted, the application of interfinger underactuation remains diverse. Establishing a unique solution for interfinger underactuation is challenging, as the proposed approach must depend on the intended objective. For instance, in-hand manipulation likely demands more individual finger movements than static grasping. Moreover, as multiple solutions for interfinger underactuation may achieve the same grasp, additional quantitative measures are needed to distinguish between different methods. Third, a significant portion of knowledge remains implicit. Much information about mechanical design is not explicitly published, as these details are often derived from practical experience rather than significant contributions to the field, making them less likely to appear in high-quality publications. Establishing a centralized framework for collecting such information could serve as a valuable resource, enabling researchers to share these insights. Fourthly, dimensioning poses a critical bottleneck in the design of anthropomorphic robot hands. Roboticists often derive dimensions from their own hands, other robot hands, or literature values, which are then subject to iterative optimization. Ideally, all dimensions would be parametrically defined in relation to hand length and width, enabling easy reuse and adaptation. Currently, however, such standards have not been established and remain challenging, considering the great variety of functional dimensions in humans. Lastly, task-based design remains an open challenge and is closely related to the first and second point. The central question is which joints to include and how to coordinate them to achieve a minimal DOA design tailored to a defined set of tasks. Studies, such as the one by Tavakoli et al. [186], offer suggestions for underactuations for each grasp in Feix's taxonomy. However, relevance of joints is not discussed. Studies, such as the one by Saliba et al. [187], investigate the relevance of joints in anthropomorphic hands, but do not analyze their relevance in the context of specific tasks.

CRediT authorship contribution statement

Daniel Gossen: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Tianyi Jin:** Writing – review & editing, Writing – original draft, Visualization, Software. **Sebastian Polzin:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. **Mark Witte:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. **Eugen Schustermann:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. **Ana Laura Urzua:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. **Clément Gosselin:** Writing – review & editing, Supervision, Conceptualization. **Mathias Hüsing:** Writing – review & editing, Supervision, Conceptualization. **Burkhard Corves:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Daniel Gossen reports financial support was provided by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Funding: This work was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC-2023 Internet of Production – 390621612.

Appendix A. LoA examples

See Tables 25–55.

Table 25

LoA examples: Thumb - elim. 1 TMC P-S DOF.

Elim. 1 TMC Joint DOF	Elim. TMC P-S DOF
2-2-1 configuration (10 (a))	
The 2-2-1 (10 (a)) configuration type has been proposed and discussed in detail in the work by Wang et al. [112]. For further information, readers are referred to the work by Wang et al. The 2-2-1 configuration is defined by simplifications of the TMC joint and closely resembles the human thumb in terms of DOF, although it is more challenging to implement. As a result, this configuration is comparably uncommon to find. [112]	
Shadow Hand [113], CEA Dexterous Hand [114], UB Hand 3 [170]	

Table 26

LoA examples: Thumb - elim. 1 MCP A-A DOF.

Elim. 1 MCP Joint DOF	Elim. MCP A-A DOF
3-1-1 configuration (10 (c))	
The 3-1-1 (10 (c)) configuration type has been proposed and discussed in detail in the work by Wang et al. [112]. For further information, readers are referred to the work by Wang et al. The TMC joint's critical role in enabling the thumb's axial rotation is incorporated in this design to specifically support pronation. This design allows all pronation-related mechanisms in the IP and MCP joints to be disregarded, effectively giving the TMC joint three DOFs. According to Wang et al. no robotic hand with this configuration had been developed, due to the challenges of realizing a compact structure that maintains functional appearance and size. However, in the course of this work, the Ethohand [72] was identified, being published after the study by Wang et al. was conducted. The Ethohand incorporates a three DOF ball joint for the TMC joint. Notably, however, efforts in this work to replicate the Ethohand's ball joint design failed, as the third DOF is highly restricted by the tendon routing. This highlights the design challenges.	
Ethohand [72]	

Table 27

LoA examples: Thumb - elim. 1 TMC P-S and 1 MCP A-A DOF [188–191].

Elim. 1 TMC Joint DOF	Elim. TMC P-S DOF
Elim. 1 MCP Joint DOF	Elim. MCP A-A DOF
2-1-1 configuration (10 (c))	
The 2-1-1 (10 (b)) configuration type has been proposed and discussed in detail in the work by Wang et al. [112]. For further information, readers are referred to the work by Wang et al. The 2-1-1 configuration is characterized by simplifications in both the MCP and TMC joints, combining the approaches of the 3-1-1 and 2-2-1 configurations. This configuration offers a lower number of DOF, simplifying both structure and control. Consequently, the majority of thumb configurations in advanced robotic hands utilize this configuration type. A total of 20 robot hands that apply the 2-1-1 configuration have been identified in the literature. [112]	
DLR Hand Serie [25,34,120], DexHand [188], UTAH/MIT Hand [19], Gifu Hand Serie [33,38], NAIST Hand Serie [115,121], TUAT/Karlsruhe Hand [30], TWENDY-ONE Hand [119], Awiwi Hand [51], iCub Hand [63], DARPA Intrinsic Hand [189], DEXMART Hand [65], UBH-IV Hand [116], Robonaut 2 Hand [47], DARPA Extrinsic Hand [190], ARTS Hand [191]	

Table 28

LoA examples: Thumb - elim. 1 TMC P-S and 2 MCP DOF [192].

Elim. 1 TMC Joint DOF	Elim. TMC P-S DOF
Elim. 2 MCP Joint DOF	Elim. MCP joint
2-0-1 configuration (10 (d))	
The 2-0-1 (10 (d)) configuration type is inspired by the surgical procedure known as MCP joint arthrodesis. Arthrodesis is typically recommended for patients with severe arthritis, instability, or deformity of the MCP joint, conditions commonly associated with rheumatoid arthritis. Due to the limited angular movement of the MCP joint in routine activities and grasps, surgeons have found that stiffening the MCP joint can effectively reduce pain while preserving functional grasping ability. [192] Technically implemented in a robot hand, this specific configuration has only been observed in the TU hand [76,111]. In this configuration, the MCP joint's DOF is reduced from two to zero, fully immobilizing it at 10 degrees of flexion and 15 degrees of abduction [76,111]. Analysis of this design shows approximately a 50 percent reduction in the thumb's workspace volume compared to an unstiffened thumb, with the restricted movement primarily affecting positions that bring the thumb close to the palm — a motion that is considered infrequent in daily tasks according to the authors [111]. Additionally, the reduction in joint count compared to conventional robotic thumbs notably decreases both cost and structural complexity, as highlighted by the authors [76,111].	
TU hand [76,111]	

Table 29

LoA examples: Thumb - elim. TMC P-S and F-E and MCP A-A DOF.

Elim. 2 TMC Joint DOF	Elim. TMC F-E, P-S DOF
Elim. 1 MCP Joint DOF	Elim. MCP A-A DOF
1-1-1 configuration (10 (c))	
The 1-1-1 (10 (e)) configuration type comprises three DOF. It could only be found in the following two robot hands: The UT Hand I [66] and the RTR II Hand [39]. In both hands, the thumb is oriented at a specific angle relative to the palm and the other fingers. The A-A movement for the opposition of the thumb is achieved through a TMC joint with a single DOF. The F-E movement of the thumb is achieved through the MCP and IP joints.	
UT Hand I [66], RTR II Hand [39]	

Table 30

LoA examples: Elim. 1 DOA - tendon coupling.

Elim. 1 DOA MCP-PIP joints	Tendon coupling of two joints
In the DLR/HIT Hand II [34], the thumb exhibits three DOF. The final two joints are mechanically coupled to one another. The coupling mechanism in the MCP and IP joints of the thumb is achieved through the use of a steel wire with a tensioning mechanism. The utilization of the steel wire ensures the transmission of force in the thumb is both flexible and secure. The coupling mechanism precludes the possibility of controlling the movements of the proximal and distal phalanges individually. The transmission ratio between them is precisely 1:1 throughout the entire range of motion [34].	
DLR/HIT Hand II [34]	
Berselli et al. [134] coupled the MCP and the IP joint with one of the drive tendons. This coupling restricts the movements of the two joints in analogy to the human hand. This tendon is not connected to an actuator, but is attached to different phalanges at both ends.	
No robot hand name	
The rotation of the IP joint of the thumb of UT Hand I [66] is also flexibly coupled to the rotation of the MCP joint via a tendon coupling. The apparatus comprises a connection of two crossed nylon ropes, guided around two pulleys. The crossed cables enable bidirectional coupling of the angle of the distal phalanx. The transmission ratio is defined by the radius ratio and is set to 2:1 by Peerdeman et al. [66]. The advantage of this configuration is that the compliance of the tendon coupling also contributes to a more flexible grip. [66]	
UT Hand I [66]	

Table 31

LoA examples: Thumb: Elim. 1 DOA - linkage coupling.

Elim. 1 DOA MCP-PIP joints	Linkage coupling of two joints
In the MCR Hand II [75,109], the movement of the IP joint is coupled with that of the MCP joint via a four-bar linkage. This implies that the angle of the IP joint is a passive degree of freedom, undergoing alteration in accordance with the angle of the MCP joint. Both the IP and MCP joints are driven by a single servomotor. The angular ratio between the MCP and IP joints of the thumb is approximately 1.41. [75,109]	
MCR Hand II [75,109]	

Table 32

LoA examples: Thumb - Elim. 2 DOA - tendon underactuation.

Elim. 2 DOA TMC-MCP-IP joints	Tendon UA of three joints
In the FTN hand [71], the F-E degrees of freedom of all three joints (IP, MCP and CMC) are connected together by a tendon. This allows for the utilization of underactuation, whereby the F-E movement of the entire thumb is achieved with a single actuator. The combination of tendon drive and torsion springs in the pin joints results in an underactuated movement of the thumb joints. This allows the phalanges of the thumb to adapt passively to the shape of the object to be gripped. Should the first phalanx of the thumb encounter an obstacle during flexion, the second and third phalanges will continue to flex until either the obstacle or their mechanical limits are reached. [71]	
FTN hand [71]	

Table 33

LoA examples: Thumb - IP Joint Mech. Design 1 DOF - Closed hinge joint.

IP Joint Mech. Design 1 DOF	Closed hinge joint
The IP joint of the thumb of the ACT Hand [57,58] is constituted by a single aluminum pin joint, which represents the F-E degree of freedom between two phalanges. A connecting arm, firmly fixed to the distal phalanx, is capable of rotation about an axis that coincides with the F-E axis of the IP joint in the proximal phalanx. A narrow notch permits the connecting arm to rotate around the pin of the F-E axis of the IP joint, thereby preserving the geometry of the three-dimensional phalanges of the ACT Hand to the greatest extent possible. Furthermore, the expansion of the joint cavity between the phalanges restricts the movement of the IP joint to the corresponding range of motion of the human IP joint [57,58].	
ACT hand [58]	

Table 34

LoA examples: Thumb - IP Joint Mech. Design 1 DOF - Rolling-contact joint [193].

IP Joint Mech. Design 1 DOF**Rolling-contact joint**

The rolling-contact joint design of the UNUPI hand [136] and the Pisa/IIT Soft Hand [69] is based on a joint known as the Hillberry joint [193], where the two cylinders are held together by metal bands wrapped around the cylinders on opposite sides. Each of the two cylinders can be considered to possess the characteristics of a revolute joint, with the profile of the cylinders defining the movement of the joint [69]. Compared to the conventional Hillberry joint, the rolling-contact joint of both hands obviate the necessity for screws, bolts or bearings. The metal bands are substituted with elastic polyurethane bands. The elastic bands are capable of withstanding significant deformations and fatigue, and are secured over the joint with an offset in the dorsal direction. The application of an appropriate pre-tensioning to the elastic bands, in conjunction with a suitable rolling profile for the two cylinders, results in a state of equilibrium in the extension position of the thumb and an enhanced passive stability. The rolling profile is achieved through the utilization of side walls on both sides of the joint, which encase the cylinder sections. This guarantees that the rolling profile remains intact even when subjected to external lateral forces. Moreover, the rolling profile incorporates multiple teeth of a tothing, thereby facilitating enhanced absorption of tangential loads on the joint. Furthermore, a minimalistic profile has been integrated into the posterior aspect of the joint in order to guarantee the accurate return to the starting position. This mechanical joint design ensures that the hand exhibits a soft and secure motion behavior upon contact, enabling the hand to recuperate in the event of an overload. The joint is therefore capable of withstanding severe disarticulation and strong impacts, thereby enhancing the robustness of the hand through the utilization of the system's inherent elasticity.

THE UNUPI hand [136], PISA/IIT SoftHand [69]

Table 35

LoA examples: Thumb - IP Joint Mech. Design 1 DOF - Compliant joint.

IP Joint Mech. Design 1 DOF**Compliant joint**

The IP joint of the UoW/ACES hand [74] enables one degree of freedom and is responsible for the F-E movement of the thumb. The IP joint employs a flexure hinge, which is compliant in nature. This indicates that lubrication and maintenance are not required, and that there are no friction losses. The range of motion of the joint has been designed to encompass a range of from 0 to 60 degrees. To evaluate the mechanical properties of the IP joint and the entire thumb, Zhou et al. [74] conducted a series of experiments. Additionally, the service life of the joint was evaluated, and a series of gripping processes were conducted. Following 1.5 million cycles of bending and unloading, the flexure hinge joint exhibited no indications of fatigue or structural failure. This suggests that the joint is sufficiently resilient for use in a prosthetic thumb. [74]

UoW/ACES Hand [74]

Table 36

LoA examples: Thumb - MCP Joint Mech. Design 1 DOF - Closed hinge joint.

MCP Joint Mech. Design 1 DOF**Closed hinge joint**

The incorporation of thumb joints in the Dexmart hand [65] represents a technical solution that aims to reproduce the functionality of the biological counterpart while simultaneously simplifying the manufacture and assembly of the entire robotic hand. The utilization of mechanical components, such as bearings or analogous elements, which have the potential to present integration challenges with sensors or drive tendons, was eschewed. Following an evaluation of the available options, a pin joint with one degree of freedom was selected as the optimal solution for the IP and MCP joints of the thumb. The joint is comprised solely of a plastic shaft that serves to hold the components together, and a circular profile that is capable of sliding along a cylindrical surface. Palli et al. [65] designate this configuration an "integrated pin joint". Additionally, the joints are capable of enduring an unlimited number of opening and closing cycles with a tensile force of the drive tendon of approximately 80 N. Nevertheless, static and sliding friction effects occur at the joint level that warrant consideration, as they can potentially result in joint jamming. Nevertheless, these issues can be mitigated through the implementation of an optimized control strategy. The IP and MCP joints of the FTN Hand [71] are each constituted by a pin joint with a number of distinctive characteristics. The joint incorporates the use of small ball bearings with the objective of reducing friction. Additionally, a torsion spring is incorporated into this joint. This configuration allows flexion to be achieved by the drive tendon as the sole active component, while extension is facilitated by the torsion spring as a passive, antagonistic element. The spring constant of the torsion spring determines the trajectory of the thumb and its flexion during free movement in the absence of external forces and obstacles. The integration of a tendon drive and torsion springs within the pin joints facilitates a coupled movement of the thumb joints. [71]

Dexmart Hand [65], FTN Hand [71]

Table 37

LoA examples: Thumb - MCP Joint Mech. Design 1 DOF - Open hinge joint.

MCP Joint Mech. Design 1 DOF**Open hinge joint**

The most significant feature of the joints of the Awiwi Hand [51] is its capacity to undergo dislocation in a manner analogous to that observed in the human thumb. This attribute enhances the overall resilience of the thumb and the entire robot hand. The pre-tensioning forces of the drive tendons permit the utilization of an open hinge joint. The joint comprises a cylindrical joint head and a joint socket covering less than 180 degrees. It should be noted that this open hinge joint is therefore unable to prevent dislocations through form fit. It can be demonstrated that the IP and MCP joints are susceptible to dislocation by external loads that generate greater forces than the drive tendons, without resulting in structural damage. In a manner analogous to that observed in human joints, the axial movement of the joint is constrained by the presence of ribs within the cylindrical joint head and the joint socket. The ribs in the joint head and in the joint socket are rounded in order to prevent damage to the joint surfaces in the event of dislocation. Forces acting parallel to the joint axis lead to torques around the joint axis. These must be equalized or absorbed by the force closure of the joint design. For this reason, the drive tendons, especially the flexors, must run as far as possible from the opposite end of the cylinder. As a result, their lever arms are maximized. As the drive cables can only apply pulling forces, two flexors are used at the ends and one extensor in the center of the joint head. This creates a triangle of forces that increases the stability of the entire joint. [51]

Awiwi Hand [51]

Table 38

LoA examples: Thumb - MCP Joint Mech. Design 1 DOF - Compliant joint.

MCP Joint Mech. Design 1 DOF**Compliant joint**

The IP and MCP joints of the UB Hand III [43,56] have been designed in accordance with the principles of compliant mechanisms. This approach enables the movement of the phalanges to be achieved through the use of elastic elements. The compliant elements are composed of tightly wound steel coil springs that are bent under the influence of drive tendons. A restricted number of coils is adequate to attain substantial deflections while circumventing the occurrence of permanent deformations and buckling. It is possible to arrange several springs in parallel in order to obtain a joint with one degree of freedom. The results of experimental investigations indicate that the center of rotation of a compliant joint can be considered to remain fixed throughout the entire angular range of the joint. It can thus be approximated that the kinematic behavior may be modeled as a revolute joint with torsional stiffness. Accordingly, the thumb may be treated as a serial robot with revolute joints. [56] A significant aspect of the design is the near kinematic decoupling of the joints, with each drive tendon solely responsible for the flexion of a single joint. This is due to the fact that the guide paths of the cables are in close proximity to the neutral bending line of the individual coil springs. [43] The flexural rigidity of the joint is largely contingent upon the design of the spring. This encompasses the configuration, dimensions and composition of the material. The resulting bending stiffness can be employed to facilitate an automatic extension of the joint, whereby the drive tendons are solely responsible for the flexion of the joints. Selecting an appropriate bending stiffness for the joint is a crucial decision. On the one hand, high stiffness can have a beneficial impact on the overall robustness of the thumb structure and on the dynamic response of the thumb. Conversely, this results in an increase in the required tensile forces of the drive tendons, which in turn necessitates an increase in the required power of the actuators. It is thus necessary to find a compromise. [43] The mechanical design of this type of joint permits the creation of a simplified structure, as the components can be integrated into the rigid links, thereby forming one-piece articulated structures and obviating the necessity for assembly operations. The reduction in the number of components results in a simpler manufacturing process, a lightweight product, a cost-effective solution and straightforward integration with external sensors and compliant fairings. [43] Furthermore, the entire thumb mechanism with these joints has demonstrated excellent reliability and repeatability, with no failures occurring after thousands of working cycles. [56].

UB Hand III [43,56]

Table 39

LoA examples: Thumb - MCP Joint Mech. Design 1 DOF - Rolling-contact joint.

MCP Joint Mech. Design 1 DOF**Rolling-contact joint**

Oh et al. [135] proposes a hybrid joint with one degree of freedom, which provides efficient omnidirectional shock absorption and regeneration at various joint dislocations. This rolling-contact joint is designed in accordance with the morphology of the human knee joint. The material is soft and thus exhibits enhanced resilience to external shocks. Furthermore, the design aims to streamline the control system and facilitate adaptability to a grasping object of any shape. The elliptical convex and concave shapes of the knee joint are modified to circular convex and concave shapes in the design of the new joint. The hemispherical geometry of the joint ensures that the ligaments remain stretched during rotation or dislocation, in a manner analogous to that observed in the knee joint. This allows the joint to withstand omnidirectional impacts and dislocations. To elaborate, the concave component serves to prevent dislocation and guarantee a stable return. In the event of impacts in the A–A direction, the hemispherical joint thus exhibits a greater potential for recovery and the maintenance of stability than the Hillberry rolling contact joint. In a rotational dislocation, the deflection of the elastic ligaments and, consequently, the elastic force are both less pronounced than in other dislocations. The range of motion available for recovery of the joint is also limited by friction and resistance. The Hillberry rolling contact joint exhibits a downward inclination when twisted, which significantly impedes the recovery process due to the exertion of a pulling force by the elastic bands. In contrast, when the hemispheric joint undergoes a twist, the socket is elevated above the hemisphere, thereby increasing the length of the elastic ligaments and facilitating their return to the original position. [135]

soft robot hand from Oh et al. [135]

Table 40

LoA examples: Thumb - TMC Joint Mech. Design 1 DOF - Closed hinge joint.

TMC Joint Mech. Design 1 DOF**Closed hinge joint**

The TMC joint of the RTR II Hand [39] exhibits a single degree of freedom, thereby limiting its functionality to the A–A movement of the thumb. The TMC joint is constituted by a four-bar linkage. The four-bar linkage was introduced with the objective of simulating the A–A movement of the human thumb and of modifying the axis of rotation of the thumb during its movement. The A–A movement of the thumb enables the RTR II Hand to perform a variety of grasping patterns, thereby enhancing the prosthesis's flexibility [39]. The TMC joint of the thumb of the UT Hand I [66] is capable of approximating the opposition movement of the human thumb with a single degree of freedom due to its positioning on the palm of the hand. The flexion movement is executed by the MCP and IP joints in concert, whereas the opposition movement is performed by the TMC joint. It is important to note that these two movements are not entirely independent of one another. The flexor for the MCP and IP joints is situated around a freely rotatable pulley on the opposition shaft of the thumb. This results in a shortening or lengthening of the flexor during opposition. It can be deduced from this that the flexion motor has the capacity to activate both the flexion and opposition degrees of freedom. However, this is prevented by the non-reversing or self-locking CMC articulated worm gear between the opposition motor and the thumb [66].

RTR II Hand [39], UT Hand I [66]

Table 41

LoA examples: Thumb - MCP Joint Mech. Design 2 DOF - Closed hinge joint.

MCP Joint Mech. Design 2 DOF	Closed hinge joint
The MCP joint of the thumb of the ACT Hand [57,58] comprises a modified universal joint with two non-orthogonal, non-intersecting axes in place of the two orthogonal, intersecting axes that would be expected. As stated by Chang and Matsuoka [58], the MCP joint is capable of only two degrees of freedom for the F-E and A-A movements between the metacarpal bone and the proximal phalanx, with the assistance of a miniature gimbal. A larger gimbal design would necessitate a larger joint cavity to permit movement along both axes of rotation. Such a design would result in the elimination of a critical area of the surface geometry of the phalanx that comes into contact with the extensor muscles of the MCP joint. A pair of miniature ball bearings provides the rotational support for the gimbal around the MCP A-A axis, which is fixed relative to the metacarpal bone. A small aluminum pin joint in the gimbal represents the MCP-F-E axis, which is fixed relative to the proximal phalanx via a connecting arm. The two axes intersect the distal end of the metacarpal bone. The curvature of the connecting arm allows for a reduction in the incision at the attachment point in the metacarpal bone, thereby preserving as much of the three-dimensional bone as possible. The configuration of the joint cavity restricts the range of motion of the miniature gimbal to that observed in the human MCP joint. It should be noted, however, that the MCP joint is capable of unrestricted movement in the A-A direction, even in the absence of any deflection in the F-E direction. In all other respects, however, it is correctly and precisely restricted in accordance with the human counterpart. [57,58]	
ACT Hand [57,58]	

Table 42

LoA examples: Thumb - TMC and MCP Joint Mech. Design 2 DOF - Closed hinge joint [194].

MCP Joint Mech. Design 2 DOF	Closed hinge joint
TMC Joint Mech. Design 2 DOF	Closed hinge joint
The utilization of a universal joint/cardan joint with orthogonal and intersecting axes represents a prevalent solution for both MCP and TMC joints with two degrees of freedom. Notable examples of anthropomorphic robot hands incorporating universal joints include the Shadow Hand [113]. Kinematically, a universal joint is constituted by two axes of rotation that converge at a single point. However, the components that comprise it require a considerable amount of space in practice. This has the effect of impairing the practicality of the application. In order to maintain the compact dimensions of the universal joint, it is essential to utilize small shafts. However, this may result in a risk of shearing when the thumb is under load. In practice, the amplitude of movement of the universal joint is constrained, and its drive tendons cannot be guided through the center of the joint. The trajectory of the drive tendons is subject to variation in accordance with the movement of the thumb, which renders the prediction of clamping points and collisions of the drive tendons a challenging undertaking. During the operation of the TMC joint prototype from TU Hand [68], it was observed that the edges of the joint made contact with the moving drive tendons. Such contact resulted in the formation of pinch points, which in turn gave rise to disturbances in the movement of the drive tendons. Consequently, the stability of the thumb was compromised [68]. A further disadvantage is that computer simulations of a thumb model incorporating universal joints for the MCP and TMC joints have yielded forces at the tip of the thumb that are not representative of the real world. Such outcomes are to be avoided in order to ensure an accurate representation of the biomechanics of the thumb [58,194].	
Shadow Hand [113], TU Hand [68]	

Table 43

LoA examples: Thumb - TMC Joint Mech. Design 2 DOF - Closed hinge joint.

TMC Joint Mech. Design 2 DOF	Closed hinge joint
The TMC joint of the thumb of the ACT hand [57,58] is composed of two pin joints with non-orthogonal axes. The two joints are situated in different phalanges, thus they do not intersect. The pin joints are situated at the extremities of a coupler and facilitate the F-E and A-A degrees of freedom. The coupler between the trapezium and metacarpal serves to ensure the correct spacing while simultaneously allowing for rotation around both axes. One bolt joint corresponds to the A-A axis of the TMC joint, which runs through the proximal end of the metacarpal bone. The other pin joint represents the F-E axis that crosses the trapezium. The narrow slits in the metacarpal bone and trapezium ensure the anatomically correct range of motion for each of the two axes. The aluminum pin joints at each rotational axis facilitate the formation of low-friction joints without the necessity to replicate the boundary conditions of biological soft tissue or to provide synovial lubrication. The modeling of the robot thumb with non-orthogonal and non-intersecting rotational axes provides the basis for its kinematic behavior, which is informed by important anatomical features. Such features include variable lever arms for the drive tendons, which facilitate the replication of the musculoskeletal dynamics observed in the human thumb. Furthermore, this approach results in a more anatomically accurate workspace and overall thumb behavior. This is achieved without the actuator system becoming more complex, since the motors are indirectly connected to the phalanges via the drive tendons, rather than being mounted directly in the joint as in other robot hands. The TMC joint of the FTN Hand [71] is constituted by two pin joints with axes that are neither orthogonal nor intersecting. The initial axis of the TMC joint is a conventional pin joint, positioned at an oblique angle to the palm of the hand as proposed by Savić et al. [71]. This joint is responsible for the A-A movement of the thumb. This allows the FTN Hand to perform a number of basic grips. In contrast, the second axis of the TMC joint is a spring-loaded pin joint. The structure, properties, advantages and influences of this joint on the entire thumb have already been described above.	
ACT Hand [57,58], FTN Hand [71]	

Table 44

LoA examples: Thumb - TMC Joint Mech. Design 2 DOF - Open hinge joint.

TMC Joint Mech. Design 2 DOF	Open hinge joint
The TMC joint of the Awiwi Hand [51] is designed as a saddle joint with two orthogonal but non-intersecting axes. The principal advantage of a saddle joint is the markedly low surface pressure. Furthermore, a saddle joint is geometrically exact and is capable of maintaining line contact throughout the entire range of motion. For these reasons, a pair of hyperboloids was selected for the sliding surfaces of the TMC joint, which together form a hyperboloid saddle joint. The hyperboloid shape enables a significant reduction in joint friction, as the force is primarily generated at the center of the joint. The drive tendons can be routed directly through the center of the joint, thereby reducing the pulling force on the tendons and achieving a linear coupling. However, due to the spatial limitations of the Awiwi Hand, it is necessary for some drive tendons to be routed externally around the TMC joint in order to provide sufficient lever arms. [51].	
Awiwi Hand [51]	

Table 45

LoA examples: Thumb - TMC Joint Mech. Design 2 DOF - Combined closed- and open hinge joint.

TMC Joint Mech. Design 2 DOF	Combined closed- and open hinge joint
Both TMC joints of the Dexmart hand [65] and the UB Hand IV [50] are required to meet specific load capacity criteria. It is necessary for the joint to permit dislocation of the thumb in the event of excessive loading or impact, in order to prevent damage to the mechanical structure of the thumb. In order to achieve this objective, a combination of two pin joints is selected for the TMC joint. The initial axis of the TMC joint is similarly configured as an “integrated pin joint” as previously delineated. However, the plastic shaft has been removed from the second axis, resulting in a joint comprising solely two sliding profiles held in contact by the pulling tension of the drive tendon. In addition to the aforementioned properties, advantages and disadvantages of integrated pin joints, which also apply to this TMC joint, the primary advantage of the selected TMC joint design is that it enhances the robustness of the mechanical structure in the event of an overload on the thumb.	
Dexmart Hand [65], UB Hand IV50	

Table 46

LoA examples: Thumb - TMC Joint Mech. Design 2 DOF - Compliant joint.

TMC Joint Mech. Design 2 DOF	Compliant joint
The TMC joint of the UB Hand III [43] and UBH Hand 3[56] is constructed in accordance with the same concept of compliant mechanisms as its IP and MCP joints. In consequence, the TMC joint, which is similarly constructed as a coil spring, exhibits the characteristics, benefits, drawbacks and effects on the thumb as previously outlined. The distinction between the TMC joint and the IP and MCP joints lies in the fact that the former possesses two degrees of freedom. Two possibilities exist for the construction of compliant joints with two degrees of freedom. On the one hand, joints with non-parallel bending axes can be realized through the use of separate joints. Conversely, two degrees of freedom can be incorporated into a single joint by utilizing a single coil spring. The TMC joint of the UB Hand III has been designed in accordance with the second variant. The movement of the two degrees of freedom is regulated by three drive tendons arranged at an angle of 120 degrees to each other. This design exhibits intriguing characteristics, as it is more compact than the separate joints and more closely approximates the kinematic behavior of certain biological joints. Moreover, the joint stiffness can be more effectively regulated by the three antagonistic tendons than by separate joints. The entire thumb structure of the UoW/ACES prosthetic hand [74] is monolithic and soft without extra assembly. Two flexural hinges are employed in the construction of the TMC joint. The first axis of the TMC joint enables the A-A movement of the thumb. This enables the thumb to alternate between a non-opposed and an opposed position in relation to the other fingers. The range of motion in the A-A direction is from 0 to 100 degrees. At 100 degrees of movement, the pad of the thumb is positioned in opposition to the middle finger. This range of motion enables the thumb to perform the typical gripping actions associated with the index and/or middle fingers. The second axis exhibits a range of motion between 0 and 90 degrees, thereby enabling the F-E movement of the thumb to be achieved. The TMC joint can be conceptualized as a two-axis flexure hinge with non-located notches. Furthermore, the thumb demonstrated adequate mechanical compliance and exhibited commendable performance in terms of power, precision, and lateral grasps with objects of varying shapes and sizes [74].	
UB Hand III [56], UBH Hand 3 [43], UoW/ACES Hand [74]	

Table 47

LoA examples: Thumb - TMC Joint Mech. Design 3 DOF - Ball joint.

TMC Joint Mech. Design 3 DOF	Ball joint
In the EthoHand [72], the ball-jointed thumb enhances the dexterity of a robotic hand by providing 3 DOF through a ball-in-socket design. It includes a ball joint connecting the MCP and IP phalanges and a socket secured to the palm. Controlled by two pairs of antagonistic tendons, this joint prevents rotation along its central axis and enables precise thumb positioning through synergistic tendon movements. The configuration of the TMC joint enables the EthoHand to execute the 33 most frequently utilized grips in activities of daily living. Furthermore, the thumb can be controlled in order to enable the EthoHand to perform precise and complex manipulation tasks within the hand. Such actions include, for instance, passing a ball between fingers or using the tip of the thumb to write text messages on a smartphone while holding the phone in the same hand. Such manipulations are feasible without the necessity for sensory or tactile feedback for control. Consequently, the TMC design facilitates the manipulation of objects with the hand while reducing the complexity of the mechanical design.	
EthoHand [72]	

Table 48

LoA examples: Thumb - Phalanx Design - Artificial phalange [195].

Phalanx design	Artificial phalange
In Biomimetic Robotic Hand from Xu and Todorov [70], artificial bones are created from laser-scanned cadaver hand models, with the thumb being unique in having only two phalanges except for the metacarpal bone. Using laser or MRI scanning, human bone structures can be accurately captured and 3D-printed, preserving critical surface details. In the early ACT hand [195], all fingers are represented by a simplified cylinder with a uniform diameter, which turns out that the performance of the extensor muscles is highly sensitive to the shape of the underlying phalanx with which they are in contact. To address these issues, the finger phalanges in the new ACT Hand [57] are designed to accurately match human bones properties. The cylindrical phalanges offer only line contact with the extensor muscles. In contrast, artificial phalanges provide surface contact. Furthermore, the cylindrical phalanges allow only a constant curvature radius for the driving cables around each joint. This results in an effective lever arm that remains constant during joint rotation. However, the biological shapes of artificial phalanges generate lever arms for the driving cables that vary with the joint angle, which is a behavior critical for the precise grasping.	
Biomimetic Robotic Hand from Xu [70], ACT Hand [57,195]	

Table 49

LoA examples: Thumb - Phalanx Length - Human-like relations.

Phalanx Length	Human-like relations
The thumb length are discussed while developing the iCub Hand [108]. The thumb of the preceding iteration of the iCub hand exhibits an additional phalanx in comparison to the human thumb. While this augmented the operational range of the thumb, the practical operational range of the other fingers is more constrained. The additional length of the thumb presents a challenge for the iCub robot in terms of its ability to grasp objects from flat surfaces in a natural position. As a consequence of the mechanical constraints imposed by the wrist, the hyperextension required to compensate for the thumb is performed via the shoulder joint. This results in an unnatural overall posture of the robot when gripping. A more natural configuration is achieved by reducing the number of phalanges in the thumb by one, thereby shortening it. The number of phalanges thus corresponds to that of the human thumb. This results in the iCub hand acquiring an anthropomorphic structure while simultaneously reducing the potential for interference. [108]	
iCub Hand [108]	

Table 50

LoA examples: KBC - TMC Positioning - Isobe.

TMC positioning	Isobe
The fourth generation of the Gifu robotic hand series, the Kinetic Humanoid Hand [55], has undergone a redesign in comparison to its predecessors. The researchers no longer relied solely on their experimental experience with the previous hands; for the first time, they took the aforementioned Isobe guidelines into account. This resulted in a modification to the position and orientation of the thumb and the remaining fingers. This approach resulted in a notable enhancement in the opposition capability of the thumb, thereby markedly elevating the dexterity of the robotic hand.	
Kinetic Humanoid Hand [55]	

Table 51

LoA examples: KBC - TMC Positioning - Euler-angle.

TMC positioning	Euler-angle
The proposed Euler-angle method enables to improve the thumb performance of the DLR/HIT Hand II. In the TMC joint position design of the revised DLR/HIT Hand II [182], following steps are followed during the design process: The fixed point O is determined by the position of the TMC joint of the thumb. Two sort of poses are determined by simulating the grasping of typical objects using a ball-and-socket joint at point O . A fixed world frame $\{O\}$ is defined at point O with arbitrary axis orientations. From measurements in the virtual environment, pose matrices P_1 and P_2 can be derived. The unit direction vector of the fixed rotation axis between Pose 1 and Pose 2 is $\mathbf{f} = (f_x, f_y, f_z)$ with the rotation angle at ϕ . Detailed transition matrix can be found in the source paper [182]. Using P_1 and P_2 , the components f_x, f_y, f_z , and ϕ can be determined. This allows the transformation of the thumb between Pose 1 and Pose 2 to be represented. To evaluate performance, a comparison of the thumb's opposition capability before and after the redesign is conducted. The effectiveness of this thumb design method is demonstrated by the fact that the opposition capability of the redesigned thumb is 2.92 times that of the original thumb from Liu et al. [34].	
revised DLR/HIT Hand II [182]	

Table 52

LoA examples: KBC - TMC Positioning - Angled towards palm and finger.

TMC positioning	Angled towards palm and finger
During the development of the UT Hand I [66], to ensure thumb opposition as efficiently and simply as possible, the thumb is positioned at an angle of 45° to the other fingers and the plane of the palm. As a result, the first axis of the thumb moves along a cone centered on a shaft. This movement closely approximates the opposition movement of the human thumb with a single degree of freedom [66]. A very similar approach is followed by the FTN Hand [71]. The angle value is set at 28.5° in the frontal plane with 58.5° in the sagittal plane. The chosen TMC joint placement enables the thumb to perform the opposition movement and to execute several fundamental grasps suitable for a variety of objects in the human environment [71].	
UT Hand I [66], FTN Hand [71]	

Table 53

LoA examples: KBC - TMC Positioning - Various positioning.

TMC positioning	Various positioning
The New Dexterity Adaptive Humanlike Robot Hand [77] includes an additional degree of freedom at the base of the thumb, allowing translational movement. As a result, the thumb can be repositioned to adjust the hand's opening. Compared with a thumb with fixed base on the palm, the observed force development and manipulation behavior for small objects were very similar for both hands. For larger objects, however, the hand with the variable thumb base achieves a larger workspace for object manipulation within the hand due to the greater hand opening. Additionally, the trajectory length for manipulating a cylinder can be doubled. Moreover, the variable design can exert a greater force (13.3 N more), leading to significantly improved grasp stability [77]. The Bebionic prosthetic Hand [46] allows several adjustment options for the thumb base position. Depending on the user's requirements, the thumb can be repositioned for additional grips or to realign the contact points. A medial-lateral adjustment mechanism enables resetting the contact to either the index and middle fingers or just the index finger. Additionally, a palmar-dorsal adjuster is integrated to change the thumb's starting position. This allows the thumb to move either towards or away from the palm to optimize the contact point of the thumb tip with the opposing fingers [46]. In daily use, the thumb can be manually locked in one of two positions: opposed or not opposed to the fingers, with an adjustment range of 68°. This saves the user from time-consuming myoelectric alignment of the thumb and enables quick selection of grip patterns. Furthermore, when locked, the thumb cannot retract under load [46].	
New Dexterity Adaptive Humanlike Robot Hand [77], Bebionic Hand [46]	

Table 54

LoA examples: KBC - TMC Positioning - Grebenstein et al.

TMC positioning	Grebenstein et al.
In the development of the Awiwi Hand [51], following observations are made with regard to the TMC joint positioning during the course of the Kapandji test [183]: (1) The intersection of the first TMC axis with the palm is a determining factor in the ability of the thumb to reach the MCP joints of the remaining fingers. (2) The thumb is in a singular position when the point of intersection is located at the MCP joint of a finger. In this instance, the thumb is unable to adopt any other position on the palm. (3) In addition, a TMC joint that is too close to the palm leads to a lateral collision between the thumb and index finger. In light of the aforementioned observations, a series of measures are devised with the aim of enhancing the efficacy of the Kapandji test: (1) In order to extend the range of accessible finger-MCP joints, it is necessary to situate the intersection of the first TMC axis with the palm at a greater distance from the finger-MCP joints. (2) In the event of a collision between the thumb and the side of the index finger, it is necessary to reposition the TMC base in a more anterior position relative to the palm.	
Awiwi Hand [51]	

Table 55

LoA examples: Finger - Mech. DIP joint design - Hyperextension.

Mech. DIP joint design	Hyperextension
Zhang et al. [118] introduce a sliding chute mechanism in the design of the DIP joint of the index finger to achieve human passive hyperextension capabilities. Unlike the DIP joint, the PIP joint is excluded from hyperextension due to its naturally limited range in humans.	
Catch-919 Hand [118]	

Appendix B. LoA tables

See Tables 56–60.

Table 56
Library of Approaches: Group “Thumb”.

Library of Approaches. Group: Thumb				
Fols	PS 1	PS 2	PS 3	PS 4
Elim. 1 MCP Joint DOF	Elim. MCP Add./Abd. DOF (e.g. Wang et al. [112])			
Elim. 1 TMC Joint DOF	Elim. TMC Pro./Sup. DOF (e.g. Lotti et al. [56])			
Elim. 2 MCP Joint DOF	Elim. MCP Joint (e.g. Pulleyking et al. [111])			
Elim. 2 TMC Joint DOF	Elim. TMC Flex.-Ext. Pro./Sup. DOF (e.g. Peerdeman et al. [66])			
IP Joint Struc. Design (1 DOF)	1 axis (e.g. Catalano et al. [69])			
MCP Joint Struc. Design (1 DOF)	1 axis (e.g. Catalano et al. [69])			
TMC Joint Struc. Design (1 DOF)	1 axis (e.g. Peerdeman et al. [66])			
MCP Joint Struc. Design (2 DOF)	2 axis not orth./non-intersecting - Add./Abd. below (e.g. Deshpande et al. [57])	2 axis orth./non-intersecting - others (e.g. Zhang et al. [118])		
TMC Joint Struc. Design (2 DOF)	2 axis orth./non-intersecting - Add./Abd. below (e.g. Grebenstein [51]),	2 axis orth./non-intersecting - Add./Abd. at top (e.g. Butterfass et al. [25])	2 axis orth./non-intersecting - others (e.g. Iwata and Sugano [119])	2 axis not orth./non-intersecting - Add./Abd. below (e.g. Deshpande et al. [57])
	2 axis not orth./non-intersecting - others (e.g. Gao et al. [77])	2 axis orth./intersecting - Add./Abd. below (e.g. Butterfass et al. [120])	2 axis orth./intersecting - Add./Abd. at top (e.g. Fukaya et al. [30])	
TMC Joint Struc. Design (3 DOF)	3 axis intersecting (e.g. Konnaris et al. [72])	3 axis - others (e.g. Liu et al. [110])		
Elim. 1 DOA MCP-PIP Joints	Tendon coupling of two joints (e.g. Butterfass et al. [25])	Linkage coupling of two joints (e.g. Liu et al. [34])	Linkage UA of two joints (e.g. Yang et al. [123])	
Elim. 2 DOA TMC-MCP-IP Joints	Linkage UA of three joints (e.g. Laliberté and Gosselin [125])	Tendon UA of three joints (e.g. Gosselin et al. [60])	Linkage coupling of three joints (e.g. Rodriguez et al. [130])	Special Coupling of three joints (e.g. Pons et al. [54])
Elim. 3 DOA TMC-MCP-IP Joints	Linkage UA of three joints (e.g. Tae-uk and Yonghwan [131])			
IP Joint Mech. Design (1 DOF)	Closed hinge joint (e.g. Deshpande et al. [57])	Open hinge joint (e.g. Grebenstein [51])	Compliant joint (e.g. Zhou et al. [74])	Rolling-contact joint (e.g. Oh et al. [135])
MCP Joint Mech. Design (1 DOF)	Closed hinge joint (e.g. Deshpande et al. [57])	Open hinge joint (e.g. Grebenstein [51])	Compliant joint (e.g. Zhou et al. [74])	Rolling-contact joint (e.g. Oh et al. [135])
TMC Joint Mech. Design (1 DOF)	Closed hinge joint (e.g. Massa et al. [39])			
MCP Joint Mech. Design (2 DOF)	Closed hinge joint (e.g. Deshpande et al. [57])			
TMC Joint Mech. Design (2 DOF)	Closed hinge joint (e.g. Butterfass et al. [25])	Open hinge joint (e.g. Grebenstein [51])	Compliant joint (e.g. Lotti et al. [43])	Rolling-contact joint (e.g. Della Santina et al. [73])
	Ball joint (e.g. Xu et al. [140])	Combined closed- and open hinge joint		
TMC Joint Mech. Design (3 DOF)	Ball joint (e.g. Konnaris et al. [72])			
Finger Structure	Rigid-sequential (e.g. Grebenstein [51])	Flexible (e.g. Dollar and Howe [45])		
Finger Size	Human-like relations (e.g. Grebenstein [51])			
Phalanx Design	Exoskeleton (e.g. Peerdeman et al. [66])	Endoskeleton (e.g. Grebenstein [51])		
Phalanx Length	Human-like relations (e.g. Grebenstein [51])			
Improving opposition	Inclination and twist of IP joint [51]			
Resetting	Torsional spring	Antagonistic Actuation	Rubber band	

Table 57

Library of Approaches: Group “Finger”.

Library of Approaches. Group: Finger				
Fols	PS 1	PS 2	PS 3	PS 4
Elim. 1 MCP Joint DOF	Elim. MCP Add./Abd. DOF (e.g. Gosselin et al. [60])			
Elim. 1 IP Joint DOF	Elim. PIP/DIP Joint (e.g. Leonardis and Frisoli [162])			
IP Joint Struc. Design (1 DOF)	1 axis (e.g. Catalano et al. [69])			
MCP Joint Struc. Design (1 DOF)	1 axis (e.g. Konnaris et al. [72])			
MCP Joint Struc. Design (2 DOF)	2 axis orth./non-intersecting - Add./Abd. below (e.g. Grebenstein [51])	2 axis not orth./non-intersecting - Add./Abd. below (e.g. Deshpande et al. [57])	2 axis orth./intersecting - Add./Abd. below (e.g. Butterfass et al. [120])	2 axis orth./intersecting - Add./Abd. at top (e.g. Fukaya et al. [30])
Elim. 1 DOA DIP-PIP Joints	Tendon coupling of two joints (e.g. Butterfass et al. [25])	Linkage coupling of two joints (e.g. Peerdeman et al. [66])	Linkage UA of two joints (e.g. Yang et al. [123])	
Elim. 1 DOA MCP-PIP Joints	Tendon coupling of two joints (e.g. Peerdeman et al. [66])	Linkage coupling of two joints (e.g. Fourie and Stopforth [165])	Linkage UA of two joints (e.g. Yang et al. [123])	
Elim. 2 DOA MCP-PIP-DIP Joints	Linkage UA of three joints (e.g. Laliberté and Gosselin [125])	Tendon UA of three joints (e.g. Gosselin et al. [60])	Linkage coupling of three joints (e.g. Rodriguez et al. [130])	Tendon Coupling of three joints (e.g. Pons et al. [54])
Elim. 3 DOA MCP-PIP-DIP Joints	Linkage UA of three joints (e.g. Tae-uk and Yonghwan [131])			
IP Joint Mech. Design (1 DOF)	Closed hinge joint (e.g. Deshpande et al. [57])	Open hinge joint (e.g. Grebenstein [51])	Compliant joint (e.g. Zhou et al. [74])	Rolling-contact joint (e.g. Oh et al. [135])
MCP Joint Mech. Design (1 DOF)	Closed hinge joint (e.g. Carrozza et al. [42])	Compliant joint (e.g. Dollar and Howe [45])		
MCP Joint Mech. Design (2 DOF)	Closed hinge joint (e.g. Butterfass et al. [25])	Open hinge joint (e.g. Grebenstein [51])	Compliant joint (e.g. Lotti et al. [43])	Rolling-contact joint (e.g. Pulleyking and Schultz [76])
	Ball joint (e.g. Xu et al. [140])			
Finger Structure	Rigid-sequential (e.g. Grebenstein [51])	Flexible (e.g. Dollar and Howe [45])		
Finger Size	Human-like relations (e.g. Grebenstein [51])			
Phalanx Design	Exoskeleton (e.g. [66])	Endoskeleton (e.g. Grebenstein [51])		
Phalanx Length	Human-like relations (e.g. Grebenstein [51])			
Resetting	Torsional spring (e.g. Sureshbabu et al. [108])	Antagonistic Actuation	Rubber band	
DIP Joint Mech. Design	Passive Hyperextension (e.g. Zhang et al. [118])			
Improving Opposition	Inclination of IP joint (e.g. Grebenstein [51])	Inclination of MCP joint (e.g. Cerveri et al. [196])		

Table 58

Library of Approaches: Group “Transmission”.

Library of Approaches. Group: Transmission				
FoIs	PS 1	PS 2	PS 3	PS 4
Type of Underactuation	Moveable Pulley (MP)	Seesaw Bar (SB)	CDC	Hybrid
Eliminating 1 DOA	Tendon Underactuation F-E LF-RF (e.g. Dalley et al. [83])	Tendon Underactuation F-E MF-IF (e.g. Carrozza et al. [80])		
Eliminating 2 DOA	Tendon Underactuation F-E LF-RF-MF (e.g. Kyberd et al. [32])	Tendon Underactuation F-E RF-MF-IF (e.g. Wang et al. [87])	Tendon Coupling A-A LF-RF-IF (e.g. Schmitz et al. [63])	
Eliminating 3 DOA	Tendon Underactuation F-E LF-RF-MF-IF (MP: [45,60,81]), (SB: [84,86,88,92,97–100]), (CDC: [78,96]), (Hyb.: [89,93,95])			
Eliminating 4 DOA	Tendon Underactuation/Coupling F-E LF-RF-MF-IF-Tb (MP: [90,91]), (SB: [30,82]), (Hyb.: [64])	Tendon Underactuation F-E LF-RF-MF-IF-Tb (e.g. Catalano et al. [69])	Tendon Underactuation A-A LF-RF-MF-IF-Tb (e.g. Della Santina et al. [73])	

Table 59

Library of Approaches: Group “Covering”.

Library of Approaches. Group: Covering				
FoIs	PS 1	PS 2	PS 3	PS 4
Adaptation	Soft Tissue/ Pads (one Material) (e.g. Grebenstein [51])	Filled Pads (e.g. Shimoga and Goldenberg [104])	None (e.g. Zhang et al. [118])	
Contact Material (Skin)	Silicon (e.g. Tomo et al. [171])	Polyurethane (e.g. Grebenstein [51])	None	Vinyl (e.g. Matsuoka [173])
Proportion of Covered Area	Full Fingercover (e.g. Lotti et al. [170])	Gloves (Finger and Palm Cover) (e.g. Grebenstein [51])	Partial Cover (e.g. Butterfass et al. [120])	Fingertips (e.g. Eguiluz et al. [137])
Surface Texture	Fingerprints (e.g. Cutkosky et al. [105])	Rounded hexagonal Pillars with Gaps (e.g. [174])	Flat	

Table 60

Library of Approaches: Group “Kinematic Base Chain”.

Library of Approaches. Group: KBC				
FoIs	PS 1	PS 2	PS 3	PS 4
Eliminating 1 HMC Joint DOF	Implementing joined HMC for Little-Ring Finger (e.g. Zhang et al. [118])	Eliminating HMC Ring Finger (e.g. Grebenstein [51])		
Eliminating 2 HMC Joint DOF	Eliminating HMC Little and Ring finger (e.g. Butterfass et al. [25])			
Eliminating 1 DOA HMC Joint	Linkage UA HMC-MCP Joints (e.g. Butterfass et al. [120])	Linkage coupling HMC-MCP Joints (e.g. Konnaris et al. [72])	Linkage Coupling Grebenstein. (e.g. Grebenstein [51])	
Mechanical HMC(CMC) Joint Design	Closed hinge joint (e.g. Zhang et al. [118])	Open hinge joint (e.g. Konnaris et al. [72])		
Mechanical Palm Design	Flat rigid surface (e.g. Kawasaki et al. [145])	Bent rigid surface (e.g. Liu et al. [34])		
TMC Joint Position	Isobe (e.g. Kawasaki et al. [55])	Euler-Angle (e.g. Wang et al. [112])	Angled towards palm and fingers (e.g. Savić et al. [71])	Anthropomorphic position (e.g. Konnaris et al. [72])
	Variable positioning (e.g. Connolly [61])	Opposing to fingers (e.g. Ueda et al. [121])	Grebenstein et al. [51]	

Data availability

The derived data is provided in the form of fields of interest and principal solutions in the manuscript.

References

- [1] C. Piazza, G. Grioli, M.G. Catalano, A. Bicchi, A century of robotic hands, *Annu. Rev. Control. Robot. Auton. Syst.* 2 (2019) 1–32, <http://dx.doi.org/10.1146/annurev-control-060117-105003>.
- [2] A. Bicchi, Hands for dexterous manipulation and robust grasping: A difficult road toward simplicity, *IEEE Trans. Robot. Autom.* 16 (2000) 652–662, <http://dx.doi.org/10.1109/70.897777>.
- [3] M. Controzzi, C. Cipriani, M.C. Carrozza, Design of artificial hands: A review, 21, ISBN: 978-3-319-03017-3, 2014, pp. 9–246, http://dx.doi.org/10.1007/978-3-319-03017-3_11,
- [4] L. Biagiotti, F. Lotti, C. Melchiorri, G. Vassura, How far is the human hand, *A Rev. Anthr. Robot. End-Effectors* (2004).
- [5] M.J. Page, J.E. McKenzie, P.M. Bossuyt, I. Boutron, T.C. Hoffmann, C.D. Mulrow, L. Shamseer, J.M. Tetzlaff, E.A. Akl, S.E. Brennan, R. Chou, J. Glanville, J.M. Grimshaw, A. Hróbjartsson, M.M. Lalu, T. Li, E.W. Loder, E. Mayo-Wilson, S. McDonald, L.A. McGuinness, L.A. Stewart, J. Thomas, A.C. Tricco, V.A. Welch, P. Whiting, D. Moher, The prisma 2020 statement: An updated guideline for reporting systematic reviews, *BMJ* 372 (2021) n71, <http://dx.doi.org/10.1136/bmj.n71>.
- [6] N.M. Kasper, E. Muschter, B. Preisig, *Das handbuch*, 1980.
- [7] D. Gossen, S. Polzin, M. Witte, C. Gosselin, M. Huesing, B. Corves, Quantitative evaluation of the relevance of hamatometacarpal dof in anthropomorphic robot hands, in: *Proceedings of the 2025 International Conference on Advanced Robotics and Mechatronics, ARM, IEEE, 2025*, In press.
- [8] J.S. Martell, G. Gini, Robotic hands: design review and proposal of new design process, *World Acad. Sci. Eng. Technol.* 26 (2007) 85–90.
- [9] E. Nagma, S. Mohd, Tendon driven robotic hands: A review, *Int. J. Mech. Eng. Robot. Res* 1 (2012) 350–357.
- [10] J.T. Belter, J.L. Segil, B. Sm, Mechanical design and performance specifications of anthropomorphic prosthetic hands: a review, *J. Rehabil. Res. Dev.* 50 (599) (2013) <http://dx.doi.org/10.1682/jrrd.2011.10.0188>.
- [11] E.N. Gama Melo, O.F. Aviles Sanchez, D. Amaya Hurtado, Anthropomorphic robotic hands: a review, *Ingeniería y Desarrollo*. 32 (2014) 279–313, <http://dx.doi.org/10.14482/inde.32.2.4715>.
- [12] C. Melchiorri, M. Kaneko, Robot hands, in: *Springer Handbook of Robotics*, vol. 46, ISBN: 978-3-319-32550-7, 2016, pp. 3–480, http://dx.doi.org/10.1007/978-3-319-32552-1_19.
- [13] J. Ten Kate, G. Smit, P. Breedveld, 3D-printed upper limb prostheses: a review, *Disabil. Rehabil.: Assist. Technol.* 12 (2017) 300–314, <http://dx.doi.org/10.1080/17483107.2016.1253117>.
- [14] E. Difonzo, G. Zappatore, G. Mantriota, G. Reina, Advances in finger and partial hand prosthetic mechanisms, *Robotics* 9 (80) (2020) <http://dx.doi.org/10.3390/robotics9040080>.
- [15] J. Vertongen, D.G. Kamper, G. Smit, H. Vallery, Mechanical aspects of robot hands, active hand orthoses, and prostheses: A comparative review, *IEEE/ASME Trans. Mechatronics* 26 (2020) 955–965, <http://dx.doi.org/10.1109/TMECH.2020.3014182>.
- [16] V. Mendez, F. Iberite, S. Shokur, S. Micera, Current solutions and future trends for robotic prosthetic hands, *Annu. Rev. Control. Robot. Auton. Syst.* 4 (2021) 595–627, <http://dx.doi.org/10.1146/annurev-control-071020-104336>.
- [17] M. Mansoor, P. Prajapati, M. Suhaib, Some study on multifinger robotic gripper, in: *2023 International Conference on Recent Advances in Electrical, Electronics & Digital Healthcare Technologies, REEDCON, IEEE, 2023*, pp. 460–465, <http://dx.doi.org/10.1109/REEDCON57544.2023.10150807>.
- [18] S. Parveen, M. Suhaib, M.A. Majid, Multifinger robotic gripper: A review, in: *2023 International Conference on Recent Advances in Electrical, Electronics & Digital Healthcare Technologies, REEDCON, IEEE, 2023*, pp. 466–470, <http://dx.doi.org/10.1109/REEDCON57544.2023.10150673>.
- [19] S. Jacobsen, E. Iversen, D. Knutti, R. Johnson, K. Biggers, Design of the utah/mit dextrous hand, in: *Proceedings. 1986 IEEE International Conference on Robotics and Automation, IEEE, 1986b*, pp. 1520–1532, <http://dx.doi.org/10.1109/ROBOT.1986.1087395>.
- [20] T. Okada, Computer control of multijointed finger system for precise object-handling, *IEEE Trans. Syst. Man Cybern.* 12 (1982) 289–299, <http://dx.doi.org/10.1109/TSMC.1982.4308818>.
- [21] J.K. Salisbury, J.J. Craig, Articulated hands: Force control and kinematic issues, *Int. J. Robot. Res.* 1 (1982) 4–17, <http://dx.doi.org/10.1177/027836498200100102>.
- [22] L. Bologni, S. Caselli, C. Melchiorri, *Design Issues for the UB Robotic Hand*, Univ. School of Engineering, 1988.
- [23] G.A. Bekey, R. Tomovic, I. Zeljkovic, Control architecture for the belgrade/usc hand, in: S.T. Venkataraman, T. Iberall (Eds.), *Dextrous Robot Hands*, Springer New York, New York, NY, ISBN: 978-1-4613-8974-3, 1990, pp. 136–149, http://dx.doi.org/10.1007/978-1-4613-8974-3_7.
- [24] A. Eusebi, C. Fantuzzi, C. Melchiorri, M. Sandri, A. Tonielli, The ub hand ii control system: design features and experimental results, in: *Proceedings of IECON'94-20th Annual Conference of IEEE Industrial Electronics, IEEE, 1994*, pp. 782–787, <http://dx.doi.org/10.1109/IECON.1994.397885>.
- [25] J. Butterfass, G. Hirzinger, S. Knoch, H. Liu, Dlr's multisensory articulated hand. i. hard-and software architecture, in: *Proceedings. 1998 IEEE International Conference on Robotics and Automation (Cat. No. 98CH36146)*, IEEE, 1998, pp. 2081–2086, <http://dx.doi.org/10.1109/ROBOT.1998.680625>.
- [26] H. Kawasaki, T. Komatsu, Mechanism design of anthropomorphic robot hand: Gifu hand i, *J. Robot. Mechatronics* 11 (1999) 269–273, <http://dx.doi.org/10.20965/jrm.1999.p0269>.
- [27] W. Townsend, The barretthand grasper—programmably flexible part handling and assembly, *Ind. Robot. Int. J.* 27 (2000) 181–188, <http://dx.doi.org/10.1108/01439910010371597>.
- [28] R.O. Ambrose, H. Aldridge, R.S. Askew, R.R. Burridge, W. Bluethmann, M. Diftler, C. Lovchik, D. Magruder, F. Rehnmark, Robonaut: Nasa's space humanoid, *IEEE Intell. Syst. their Appl.* 15 (2000) 57–63, <http://dx.doi.org/10.1109/5254.867913>.
- [29] P.J. Kyberd, P.H. Chappell, The southampton hand: an intelligent myoelectric prosthesis, *J. Rehabil. Res. Dev.* 31 (1994).
- [30] N. Fukaya, S. Toyama, T. Asfour, R. Dillmann, Design of the tuat/karlsruhe humanoid hand, in: *Proceedings of the 2000 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS, 2000*, pp. 1754–1759, <http://dx.doi.org/10.1109/IROS.2000.895225>.
- [31] C. Light, P. Chappell, Development of a lightweight and adaptable multiple-axis hand prosthesis, *Med. Eng. Phys.* 22 (2000) 679–684, [http://dx.doi.org/10.1016/S1350-4533\(01\)00017-0](http://dx.doi.org/10.1016/S1350-4533(01)00017-0).
- [32] P.J. Kyberd, C. Light, P.H. Chappell, J.M. Nightingale, D. Whatley, M. Evans, The design of anthropomorphic prosthetic hands: A study of the southampton hand, *Robotica* 19 (2001) 593–600, <http://dx.doi.org/10.1017/S0263574701003538>.
- [33] H. Kawasaki, T. Mouri, K. Yoshikawa, J. Takai, S. Ito, Anthropomorphic robot hand: Gifu hand iii, in: *International Conference on Control, Automation and Systems, ICCAS, 2002b*, pp. 1288–1293.
- [34] H. Liu, K. Wu, P. Meusel, N. Seitz, G. Hirzinger, M.H. Jin, Y.W. Liu, S.W. Fan, T. Lan, Z.P. Chen, Multisensory five-finger dexterous hand: The dlr/hit hand II, in: *Proceedings of the 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS, IEEE, 2008*, pp. 3692–3697, <http://dx.doi.org/10.1109/IROS.2008.4650624>.

- [35] GAZEAU J, F. Heintz, M. Arsicault, LALLEMAND J, A polyarticulated mechanical hand with 16 degrees of freedom—synthesis in the different sides of experimental site, in: Proc. of the 3rd France-Japan Congress & 1st Europe-Asia Congress on Mechatronics, 1996.
- [36] J. Gazeau, S. Zehloul, M. Arsicault, J. Lallemand, The lms hand: force and position controls in the aim of the fine manipulation of objects, in: Proceedings 2001 IEEE International Conference on Robotics and Automation, ICRA, IEEE, 2001, pp. 2642–2648, <http://dx.doi.org/10.1109/ROBOT.2001.933021>.
- [37] S. Schulz, C. Pylatiuk, G. Bretthauer, A new ultralight anthropomorphic hand, in: Proceedings 2001 IEEE International Conference on Robotics and Automation, ICRA, IEEE, 2001, pp. 2437–2441, <http://dx.doi.org/10.1109/ROBOT.2001.932988>.
- [38] H. Kawasaki, T. Komatsu, K. Uchiyama, Dexterous anthropomorphic robot hand with distributed tactile sensor: Gifu hand II, IEEE/ASME Trans. Mechatronics 7 (2002a) 296–303, <http://dx.doi.org/10.1109/TMECH.2002.802720>.
- [39] B. Massa, S. Roccella, M.C. Carrozza, P. Dario, Design and development of an underactuated prosthetic hand, in: Proceedings 2002 IEEE International Conference on Robotics and Automation (Cat. No. 02CH37292), IEEE, 2002, pp. 3374–3379, <http://dx.doi.org/10.1109/ROBOT.2002.1014232>.
- [40] Jingzhou Yang, Esteban Peña Pitarch, Karim Abdel-Malek, Amos Patrick, Lars Lindkvist, A multi-fingered hand prosthesis, Mech. Mach. Theory 39 (2004) 555–581, <http://dx.doi.org/10.1016/j.mechmachtheory.2004.01.002>.
- [41] S. Roccella, M.C. Carrozza, G. Cappiello, P. Dario, J.J. Cabibihan, M. Zecca, H. Miwa, K. Itoh, M. Marsumoto, Design, fabrication and preliminary results of a novel anthropomorphic hand for humanoid robotics: Rch-1, in: Proceedings of the 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), IEEE, IEEE, 2004, pp. 266–271, <http://dx.doi.org/10.1109/IROS.2004.1389363>.
- [42] M.C. Carrozza, C. Suppo, F. Sebastiani, B. Massa, F. Vecchi, R. Lazzarini, M.R. Cutkosky, P. Dario, The spring hand: Development of a self-adaptive prosthesis for restoring natural grasping, Auton. Robots 16 (2004a) 125–141, <http://dx.doi.org/10.1023/B:AURO.0000016863.48502.98>.
- [43] F. Lotti, P. Tiezzi, G. Vassura, L. Biagiotti, C. Melchiorri, Ubh 3: an anthropomorphic hand with simplified endo-skeletal structure and soft continuous fingerpads, in: Proceedings 2004 IEEE International Conference on Robotics and Automation, ICRA, vol. 5, IEEE, 2004, pp. 4736–4741, <http://dx.doi.org/10.1109/ROBOT.2004.1302466>.
- [44] T.B. Inc, Touch bionics website, 2013, [Internet].
- [45] A.M. Dollar, R.D. Howe, The sdm hand as a prosthetic terminal device: A feasibility study, in: 2007 IEEE 10th International Conference on Rehabilitation Robotics, 2007, pp. 978–983, <http://dx.doi.org/10.1109/ICORR.2007.4428542>.
- [46] C. Medynski, B. Rattray, Bebionic prosthetic design, in: Myoelectric Symposium, 2011.
- [47] L.B. Bridgwater, C. Ihrke, M.A. Diftler, M.E. Abdallah, N.A. Radford, J. Rogers, S. Yayathi, R.S. Askew, D.M. Linn, The robonaut 2 hand—designed to do work with tools, in: Proceedings 2012 IEEE International Conference on Robotics and Automation (ICRA), IEEE, IEEE, 2012, pp. 3425–3430, <http://dx.doi.org/10.1109/ICRA.2012.6224772>.
- [48] V. Systems, Vincent hand, 2013, [Internet].
- [49] O. Bock, Michelangelo Operation Manual, Duderstadt, Germany, 2012.
- [50] C. Melchiorri, G. Palli, G. Berselli, G. Vassura, Development of the ub hand IV: Overview of design solutions and enabling technologies, IEEE Robot. Autom. Mag. 20 (2013) 72–81, <http://dx.doi.org/10.1109/MRA.2012.2225471>.
- [51] M. Grebenstein, Approaching Human Performance: The Functionality-Driven Awiwi Robot Hand, in: Springer Tracts in Advanced Robotics 98 STAR, ISBN: 978-3-319-03593-2, 2016, <http://dx.doi.org/10.1007/978-3-319-03593-2>.
- [52] S.W. Ruehl, C. Parltz, G. Heppner, A. Hermann, R. Dillmann, Experimental evaluation of the schunk 5-finger gripping hand for grasping tasks, in: 2014 IEEE International Conference on Robotics and Biomimetics (ROBIO 2014), IEEE, 2014, pp. 2465–2470, <http://dx.doi.org/10.1109/robio.2014.7090710>.
- [53] I. Cerulo, F. Ficuciello, V. Lippello, B. Siciliano, Teleoperation of the schunk s5fh under-actuated anthropomorphic hand using human hand motion tracking, Robot. Auton. Syst. 89 (2017) 75–84, <http://dx.doi.org/10.1016/j.robot.2016.12.004>.
- [54] J.L. Pons, E. Rocon, R. Ceres, D. Reynaerts, B. Saro, S. Levin, W. Van Moorleghe, The manus-hand dextrous robotics upper limb prosthesis: mechanical and manipulation aspects, Auton. Robots 16 (2004) 143–163, <http://dx.doi.org/10.1023/B:AURO.0000016862.38337.f1>.
- [55] H. Kawasaki, T. Mouri, S. Ito, Toward next stage of kinetic humanoid hand, in: Proceedings World Automation Congress, 2004, pp. 129–134.
- [56] F. Lotti, P. Tiezzi, G. Vassura, L. Biagiotti, G. Palli, C. Melchiorri, Development of ub hand 3: Early results, in: Proceedings of the 2005 IEEE International Conference on Robotics and Automation, IEEE, 2005, pp. 4488–4493, <http://dx.doi.org/10.1109/ROBOT.2005.1570811>.
- [57] A.D. Deshpande, Z. Xu, M.J.V. Weghe, B.H. Brown, J. Ko, L.Y. Chang, D.D. Wilkinson, S.M. Bidic, Y. Matsuoka, Mechanisms of the anatomically correct testbed hand, IEEE/ASME Trans. Mechatronics 18 (2013) 238–250, <http://dx.doi.org/10.1109/TMECH.2011.2166801>.
- [58] L.Y. Chang, Y. Matsuoka, A kinematic thumb model for the act hand, in: Proceedings 2006 IEEE International Conference on Robotics and Automation, ICRA, IEEE, 2006, pp. 1000–1005, <http://dx.doi.org/10.1109/ROBOT.2006.1641840>.
- [59] M.C. Carrozza, G. Cappiello, S. Micera, B.B. Edin, L. Beccai, C. Cipriani, Design of a cybernetic hand for perception and action, Biol. Cybernet. 95 (2006) 629–644, <http://dx.doi.org/10.1007/s00422-006-0124-2>.
- [60] C. Gosselin, F. Pelletier, T. Laliberte, An anthropomorphic underactuated robotic hand with 15 dofs and a single actuator, in: 2008 IEEE International Conference on Robotics and Automation, 2008, pp. 749–754, <http://dx.doi.org/10.1109/ROBOT.2008.4543295>.
- [61] C. Connolly, Prosthetic hands from touch bionics, Ind. Robot. Int. J. 35 (2008) 290–293, <http://dx.doi.org/10.1108/01439910810876364>.
- [62] I.N. Gaiser, C. Pylatiuk, S. Schulz, A. Kargov, R. Oberle, T. Werner, The fluidhand iii: A multifunctional prosthetic hand, JPO: J. Prosthetics Orthot. 21 (2009) 91–96, <http://dx.doi.org/10.1097/JPO.0b013e3181a1ca54>.
- [63] A. Schmitz, U. Pattacini, F. Nori, L. Natale, G. Metta, G. Sandini, Design, realization and sensorization of the dexterous icub hand, in: 2010 10th IEEE-RAS International Conference on Humanoid Robots, IEEE, 2010, pp. 186–191, <http://dx.doi.org/10.1109/ICHR.2010.5686825>.
- [64] J.T. Belter, A.M. Dollar, Novel differential mechanism enabling two dof from a single actuator: application to a prosthetic hand, in: IEEE International Conference on Rehabilitation Robotics, 2013, 6650441, <http://dx.doi.org/10.1109/ICORR.2013.6650441>.
- [65] G. Palli, C. Melchiorri, G. Vassura, U. Scarcia, L. Moriello, G. Berselli, A. Cavallo, G. de Maria, C. Natale, S. Pirozzi, C. May, F. Ficuciello, B. Siciliano, The dextrart hand: Mechatronic design and experimental evaluation of synergy-based control for human-like grasping, Int. J. Robot. Res. 33 (2014) 799–824, <http://dx.doi.org/10.1177/0278364913519897>.
- [66] B. Peerdeman, M. Valori, D. Brouwer, E. Hekman, S. Misra, S. Stramigioli, Ut hand I: A lock-based underactuated hand prosthesis, Mech. Mach. Theory 78 (2014) 307–323, <http://dx.doi.org/10.1016/j.mechmachtheory.2014.03.018>.
- [67] M. Grebenstein, M. Chalon, G. Hirzinger, R. Siegwart, A method for hand kinematics designers 7 billion perfect hands, in: 1st International Conference on Applied Bionics and Biomechanics ICABB-2010, 2010.
- [68] S. Pulleyking, J. Schultz, A compliant rolling ellipsoidal thumb joint for the TU hand, 2023, <http://dx.doi.org/10.36227/techrxiv.22199395.v1>.
- [69] M.G. Catalano, G. Grioli, E. Farnioli, A. Serio, M. Bonilla, M. Garabini, C. Piazza, M. Gabiccini, A. Bichi, From soft to adaptive synergies: The pisa/iit soft-hand, in: M. Bianchi, A. Moscatelli (Eds.), Human and Robot Hands, in: Springer Series on Touch and Haptic Systems, Springer International Publishing, Cham, ISBN: 978-3-319-26706-7, 2016, pp. 101–125, http://dx.doi.org/10.1007/978-3-319-26706-7_8.
- [70] Z. Xu, E. Todorov, Design of a highly biomimetic anthropomorphic robotic hand towards artificial limb regeneration, in: Proceedings 2016 IEEE International Conference on Robotics and Automation, ICRA, IEEE, 2016, pp. 3485–3492, <http://dx.doi.org/10.1109/ICRA.2016.7487528>.
- [71] S. Savić, M. Raković, M. Penčić, M. Nikolić, S. Dudić, B. Borovac, Design of an underactuated adaptive robotic hand with force sensing, in: International Conference on Electrical, Electronic and Computing Engineering IeTRAN.

- [72] C. Konnaris, C. Gavriel, A.A. Thomik, A.A. Faisal, Ethohand: A dexterous robotic hand with ball-joint thumb enables complex in-hand object manipulation, in: 2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics, BioRob, IEEE, 2016, pp. 1154–1159, <http://dx.doi.org/10.1109/BIO ROB.2016.7523787>.
- [73] C. Della Santina, C. Piazza, G. Grioli, M.G. Catalano, A. and Bicchi, Toward dexterous manipulation with augmented adaptive synergies: The pisa/iit soft hand 2, IEEE Trans. Robot. 34 (2018a) 1141–1156, <http://dx.doi.org/10.1109/TRO.2018.2830407>.
- [74] H. Zhou, A. Mohammadi, D. Oetomo, G. Alici, A novel monolithic soft robotic thumb for an anthropomorphic prosthetic hand, IEEE Robot. Autom. Lett. 4 (2019a) 602–609, <http://dx.doi.org/10.1109/LRA.2019.2892203>.
- [75] H. Yang, G. Wei, L. Ren, Design and development of a linkage-tendon hybrid driven anthropomorphic robotic hand, in: H. Yu, J. Liu, L. Liu, Z. Ju, Y. Liu, D. Zhou (Eds.), Intelligent Robotics and Applications, in: Lecture Notes in Computer Science, vol. 11740, Springer International Publishing, Cham, 2019, pp. 117–128, http://dx.doi.org/10.1007/978-3-030-27526-6_11.
- [76] S. Pulleyking, J. Schultz, Flexure hinge-based biomimetic thumb with a rolling-surface metacarpal joint, in: Proceedings 2020 IEEE International Conference on Robotics and Automation, ICRA, IEEE, 2020, pp. 2960–2966, <http://dx.doi.org/10.1109/ICRA40945.2020>.
- [77] G. Gao, A. Dwivedi, M. Liarokapis, The new dexterity adaptive humanlike robot hand: Employing a reconfigurable palm for robust grasping and dexterous manipulation, in: Proceedings 2023 IEEE International Conference on Robotics and Automation, ICRA, IEEE, 2023, pp. 10310–10316, <http://dx.doi.org/10.1109/ICRA48891.2023.10161369>.
- [78] R. Tomovic, G. Boni, An adaptive artificial hand, IRE Trans. Autom. Control. 7 (1962) 3–10, <http://dx.doi.org/10.1109/TAC.1962.1105456>.
- [79] H. de Visser, J. Herder, Force-directed design of a voluntary closing hand prosthesis, J. Rehabil. Res. Dev. 37 (2000) 261–271, <http://dx.doi.org/10.1115/DETC2000/MECH-14149>.
- [80] M.C. Carrozza, F. Vecchi, F. Sebastiani, G. Cappiello, S. Roccella, M. Zecca, R. Lazzarini, P. Dario, Experimental analysis of an innovative prosthetic hand with proprioceptive sensors, in: Proceedings 2003 IEEE International Conference on Robotics and Automation, ICRA, IEEE, 2003, pp. 2230–2235, <http://dx.doi.org/10.1109/ROBOT.2003.1241925>.
- [81] L. Birglen, C.M. Gosselin, Force analysis of connected differential mechanisms: Application to grasping, Int. J. Robot. Res. 25 (2006) 1033–1046, <http://dx.doi.org/10.1177/0278364906068942>.
- [82] Y. Kamikawa, T. Maeno, Underactuated five-finger prosthetic hand inspired by grasping force distribution of humans, in: Proceedings of the 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS, IEEE, 2008, pp. 717–722, <http://dx.doi.org/10.1109/IROS.2008.4650628>.
- [83] S.A. Dalley, T.E. Wiste, T.J. Withrow, M. Goldfarb, Design of a multifunctional anthropomorphic prosthetic hand with extrinsic actuation, IEEE/ASME Trans. Mechatronics 14 (2009) 699–706, <http://dx.doi.org/10.1109/TMECH.2009.2033113>.
- [84] M. Baril, T. Laliberté, F. Guay, C. Gosselin, Static analysis of single-input/multiple-output tendon-driven underactuated mechanisms for robotic hands, in: ASME 2010 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 2010, pp. 155–164, <http://dx.doi.org/10.1115/DETC2010-28933>.
- [85] C. Cipriani, M. Controzzi, M.C. Carrozza, Objectives, criteria and methods for the design of the smarthand transradial prosthesis, Robotica 28 (2010) 919–927, <http://dx.doi.org/10.1017/S0263574709990750>.
- [86] T. Laliberté, M. Baril, F. Guay, C. Gosselin, Towards the design of a prosthetic underactuated hand, Mech. Sci. 1 (2010) 19–26, <http://dx.doi.org/10.5194/ms-1-19-2010>.
- [87] L. Wang, J. DelPreto, S. Bhattacharyya, J. Weisz, P.K. Allen, A highly-underactuated robotic hand with force and joint angle sensors, in: Proceedings of the 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS, IEEE, 2011, pp. 1380–1385, <http://dx.doi.org/10.1109/IROS.2011.6095147>.
- [88] M. Baril, T. Laliberté, C. Gosselin, F. Routhier, On the design of a mechanically programmable underactuated anthropomorphic prosthetic gripper, J. Mech. Des. (2013) 135, <http://dx.doi.org/10.1115/1.4025493>.
- [89] R.R. Ma, L.U. Odhner, A.M. Dollar, A modular, open-source 3d printed underactuated hand, in: Proceedings 2013 IEEE International Conference on Robotics and Automation, ICRA, IEEE, 2013, pp. 2737–2743, <http://dx.doi.org/10.1109/ICRA.2013.6630954>.
- [90] M.G. Catalano, G. Grioli, E. Farnioli, A. Serio, C. Piazza, A. Bicchi, Adaptive synergies for the design and control of the pisa/iit soft hand, Int. J. Robot. Res. 33 (2014) 768–782, <http://dx.doi.org/10.1177/0278364913518998>.
- [91] V. Niola, C. Rossi, S. Savino, S. Troncone, An underactuated mechanical hand: A first prototype, in: 2014 23rd International Conference on Robotics in Alpe-Adria-Danube Region, RAAD, pp. 1–6, <http://dx.doi.org/10.1109/RAAD.2014.7002225>.
- [92] G.P. Kontoudis, M.V. Liarokapis, A.G. Zisimatos, C.I. Mavrogiannis, K.J. Kyriakopoulos, Open-source, anthropomorphic, underactuated robot hands with a selectively lockable differential mechanism: Towards affordable prostheses, in: Proceedings of the 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS, IEEE, 2015, pp. 5857–5862, <http://dx.doi.org/10.1109/IROS.2015.7354209>.
- [93] A. Mottard, T. Laliberté, C. Gosselin, Underactuated tendon-driven robotic/prosthetic hands: Design issues, in: 2017 Proceedings of Robotics Science and Systems, 2017, pp. 1–9.
- [94] T. Wiste, M. Goldfarb, Design of a simplified compliant anthropomorphic robot hand, in: Proceedings 2017 IEEE International Conference on Robotics and Automation, ICRA, IEEE, 2017, pp. 3433–3438, <http://dx.doi.org/10.1109/ICRA.2017.7989391>.
- [95] P. Weiner, J. Starke, F. Hundhausen, J. Beil, T. Asfour, The kit prosthetic hand: Design and control, in: Proceedings of the 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS, IEEE, 2018, <http://dx.doi.org/10.1109/IROS.2018.8593851>.
- [96] K. Mizushima, T. Oku, Y. Suzuki, T. Tsuji, T. Watanabe, Multi-fingered robotic hand based on hybrid mechanism of tendon-driven and jamming transition, in: 2018 IEEE International Conference on Soft Robotics, RoboSoft, 2018, pp. 376–381, <http://dx.doi.org/10.1109/ROBOSOFT.2018.8404948>.
- [97] G.P. Kontoudis, M. Liarokapis, K.G. Vamvoudakis, A compliant, underactuated finger for anthropomorphic hands, in: IEEE International Conference on Rehabilitation Robotics, 2019, pp. 682–688, <http://dx.doi.org/10.1109/ICORR.2019.8779435>.
- [98] H. Liu, B. Zhao, Z. Liu, K. Xu, Design of a lightweight single-actuator multi-grasp prosthetic hand with force magnification, J. Mech. Robot. 12 (2020) <http://dx.doi.org/10.1115/1.4047438>.
- [99] N. Nikafrooz, A. Leonessa, A single-actuated, cable-driven, and self-contained robotic hand designed for adaptive grasps, Robotics 10 (2021) 109, <http://dx.doi.org/10.3390/robotics10040109>.
- [100] B.Y. Sun, X. Gong, J. Liang, W.B. Chen, Z.L. Xie, C. Liu, C.H. Xiong, Design principle of a dual-actuated robotic hand with anthropomorphic self-adaptive grasping and dexterous manipulation abilities, IEEE Trans. Robot. 38 (2022) 2322–2340, <http://dx.doi.org/10.1109/TRO.2021.3132532>.
- [101] V.K. Nanayakkara, G. Cottugno, N. Vitzilaos, D. Venetsanos, T. Nanayakkara, M.N. Sahinkaya, The role of morphology of the thumb in anthropomorphic grasping: A review, Front. Mech. Eng. 3 (2017) <http://dx.doi.org/10.3389/fmech.2017.00005>.
- [102] L. Birglen, T. Laliberté, C. Gosselin, Underactuated Robotic Hands, Springer, ISBN: 978-3-540-77459-4, 2008, <http://dx.doi.org/10.1007/978-3-540-77459-4>.
- [103] K. Shimoga, A. Goldenberg, Soft materials for robotic fingers, in: Proceedings of the 1992 IEEE International Conference on Robotics and Automation, ICRA, IEEE, 1992, <http://dx.doi.org/10.1109/ROBOT.1992.220069>.
- [104] K. Shimoga, A. Goldenberg, Soft robotic fingertips, Int. J. Robot. Res. (1996) <http://dx.doi.org/10.1177/027836499601500402>.
- [105] M. Cutkosky, J. Jourdain, P. Wright, Skin materials for robotic fingers, in: Proceedings of the 1987 IEEE International Conference on Robotics and Automation, ICRA, IEEE, 1987, pp. 1649–1654, <http://dx.doi.org/10.1109/ROBOT.1987.1087913>.

- [106] L. Biagiotti, C. Melchiorri, P. Tiezzi, G. Vassura, Modelling and identification of soft pads for robotic hands, in: Proceedings of the 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS, IEEE, 2005, pp. 2786–2791, <http://dx.doi.org/10.1109/IROS.2005.1545529>.
- [107] M. Controzzi, M.D. Alonzo, C. Peccia, C.M. Oddo, Bioinspired fingertip for anthropomorphic robotic hands, *Appl. Bionics Biomech.* 11 (2014) <http://dx.doi.org/10.3233/ABB-140092>.
- [108] A.V. Sureshbabu, G. Metta, A. Parmiggiani, A new cost effective robot hand for the icub humanoid, in: Proceedings of the 2015 IEEE-RAS International Conference on Humanoid Robots (Humanoids), IEEE, 2015, pp. 750–757, <http://dx.doi.org/10.1109/HUMANOIDS.2015.7363454>.
- [109] H. Yang, G. Wei, L. Ren, Z. Qian, K. Wang, H. Xiu, W. Liang, An affordable linkage-and-tendon hybrid-driven anthropomorphic robotic hand—mcr-hand II, *J. Mech. Robot.* 13 (2021) <http://dx.doi.org/10.1115/1.4049744>.
- [110] H. Liu, P. Meusel, N. Seitz, B. Willberg, G. Hirzinger, M.H. Jin, Y.W. Liu, R. Wei, Z.W. Xie, The modular multisensory dlr-hit-hand, *Mech. Mach. Theory* 42 (2007) 612–625, <http://dx.doi.org/10.1016/j.mechmachtheory.2006.04.013>.
- [111] S. Pulleyking, D. Das, J. Schultz, Simplified robotic thumb inspired by surgical intervention, in: 2016 6th IEEE International Conference on Biomedical Robotics and Biomechanics, BioRob, IEEE, 2016, pp. 1200–1206, <http://dx.doi.org/10.1109/BIOROB.2016.7523794>.
- [112] H. Wang, S. Fan, H. Liu, Thumb configuration and performance evaluation for dexterous robotic hand design, *J. Mech. Des.* (2017a) 139, <http://dx.doi.org/10.1115/1.4034837>.
- [113] D. Sharma, K. Tokas, A. Puri, K. Sharda, Shadow hand, *J. Adv. Res. Appl. Sci.* (ISSN: 2208-2352) 1 (2014) 04–07, <http://dx.doi.org/10.53555/nnas.v1i1.692>.
- [114] J. Martin, M. Grossard, Design of a fully modular and backdrivable dexterous hand, *Int. J. Robot. Res.* 33 (2014) 783–798, <http://dx.doi.org/10.1177/0278364913511677>.
- [115] Y. Kurita, Y. Ono, A. Ikeda, T. Ogasawara, Naist hand 2: Human-sized anthropomorphic robot hand with detachable mechanism at the wrist, in: 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, IEEE, 2009, pp. 2271–2276, <http://dx.doi.org/10.1109/IROS.2009.5354439>.
- [116] G. Palli, S. Pirozzi, An optical joint position sensor for anthropomorphic robot hands, in: 2013 IEEE International Conference on Robotics and Automation, IEEE, 2013, pp. 2765–2770, <http://dx.doi.org/10.1109/ICRA.2013.6630958>.
- [117] Konstantinos Andrianesis, Anthony Tzes, Development and control of a multifunctional prosthetic hand with shape memory alloy actuators, *Journal of Intelligent & Robotic Systems* 78 (2015) 257–289, <http://dx.doi.org/10.1007/s10846-014-0061-6>.
- [118] Z. Zhang, T. Han, J. Pan, Z. Wang, Catch-919 hand: Design of a 9-actuator 19-dof anthropomorphic robotic hand, 2018, <http://dx.doi.org/10.48550/arXiv.1809.04290>, arXiv preprint [arXiv:1809.04290](https://arxiv.org/abs/1809.04290).
- [119] H. Iwata, S. Sugano, Design of anthropomorphic dexterous hand with passive joints and sensitive soft skins, in: 2009 IEEE/SICE International Symposium on System Integration, SII, IEEE, 2009, pp. 129–134, <http://dx.doi.org/10.1109/SI.2009.5384542>.
- [120] J. Butterfass, M. Grebenstein, H. Liu, G. Hirzinger, Dlr-hand II: next generation of a dextrous robot hand, in: Proceedings 2001 IEEE International Conference on Robotics and Automation, ICRA, IEEE, 2001, pp. 109–114, <http://dx.doi.org/10.1109/ROBOT.2001.932538>.
- [121] J. Ueda, M. Kondo, T. Ogasawara, The multifingered naist hand system for robot in-hand manipulation, *Mech. Mach. Theory* 45 (2010) 224–238, <http://dx.doi.org/10.1016/j.mechmachtheory.2009.08.007>.
- [122] C.M. Gosselin, Adaptive robotic mechanical systems: A design paradigm, *J. Mech. Des.* 128 (2006) 192–198, <http://dx.doi.org/10.1115/1.2120781>.
- [123] D.p Yang, J.d Zhao, Y.k Gu, X.q Wang, N. Li, L. Jiang, H. Liu, H. Huang, D.w Zhao, An anthropomorphic robot hand developed based on underactuated mechanism and controlled by emg signals, *J. Bionic Eng.* 6 (2009) 255–263, [http://dx.doi.org/10.1016/S1672-6529\(08\)60119-5](http://dx.doi.org/10.1016/S1672-6529(08)60119-5).
- [124] Sungjae Min, Sooyeong Yi, Development of cable-driven anthropomorphic robot hand, *IEEE Robotics and Automation Letters* 6 (2) (2021) 1176–1183, <http://dx.doi.org/10.1109/LRA.2021.3056375>.
- [125] T. Laliberté, C.M. Gosselin, Underactuation in space robotic hands, in: Proceeding of the Sixth International Symposium on Artificial Intelligence, Robotics and Automation in Space ISAIRAS: A New Space Odyssey, 2001.
- [126] Norsinnira Zainul Azlan, Hiroshi Yamaura, Anthropomorphic finger with optimized geometric parameters for pinching and grasping tasks, *Mechanism and Machine Theory* 49 (2012) 52–66, <http://dx.doi.org/10.1016/j.mechmachtheory.2011.11.005>.
- [127] Wu Licheng, Kong Yanxuan, Li Xiali, A fully rotational joint underactuated finger mechanism and its kinematics analysis, *International Journal of Advanced Robotic Systems* 13 (5) (2016) <http://dx.doi.org/10.1177/1729881416663373>, 1729881416663373.
- [128] Daniele Esposito, Sergio Savino, Emilio Andreozzi, Chiara Cosenza, Vincenzo Niola, Paolo Bifulco, The “Federica” Hand, *Bioengineering* 8 (9) (2021) 128, <http://dx.doi.org/10.3390/bioengineering8090128>.
- [129] Marco Ceccarelli, M Zottola, Design and simulation of an underactuated finger mechanism for LARM Hand, *Robotica* 35 (3) (2017) 483–497, <http://dx.doi.org/10.1017/S0263574715000648>.
- [130] N.E.N. Rodriguez, G. Carbone, M. Ceccarelli, Optimal design of driving mechanism in a 1-dof anthropomorphic finger, *Mech. Mach. Theory* 41 (2006) 897–911, <http://dx.doi.org/10.1016/j.mechmachtheory.2006.03.016>.
- [131] K. Tae-uk, O. Yonghwan, Design of spatial adaptive fingered gripper using spherical five-bar mechanism, in: Proceedings of the 2014 International Conference on Advanced Mechatronic Systems, vol. 14, 2014, pp. 5–150, <http://dx.doi.org/10.1109/ICAMEchS.2014.6911640>.
- [132] Seokwon Lee, Samyeul Noh, Yongkwun Lee, Jong Hyeon Park, Development of bio-mimetic robot hand using parallel mechanisms, in: 2009 IEEE International Conference on Robotics and Biomimetics (ROBIO), IEEE, 2009, pp. 550–555, <http://dx.doi.org/10.1109/ROBIO.2009.5420706>.
- [133] Panipat Wattanasiri, Pairat Tangpornprasert, Chanyaphan Virulsri, Design of multi-grip patterns prosthetic hand with single actuator, *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 26 (6) (2018) 1188–1198, <http://dx.doi.org/10.1109/TNSRE.2018.2829152>.
- [134] G. Berselli, G. Borghesan, M. Brandi, C. Melchiorri, C. Natale, G. Palli, S. Pirozzi, G. Vassura, Integrated mechatronic design for a new generation of robotic hands, *IFAC Proc. Vol.* 42 (2009) 8–13, <http://dx.doi.org/10.3182/20090909-4-JP-2010.00004>.
- [135] D.J. Oh, Z.Y. Li, J.H. Kim, H.R. Choi, H. Moon, J.C. Koo, A flexible self-recovery finger joint for a tendon-driven robot hand, *Rev. Sci. Instrum.* 91 (2020) 115002, <http://dx.doi.org/10.1063/5.0020137>.
- [136] M.G. Catalano, G. Grioli, A. Serio, E. Farnioli, C. Piazza, A. Bicchi, Adaptive synergies for a humanoid robot hand, in: Proceedings of the 2012 IEEE-RAS International Conference on Humanoid Robots, Humanoids, IEEE, 2012, pp. 7–14, <http://dx.doi.org/10.1109/HUMANOIDS.2012.6651492>.
- [137] A.G. Eguiluz, I. Rano, S.A. Coleman, T.M. McGinnity, Reliable object handover through tactile force sensing and effort control in the shadow robot hand, in: Proceedings 2017 IEEE International Conference on Robotics and Automation, ICRA, IEEE, 2017, pp. 372–377, <http://dx.doi.org/10.1109/ICRA.2017.7989048>.
- [138] S. Davis, N.G. Tsarakakis, D.G. Caldwell, The initial design and manufacturing process of a low cost hand for the robot icub, *IEEE-RAS Int. Conf. Humanoid Robot.* 8 (2008) 40–45, <http://dx.doi.org/10.1109/ICHR.2008.4755929>.
- [139] Cosimo Della Santina, Cristina Piazza, Giorgio Grioli, Manuel G Catalano, Antonio Bicchi, Toward dexterous manipulation with augmented adaptive synergies: The pisa/iit softand 2, *IEEE Transactions on Robotics* 34 (5) (2018) 1141–1156, <http://dx.doi.org/10.1109/TRO.2018.2830407>.
- [140] Z. Xu, V. Kumar, E. Todorov, A low-cost and modular, 20-dof anthropomorphic robotic hand: Design, actuation and modeling, in: Proceedings of the 2013 IEEE-RAS International Conference on Humanoid Robots (Humanoids), IEEE, IEEE, 2013, pp. 368–375, <http://dx.doi.org/10.1109/HUMANOIDS.2013.7030001>.
- [141] M Riabtev, V Petuya, M Urizar, E Macho, Design and analysis of an active 2-DOF lockable joint, *Mechanics Based Design of Structures and Machines* 50 (8) (2022) 2736–2759, <http://dx.doi.org/10.1080/15397734.2020.1784203>.
- [142] K.L. Moore, A.F. Dalley, *Clinically Oriented Anatomy*, Wolters kluwer india Pvt Ltd., ISBN: 978-1496347213, 2018.

- [143] C. Melchiorri, G. Vassura, Mechanical and control issues for integration of an arm-hand robotic system, in: R. Chatila, G. Hirzinger (Eds.), *Experimental Robotics II*, in: Lecture Notes in Control and Information Sciences, vol. 190, Springer, London, 1993, pp. 136–152, <http://dx.doi.org/10.1007/BFb0036136>.
- [144] F. Lotti, G. Vassura, A novel approach to mechanical design of articulated fingers for robotic hands, in: *IEEE/RSJ International Conference on Intelligent Robots and Systems*, IEEE, 2002, pp. 1687–1692, <http://dx.doi.org/10.1109/IRDS.2002.1043998>.
- [145] H. Kawasaki, T. Mouri, T. Endo, Review of gifu hand and its application, *Mech. Based Des. Struct. Mach.* 39 (2011) 210–228, <http://dx.doi.org/10.1080/15397734.2011.550857>.
- [146] M. Chalon, M. Grebenstein, T. Wimböck, G. Hirzinger, The thumb: Guidelines for a robotic design, in: *Proceedings 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS, IEEE*, 2010, pp. 5886–5893, <http://dx.doi.org/10.1109/IROS.2010.5650454>.
- [147] Deutsches Institut für Normung e.V., DIN 33402-2, 2020.
- [148] M. Vergara, M.J. Agost, V. Gracia-Ibáñez, Dorsal and palmar aspect dimensions of hand anthropometry for designing hand tools and protections, *Hum. Factors Ergon. Manuf. Serv. Ind.* 28 (2018) 17–28, <http://dx.doi.org/10.1002/hfm.20714>.
- [149] S.C. Jee, Y.S. Lee, J.H. Lee, S. Park, B. Jin, M.H. Yun, Anthropometric classification of human hand shapes in korean population, in: *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, SAGE Publications Sage CA, Los Angeles, CA, 2016, pp. 1200–1204, <http://dx.doi.org/10.1177/1541931213601281>.
- [150] J.C. Becker, N.V. Thakor, A study of the range of motion of human fingers with application to anthropomorphic designs, *IEEE Trans. Bio-Medical Eng.* 35 (1988) 110–117, <http://dx.doi.org/10.1109/10.1348>.
- [151] M.C. Hume, H. Gellman, H. McKellop, R.H. Brumfield, Functional range of motion of the joints of the hand, *J. Hand Surg.* 15 (1990) 240–243, [http://dx.doi.org/10.1016/0363-5023\(90\)90102-W](http://dx.doi.org/10.1016/0363-5023(90)90102-W).
- [152] M. El-Shennawy, K. Nakamura, R.M. Patterson, S.F. Viegas, Three-dimensional kinematic analysis of the second through fifth carpometacarpal joints, *J. Hand Surg.* 26 (2001) 1030–1035, <http://dx.doi.org/10.1053/jhsu.2001.28761>.
- [153] S. Cobos, M. Ferre, M.A. Sanchez Uran, J. Ortego, C. Pena, Efficient human hand kinematics for manipulation tasks, in: *Proceedings of the 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS, IEEE*, 2008, pp. 2246–2251, <http://dx.doi.org/10.1109/IROS.2008.4651053>.
- [154] M.J. Barakat, J. Field, J. Taylor, The range of movement of the thumb, *Hand (New York, N.Y.)* 8 (2013) 179–182, <http://dx.doi.org/10.1007/s11552-013-9492-y>.
- [155] J.G. Ngeo, T. Tamei, T. Shibata, Continuous and simultaneous estimation of finger kinematics using inputs from an emg-to-muscle activation model, *J. Neuroeng. Rehabil.* 11 (2014) 122, <http://dx.doi.org/10.1186/1743-0003-11-122>.
- [156] E. Peña-Pitarch, N.T. Falguera, J.J. Yang, Virtual human hand: model and kinematics, *Comput. Methods Biomech. Biomed. Eng.* 17 (2014) 568–579, <http://dx.doi.org/10.1080/10255842.2012.702864>.
- [157] G.I. Bain, N. Polites, B.G. Higgs, R.J. Heptinstall, A.M. McGrath, The functional range of motion of the finger joints, *J. Hand Surg. Eur.* 40 (2015) 406–411, <http://dx.doi.org/10.1177/1753193414533754>.
- [158] K.S. Lee, M.C. Jung, Ergonomic evaluation of biomechanical hand function, *Saf. Heal. At Work.* 6 (2015) 9–17, <http://dx.doi.org/10.1016/j.shaw.2014.09.002>.
- [159] F.P.J. van der Hulst, S. Schatzle, C. Preusche, A. Schiele, A functional anatomy based kinematic human hand model with simple size adaptation, in: *Proceedings 2012 IEEE International Conference on Robotics and Automation, ICRA, IEEE*, 2012, pp. 5123–5129, <http://dx.doi.org/10.1109/ICRA.2012.6225350>.
- [160] I.A. Kapanji, *The physiology of the joint*, 1987, lower limb. 2.
- [161] M. Grebenstein, M. Chalon, W. Friedl, S. Haddadin, T. Wimböck, G. Hirzinger, R. Siegwart, The hand of the dlr hand arm system: Designed for interaction, *Int. J. Robot. Res.* 31 (2012) 1531–1555, <http://dx.doi.org/10.1177/0278364912459209>.
- [162] D. Leonardis, A. Frisoli, Cora hand: a 3d printed robotic hand designed for robustness and compliance, *Meccanica* 55 (2020) 1623–1638, <http://dx.doi.org/10.1007/s11012-020-01188-0>.
- [163] J. Zhou, X. Chen, U. Chang, J.T. Lu, C.C.Y. Leung, Y. Chen, Y. Hu, Z. Wang, A soft-robotic approach to anthropomorphic robotic hand dexterity, *Ieee Access* 7 (2019b) 101483–101495, <http://dx.doi.org/10.1109/access.2019.2929690>.
- [164] Hai Huang, Li Jiang, Yiwei Liu, Linqi Hou, Hegao Cai, Hong Liu, The mechanical design and experiments of HIT/DLR prosthetic hand, in: *2006 IEEE International Conference on Robotics and Biomimetics, IEEE*, 2006, pp. 896–901, <http://dx.doi.org/10.1109/ROBIO.2006.340339>.
- [165] R. Fourie, 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)*, IEEE, 2017, pp. 38–43, <http://dx.doi.org/10.1109/robomech.2017.8261120>.
- [166] M. Tavakoli, A.T. de Almeida, Adaptive under-actuated anthropomorphic hand: Isr-soft-hand, in: *Proceedings of the 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS, IEEE*, 2014, pp. 1629–1634, <http://dx.doi.org/10.1109/IROS.2014.6942773>.
- [167] C. Cipriani, M. Controzzi, M.C. Carrozza, The smarthand transradial prosthesis, *J. Neuroeng. Rehabil.* 8 (2011) 1–14, <http://dx.doi.org/10.1186/1743-0003-8-29>.
- [168] J.T. Belter, A.M. Dollar, Performance characteristics of anthropomorphic prosthetic hands, in: *IEEE International Conference on Rehabilitation Robotics*, 2011, pp. 1–7, <http://dx.doi.org/10.1109/icorr.2011.5975476>.
- [169] J.N. Ingram, K.P. Kording, I.S. Howard, D.M. Wolpert, The statistics of natural hand movements, *Exp. Brain Res.* 188 (2008) 223–236, <http://dx.doi.org/10.1007/s00221-008-1355-3>.
- [170] F. Lotti, P. Tiezzi, G. Vassura, L. Biagiotti, G. Palli, C. Melchiorri, Development of ub hand 3: Early results, in: *Proceedings of the 2005 IEEE International Conference on Robotics and Automation, ICRA, IEEE*, 2005, pp. 4488–4493, <http://dx.doi.org/10.1109/ROBOT.2005.1570811>.
- [171] T.P. Tomo, A. Schmitz, W.K. Wong, H. Kristanto, S. Somlor, J. Hwang, L. Jamone, S. Sugano, Covering a robot fingertip with uskin: A soft electronic skin with distributed 3-axis force sensitive elements for robot hands, *IEEE Robot. Autom. Lett.* 3 (2018) 124–131, <http://dx.doi.org/10.1109/LRA.2017.2734965>.
- [172] F. Shao, T.H. Childs, B. Henson, Developing an artificial fingertip with human friction properties, *Tribol. Int.* 42 (2009) 1575–1581, <http://dx.doi.org/10.1016/j.triboint.2009.02.005>.
- [173] Y. Matsuoka, The mechanisms in a humanoid robot hand, *Auton. Robots* 4 (1997) 199–209, <http://dx.doi.org/10.1023/A:1008873918987>.
- [174] Wilson Ruotolo, Rachel Thomasson, Joel Herrera, Alex Grubele, Mark Cutkosky, Distal hyperextension is handy: High range of motion in cluttered environments, *IEEE Robot. Autom. Lett.* (2020) <http://dx.doi.org/10.1109/LRA.2020.2965914>.
- [175] Dai Chu, Caihua Xiong, Zhiyi Huang, Jinhao Yang, Jiaji Ma, Jiarui Zhang, Bai-yang Sun, Junjie Cai, Human palm performance evaluation and the palm design of humanoid robotic hands, *IEEE Robot. Autom. Lett.* 9 (3) (2024) 2463–2470, <http://dx.doi.org/10.1109/LRA.2024.3354619>.
- [176] P.S. Lee, C. Sjaarda, R. Cornelious, R.Z. Gao, K. Lu, C.L. Ren, Naturally compliant dexterous anthropomorphic hand via novel modular soft-rigid hybrid robotics approach: Design rationale, assembly methods, and evaluation, in: *2023 32nd IEEE International Conference on Robot and Human Interactive Communication, RO-MAN, IEEE*, 2023, pp. 2281–2287, <http://dx.doi.org/10.1109/RO-MAN57019.2023.10309552>.
- [177] A. Farinha, P.U. Lima, A novel underactuated hand suitable for human-oriented domestic environments, in: *2016 International Conference on Autonomous Robot Systems and Competitions, ICARSC, IEEE*, 2016, pp. 106–111, <http://dx.doi.org/10.1109/ICARSC.2016.21>.
- [178] P. van der Smagt, G. Stillfried, Using mrt data to compute a hand kinematic model, in: *Proceedings of MOVIC 2008*, 2008.
- [179] G. Stillfried, P. van der Smagt, R. Balasubramanian, Y. Matsuoka, Human hand kinematics based on mri imaging, in: *Understanding the Human Hand for Advancing Robotic Manipulation Workshop At Robotics: Science and Systems*, 2009.

- [180] G. Stillfried, P. van der Smagt, Movement model of a human hand based on magnetic resonance imaging (MRI), 2010.
- [181] G. Stillfried, U. Hillenbrand, M. Settles, P. van der Smagt, Mri-based skeletal hand movement model, in: *The Human Hand As an Inspiration for Robot Hand Development*, Springer, Cham, ISBN: 978-3-319-03016-6, 2014, pp. 49–75, http://dx.doi.org/10.1007/978-3-319-03017-3_3.
- [182] H. Wang, S. Fan, H. Liu, An anthropomorphic design guideline for the thumb of the dexterous hand, in: 2012 IEEE International Conference on Mechatronics and Automation, 2012, pp. 777–782, <http://dx.doi.org/10.1109/ICMA.2012.6283241>.
- [183] A. Kapandji, Clinical test of apposition and counter-apposition of the thumb, *Ann. de Chir. de la Main: Organe Off. Des Soc. de Chir. de la Main* 5 (1986) 67–73, [http://dx.doi.org/10.1016/s0753-9053\(86\)80053-9](http://dx.doi.org/10.1016/s0753-9053(86)80053-9).
- [184] Thomas Feix, Javier Romero, Heinz-Bodo Schmiedmayer, Aaron M. Dollar, Danica Kragic, The grasp taxonomy of human grasp types, *IEEE Transactions on Human-Machine Systems* 46 (2016) 66–77, <http://dx.doi.org/10.1109/thms.2015.2470657>.
- [185] A. Vazhapilli Sureshababu, G. Metta, A. Parmiggiani, A systematic approach to evaluating and benchmarking robotic hands—the ffp index, *Robotics* 8 (7) (2019) <http://dx.doi.org/10.3390/robotics8010007>.
- [186] M. Tavakoli, B. Enes, J. Santos, L. Marques, A.T. de Almeida, Underactuated anthropomorphic hands: Actuation strategies for a better functionality, *Robot. Auton. Syst.* 74 (2015) 267–282, <http://dx.doi.org/10.1016/j.robot.2015.08.011>.
- [187] M.A. Saliba, A. Chetcuti, M.J. Farrugia, Towards the rationalization of anthropomorphic robot hand design: Extracting knowledge from constrained human manual dexterity testing, *Int. J. Humanoid Robot.* 10 (2013) 1350001, <http://dx.doi.org/10.1142/s0219843613500011>.
- [188] M. Chalon, A. Wedler, A. Baumann, W. Bertleff, A. Beyer, M. Butterfaß, R. Gruber, F. Hacker, E. Kraemer, et al., Dexhand: a space qualified multi-fingered robotic hand, in: 2011 IEEE International Conference on Robotics and Automation, IEEE, 2011, pp. 2204–2210, <http://dx.doi.org/10.1109/ICRA.2011.5979923>.
- [189] R. Weir, M. Mitchell, S. Clark, G. Puchhammer, M. Haslinger, R. Grausenburger, N. Kumar, R. Hofbauer, P. Kushnigg, V. Cornelius, et al., The intrinsic hand—a 22 degree-of-freedom artificial hand-wrist replacement, in: *Proc Myoelectric Controls/Powered Prosthetics Symposium*, Duke University Durham, NC, 2008, pp. 233–237.
- [190] M. Mitchell, R.F. Weir, Development of a clinically viable multifunctional hand prosthesis, in: *Myoelectric Symposium*, 2008.
- [191] M. Controzzi, C. Cipriani, B. Jehenne, M. Donati, M.C. Carrozza, Bio-inspired mechanical design of a tendon-driven dexterous prosthetic hand, in: 2010 Annual International Conference of the IEEE Engineering in Medicine and Biology, IEEE, 2010, pp. 499–502, <http://dx.doi.org/10.1109/IEMBS.2010.5627148>.
- [192] J.C. Vanderzanden, B.D. Adams, J.J. Guan, Mcp arthrodesis using an intramedullary interlocking device, *Hand* 9 (2014) 209–213, <http://dx.doi.org/10.1007/s11552-013-9579-5>.
- [193] B. Hillberry, A. Hall Jr., Rolling contact joint, 1976, *Granted Patent 3*.
- [194] K. Dermitzakis, A. Ioannides, H.t Lin, Robotic thumb grasp-based range of motion optimisation. Annual international conference of the IEEE engineering in medicine and biology society, in: *IEEE Engineering in Medicine and Biology Society. Annual International Conference* 2013, 2013, pp. 3163–3166, <http://dx.doi.org/10.1109/EMBC.2013.6610212>.
- [195] M. Vande Weghe, M. Rogers, M. Weissert, Y. Matsuoka, The act hand: design of the skeletal structure, in: *Proceedings 2004 IEEE International Conference on Robotics and Automation, ICRA*, vol. 4, IEEE, 2004, pp. 3375–3379, <http://dx.doi.org/10.1109/ROBOT.2004.1308775>.
- [196] P. Cerveri, E.De. Momi, M. Marchente, N. Lopomo, G. Baud-Bovy, R. Barros, G. Ferrigno, In vivo validation of a realistic kinematic model for the trapezio-metacarpal joint using an optoelectronic system, *Ann. Biomed. Eng.* 36 (2008) 1268–1280, <http://dx.doi.org/10.1007/s10439-008-9499-7>.