

Review

Mechanical Design Strategies of Dexterous Robotic Hands for Enhanced Precision Grasping: A Review

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Abstract

Precision grasping is a fundamental capability for dexterous robotic manipulation, enabling robots to handle small objects, perform delicate tasks, and interact safely with complex environments. However, achieving stable and accurate fingertip control remains challenging due to mechanical complexity, actuation limitations, and sensing constraints. This paper presents a comprehensive review of robotic hand designs from the perspective of precision grasping. The review analyzes key aspects of mechanical architecture, including finger kinematic structures, actuation and transmission systems, structural materials and fabrication methods, mechanical intelligence, and control-oriented mechanical design. Different design strategies such as fully actuated fingers, underactuated mechanisms, tendon-driven systems, linkage-based architectures, and soft robotic structures are compared in terms of dexterity, adaptability, accuracy, and system complexity. The analysis highlights several important trends, including the transition toward compliant and bio-inspired mechanisms, the integration of lightweight materials and additive manufacturing, and the increasing role of sensor–structure integration for precise force and position control. Despite significant progress, challenges such as friction, hysteresis, transmission compliance, and limited integration space still affect grasping accuracy and reliability. Based on the reviewed literature, future research should focus on hybrid actuation strategies, bio-inspired structural design, graded material architectures with structurally integrated sensing, and modular platforms to improve precision manipulation and system robustness in next-generation robotic hands.

Keywords: precision grasping; mechanical design; dexterous robotic hands; tendon-driven actuation; soft robotic hands



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1. Introduction

Dexterous robotic hands are a key enabling technology for robots operating in complex, unstructured, and human-centered environments. Compared with simple grippers, dexterous hands aim to provide a richer combination of kinematic versatility, contact adaptability, and manipulation capability, thereby allowing robots to grasp, reposition, and interact with objects of varying size, shape, and fragility. Inspired by the human hand, many robotic hand designs incorporate anthropomorphic finger arrangements, multi-degree-of-freedom (DOF) joints, tendon-like transmissions, and coordinated actuation principles to approach human-like dexterity [1–3]. Such developments have supported progress in service robotics, humanoid systems, prosthetics, teleoperation, and advanced manufacturing, where accurate and reliable object handling is increasingly required.

Representative platforms such as the Robonaut hand, the TUAT/Karlsruhe humanoid hand, HIRO III, and anthropomorphic hands developed for assistive or technological processes illustrate how dexterous robotic hands have evolved across space, haptic, assistive, and industrial domains [4–8]. Related human-scale systems, including Gifu Hand III and its master–slave extension, ultralight anthropomorphic hands, RCH-1, and dual-turning four-finger designs, further broadened the design space for compact and human-centered manipulation [9–11]. Haptic-interface-oriented embodiments and humanoid-hand mechanisms have likewise emphasized the importance of coordinated opposition, compact packaging, and intuitive interaction in anthropomorphic hand design [12–15].

Among the many functions expected from dexterous robotic hands, precision grasping is one of the most fundamental yet technically demanding. Unlike power grasping, which mainly emphasizes gross force closure and load support, precision grasping requires accurately located, mechanically stable, and controllably regulated fingertip contacts during interaction with small, delicate, or geometrically constrained objects [16,17]. This capability is essential for tasks such as pinching, fingertip grasping, in-hand adjustment, tool handling, and manipulation in cluttered or uncertain environments. In practice, the quality of precision grasping depends not only on control algorithms, but also on how the hand is mechanically embodied. The kinematic structure defines reachable grasp postures, the transmission determines motion fidelity and force routing, the material system shapes stiffness and contact adaptation, and the sensing layout affects the observability of grasp states.

1.1. Operational Definition and Quantitative Scope of Precision Grasping

In this review, precision grasping is defined more restrictively than a general grasp category such as pinch, tripod, or power grasp. It denotes a fingertip-dominant manipulation capability in which a robotic hand can establish, regulate, reproduce, and stabilize localized contacts on small object features or task-relevant surfaces. This definition is intentionally mechanical: precision grasping is treated as an outcome of kinematic accuracy, transmission transparency, local structural compliance, contact friction, and fingertip sensing, rather than as a property produced by the controller alone. Because the literature does not yet provide a single universally accepted numerical standard for precision grasping, the following thresholds are used as operational benchmarks for this review. They are selected to connect the reviewed hardware strategies to measurable outcomes reported or implied in dexterous-hand design, fingertip sensing, benchmarking, compliance, and slip-stability studies [1,3,18–28]. Transmission transparency denotes how faithfully actuator-side displacement or torque is transmitted to the joint or fingertip after losses due to tendon stretch, routing friction, backlash, linkage clearance, elastic deformation, and hysteresis. Force transparency denotes how accurately contact force at the fingertip can be inferred, commanded, or regulated from actuator-side, joint-side, or contact-side sensing after the same mechanical losses are considered. Therefore, a robotic hand can be dexterous in kinematic appearance but still weak for precision grasping if its transmission and force pathways are not transparent.

First, fingertip placement accuracy/resolution is defined as the ability to place the fingertip contact point with a lateral error below approximately 1 mm under controlled approach conditions. This criterion is critical in fingertip pinching, peg- or tool-oriented manipulation, and tasks involving small or localized contact regions. Mechanically, it is governed by joint-axis placement, linkage accuracy, bearing clearance, tendon elongation, backlash, and hysteresis in the transmission path [19,24].

Second, micro-force regulation sensitivity is defined as the ability to regulate fingertip contact force within approximately ± 0.1 to ± 0.5 N in the low-force range. This capabil-

ity is necessary for handling light, fragile, deformable, or low-friction objects without crushing, dropping, or inducing unintended slip. At the hardware level, it is influenced by actuator backdrivability, joint friction, tendon or linkage compliance, force/torque or tactile sensor integration, and the mechanical coupling between the actuator and contact point [18,22,23,29,30].

Third, contact repeatability is defined as the ability to reproduce the fingertip contact location with a standard deviation below approximately 0.5 mm across repeated grasps of the same object under comparable approach and loading conditions. This criterion separates occasional successful grasping from precision-oriented hardware performance. It captures accumulated errors caused by tendon pretension drift, routing friction, elastic recovery, joint clearance, structural deformation, and inconsistent passive adaptation [19,20].

Fourth, local structural compliance range is defined as the ability of the fingertip and distal phalanx region to accommodate approximately 1–2 mm of geometric uncertainty while maintaining stable force transmission. This criterion does not imply that the whole hand should be soft. For precision grasping, compliance should be spatially distributed: compliant or high-friction materials are beneficial at contact interfaces, whereas dimensionally stable structures are required at joint axes, bearing seats, tendon anchors, and transmission interfaces. Precision therefore depends on the spatial distribution of stiffness, compliance, and friction, rather than on global softness or rigidity alone [1,3,21,31,32].

Fifth, disturbance resistance or slip margin is defined as the ability to tolerate small external disturbances of at least approximately 1–2 N without slip onset or loss of localized contact. Accurate fingertip placement is insufficient if the grasp cannot maintain stable normal and tangential contact forces under perturbation. This margin is determined by fingertip friction, contact geometry, normal-force regulation, tactile feedback, and mechanical suppression of uncontrolled micro-slip [27,28].

Together, these criteria distinguish precision grasping from power grasping. Power grasping prioritizes gross object enclosure, large contact area, and high force capacity, whereas precision grasping prioritizes contact localization, low-force controllability, repeatability, and slip-resistant fingertip interaction. Accordingly, the design strategies reviewed in the following sections—including underactuation, tendon routing, linkage-driven transmission, variable stiffness, compliant fingertips, and hybrid rigid-soft structures—are evaluated according to how they improve or degrade these five quantitative criteria. Underactuation is considered precision-enabling only when passive adaptation does not compromise contact repeatability; tendon-driven transmission is considered precision-oriented only when pretension, friction, and elongation are controlled; and compliant or soft structures are considered beneficial only when their deformation is localized at the contact interface rather than at position-critical joints. The five criteria and their hardware drivers are summarized in Table 1, which is used as the screening framework for the later comparisons.

Table 1. Quantitative criteria defining precision grasping as used in this review.

Criterion	Operational Threshold Used in This Review	Primary Hardware Driver	Representative Supporting References
Fingertip placement accuracy/resolution	<1 mm lateral contact-point error	Kinematic structure; joint-axis accuracy; backlash; tendon elongation; transmission hysteresis	[19,24]
Micro-force regulation sensitivity	± 0.1 to ± 0.5 N in the low-force range	Actuator backdrivability; transmission compliance; friction; fingertip force/tactile sensing	[18,22,23,29,30]

Table 1. *Cont.*

Criterion	Operational Threshold Used in This Review	Primary Hardware Driver	Representative Supporting References
Contact repeatability, 1 sigma	<0.5 mm across repeated grasps	Transmission type; tendon pretension; routing friction; joint clearance; elastic recovery	[19,20]
Local structural compliance range	1–2 mm geometric adaptation at the fingertip/distal phalanx	Material stiffness distribution; compliant pads; rigid-soft interfaces; distal phalanx design	[1,21,31,32]
Disturbance resistance/slip margin	>1–2 N before slip onset or contact loss	Fingertip friction; contact geometry; normal-force regulation; tactile slip detection	[27,28]

Note: The numerical thresholds in this table are used as operational screening criteria for this review. They should be interpreted as precision-oriented targets for comparing mechanical design strategies, not as a universal standard that all robotic-hand studies must report.

1.2. Mechanical Design Challenges for Precision Grasping

To enhance grasping performance, robotic hand research has explored a wide spectrum of mechanical strategies, ranging from anthropomorphic finger architectures with enlarged opposition workspace to task-oriented redesign of palm and finger-base configuration. Underactuated and synergy-based mechanisms remain especially attractive because they redistribute motion and force passively during contact, improving object conformity while limiting actuator count [33–35]. Linkage-based and hybrid actuation architectures, including rigid-link, torque-limited, and biologically inspired parallel-drive concepts, have been developed to improve repeatability, compactness, and transmission robustness [19,36–38]. Alternative actuation technologies, such as ultrasonic-motor fingers with elastic elements and optimized tendon-driven geometries, further show that transmission layout itself strongly affects controllability and positioning fidelity [39,40]. In parallel, soft and compliant robotic hands have introduced new possibilities for safe interaction and shape-conforming grasping, including pin-array and Fin-Ray-inspired morphologies that tailor contact adaptation through structure rather than through rigid articulation alone [32,41–43]. Recent studies on active-palm, reconfigurable, and variable-stiffness soft hands indicate that compliant architectures can also support more deliberate post-contact stabilization when their deformation is mechanically guided [44,45]. Advances in smart materials, embedded sensing, and compact actuation, including SMA-integrated fingers and structurally embedded tactile components, have further expanded the design space of dexterous hands for precision-oriented tasks [46–49].

Despite these advances, reliable precision grasping remains difficult to achieve because it emerges from tightly coupled trade-offs across mechanics, actuation, sensing, and controllability. High-DOF hands may provide richer motion capability, but they also increase structural complexity, packaging difficulty, calibration burden, and control dimensionality. Tendon-driven and underactuated mechanisms offer lightweight and adaptive behavior, yet they often introduce friction, elasticity, backlash, hysteresis, coupling effects, and transmission uncertainty that degrade motion accuracy and force consistency [50,51]. Likewise, compliant and soft structures improve contact adaptation and safety, but may reduce stiffness, repeatability, and grasp-state observability when precise fingertip regulation is required. In addition, the limited volume inside the palm and fingers makes it challenging to simultaneously integrate actuators, sensors, transmission paths, and electronics without sacrificing compactness, robustness, or maintainability. As a result, precision grasping should be understood as a system-level outcome shaped by both hand mechanics and control-oriented embodiment.

1.3. Review Gaps, Scope, and Organization

A considerable body of the review literature has already examined robotic hands from several important perspectives, including the historical evolution of robotic hands, multi-fingered manipulation, sensory perception, learning-based dexterous manipulation, and human-like hand design [26,52–54]. Broader surveys and design-oriented reviews have also examined robot hand systems, general design methodologies for robotic hands, and the evolving role of anthropomorphic hands in human–robot interaction [55–58]. However, the existing literature remains dispersed across separate viewpoints such as kinematic design, actuation technologies, tactile sensing, or task-level manipulation. A focused review that systematically connects these mechanical design choices to their consequences for precision grasping performance remains limited. In particular, there is a need for a design-centered synthesis that explains how kinematic architecture, actuation and transmission strategy, structural material selection, mechanical intelligence, sensor integration, and hardware nonidealities jointly influence grasp stability, positioning accuracy, adaptability, and implementation reliability.

Accordingly, this paper presents a comprehensive review of dexterous robotic hands from the perspective of mechanical design strategies for enhanced precision grasping. Rather than classifying robotic hands only by appearance, actuation type, or task category, the review links hardware-level design choices to the functional attributes defined above: fingertip positioning accuracy, contact repeatability, grasp stability, contact adaptability, force transmission, disturbance resistance, and implementation reliability. The scope is limited to dexterous robotic hands whose mechanical embodiment is relevant to precision grasping, including anthropomorphic, underactuated, tendon-driven, linkage-based, soft, hybrid, and sensor-integrated designs. Purely control-oriented, perception-oriented, or task-planning studies are considered only when they provide direct implications for mechanical design, sensor-mechanism integration, or control-oriented hardware embodiment.

The literature for this review was identified through systematic searches of IEEE Xplore, Scopus, and Web of Science, supplemented by manual reference tracking from key survey articles. The search covered publications available up to January 2026, with particular attention to recent work from 2023–2026. Search terms included combinations of “dexterous robotic hand”, “precision grasping”, “underactuated hand”, “tendon-driven”, “soft robotic hand”, “mechanical design”, “kinematic structure”, and “tactile sensing”. Priority was given to peer-reviewed journal articles and conference proceedings in IEEE Transactions on Robotics, IEEE Robotics and Automation Letters, and related robotics, mechatronics, prosthetics, and soft-robotics venues. Rather than attempting an exhaustive task-by-task survey of all robotic grasping studies, the literature is synthesized through comparative design analysis, with emphasis on how mechanical architecture, actuation and transmission, structural materials and fabrication, mechanical intelligence, sensing integration, and hardware nonidealities influence precision-oriented manipulation performance.

To provide a focused and coherent review logic, Figure 1 summarizes the relationship between mechanical design strategies and enhanced precision grasping in dexterous robotic hands. The framework links five interdependent aspects: design architecture, mechanism-level effects, sensor integration, precision-grasping outcomes, and mechanical error sources. This framework is intended to help readers understand not only what types of dexterous robotic hands have been developed, but also why certain design principles are more suitable than others for accurate, stable, and adaptable fingertip interaction. In particular, precision grasping depends not only on kinematic and control design, but also on the spatial distribution of structural materials, because the placement of stiffness, compliance, and friction within the hand determines whether localized fingertip contacts can be formed and maintained with the accuracy required for precision tasks.

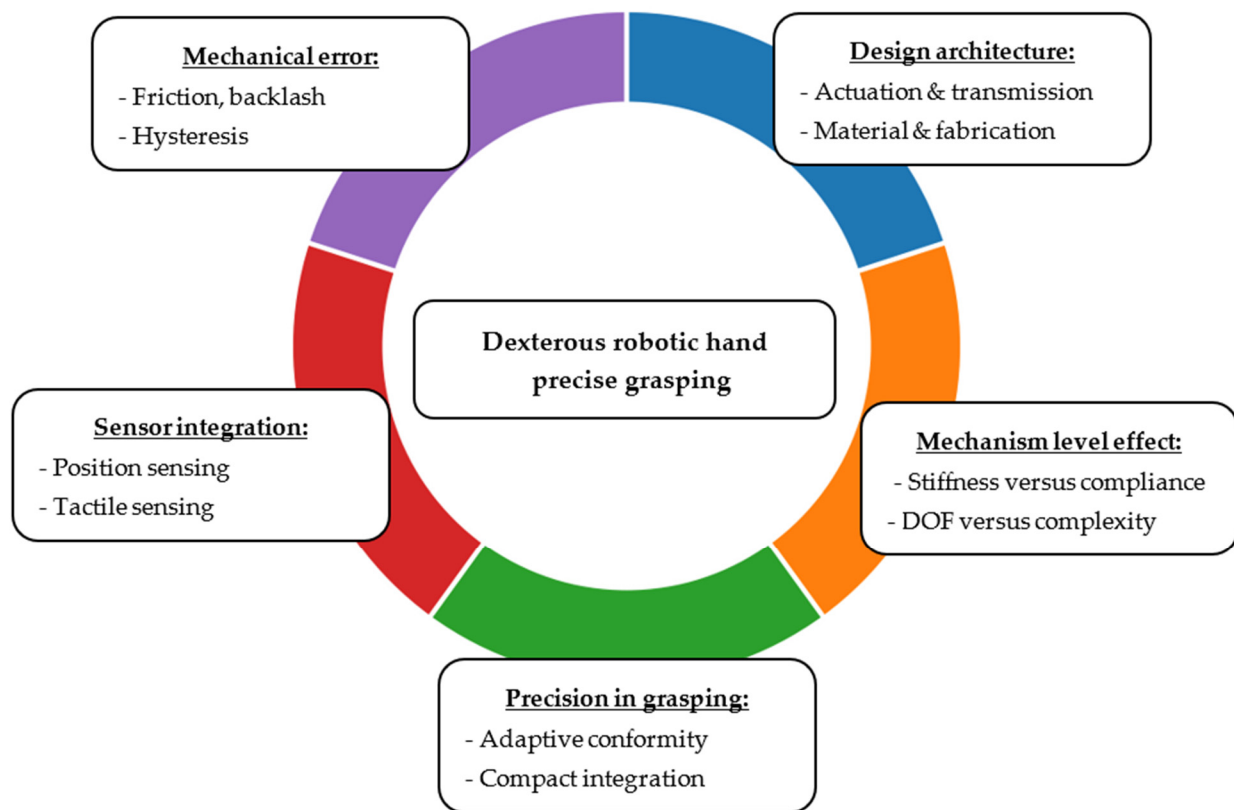


Figure 1. Review logic centered on enhanced precision grasping in dexterous robotic hands.

The three engineering paradoxes developed in Section 4.1 are therefore introduced as the organizing thread of the review: (i) kinematic complexity versus control robustness, (ii) remote actuation/tendon routing versus frictional hysteresis, and (iii) compliance or soft mechanical intelligence versus precise force transduction. These paradoxes help connect the subsequent mechanical sections to the final design recommendations. To make causal logic explicit, the revised analysis follows the sequence: mechanical choice, dominant error source, measurable precision-grasping outcome. For example, remote tendon actuation reduces distal inertia but can introduce tendon stretch, friction, and pretension drift; these errors appear as fingertip placement scatter, force-regulation error, and slip sensitivity. Linkage transmission improves geometric determinacy but can accumulate pin, bearing, and closed-loop tolerance errors; these errors appear as lost motion and reduced repeatability. Soft or compliant structures increase contact tolerance but can reduce endpoint observability and force transparency if compliance is not localized at the contact interface.

The remainder of this paper is organized as follows. Section 2, Mechanical Architecture and Design Trends, reviews four mechanical domains: kinematic structures (Section 2.1), transmission systems and actuation (Section 2.2), structural materials and fabrication (Section 2.3), and mechanical intelligence (Section 2.4). Section 3, Control-Oriented Design, discusses sensor–structure integration (Section 3.1) and hardware challenges for control (Section 3.2). Section 4, Discussion and Future Directions, synthesizes the main implications through six subsections: top three engineering paradoxes in precision-oriented dexterous hand design (Section 4.1), toward mechanically intelligent embodiment and hybrid actuation (Section 4.2), sensing, learning, and human-in-the-loop control (Section 4.3), reliability, evaluation metrics, and translation to applications (Section 4.4), open-source ecosystems and benchmark-ready embodiment for precision grasping (Section 4.5), and limitations of this review (Section 4.6). Finally, Section 5 presents the Conclusions.

2. Mechanical Architecture and Design Trends

2.1. Kinematic Structures

The kinematic structure of a dexterous robotic hand determines the size and connectivity of the fingertip workspace, the attainable contact configurations, and ultimately the ability to perform precision grasps. For precision manipulation, the decisive requirement is not merely a high total number of degrees of freedom (DOFs), but an effective distribution of DOFs among the thumb, the index finger, and the remaining fingers, so that the hand can generate stable pad-to-pad, tip-to-tip, and lateral contacts while maintaining controllable internal forces [3,16,59]. Consequently, recent robotic-hand design has moved from simply maximizing kinematic complexity toward allocating task-relevant DOFs to joints that most strongly influence opposition, contact orientation, and fingertip positioning accuracy. Structural DOF refers to the number of independent joint motions permitted by the mechanical skeleton. Actuated DOF or DoA refers to the number of independently driven variables. Effective task DOF (DoE) refers to the subset of structural and actuated motions that actually changes the contact pose, opposition geometry, force direction, or local contact stability during a target grasp. This distinction is essential because passive joints, spring-coupled joints, underactuated joints, and contact-dependent motions all contribute to hand mobility. To make this principle operational, the distribution of task-relevant DOFs can be evaluated through indicators: (i) the opposition-workspace overlap shared by the thumb, index, and middle fingertips; (ii) the effective-to-structural DOF ratio, i.e., the fraction of DOFs that actually change the contact pose or opposition geometry during a target grasp; and (iii) the contact repeatability of the final fingertip point across repeated closures. Together, these indicators enable task-specific comparison of robotic hands with different nominal DOF counts.

At the finger level, most anthropomorphic hands preserve the human joint sequence of the metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints, because this arrangement provides a compact serial chain with sufficient curvature adaptation and distal reach [60,61]. A common configuration assigns one flexion–extension DOF to the PIP and DIP joints and one or two DOFs to the MCP joint, the latter usually combining flexion–extension with adduction–abduction. This architecture is evident in the Gifu Hand III, whose four fingers each have four joints but three controllable DOFs, while the thumb retains four independent DOFs; importantly, the distal joint is mechanically coupled to the proximal interphalangeal joint through a four-bar linkage, thereby preserving human-like curling with reduced actuation burden [62]. Similar design logic appears in KITECH-Hand and the integrated linkage-driven dexterous anthropomorphic robotic hand, where a 2-DOF MCP joint is combined with independently driven flexion joints to expand the fingertip workspace and improve contact reorientation during pinch, tripod, and lateral grasps [19,63]. More recent hands continue this trend toward higher anthropomorphism while attempting to preserve compactness. For example, CasiaHand adopts a 15-DOF tendon-driven architecture at human scale, whereas a recent lightweight prosthetic hand reaches 19 DOFs to recover a broader set of human-like grasping modes [2,64]. Earlier multi-fingered-hand design studies and more recent analyses likewise indicate that the functional value of additional DOFs depends more on their allocation across the thumb base, palmar configuration, and distal coupling than on the nominal DOF count alone [65,66].

Classical multi-fingered-hand design studies already suggested that the value of additional joints depends less on absolute kinematic complexity than on how DOFs are allocated to reachable contact sets and opposition functions [67]. Experimental platforms high-DOF hands further confirm that precision-oriented architecture depends strongly on the distribution of independent thumb and finger motions rather than on actuator count

alone [62,68,69]. More recent work on redesigning palmar configuration in underactuated hands similarly indicates that palm geometry and finger-base arrangement can be as influential as distal articulation for dexterous functionality.

For precision grasping, the most influential DOFs are those that shape thumb opposition and regulate the relative pose between the thumb and the index and middle fingers. The thumb cannot be treated as a simple finger placed in opposition; rather its base kinematics determine whether the hand can form stable pad-to-pad contact, align contact normals, and adjust to small objects with different local curvatures. Accordingly, robotic hands designed for fine manipulation frequently endow the thumb base or MCP region with multiple rotational DOFs, enabling flexion–extension together with abduction-adduction or opposition-like motion [70]. A comparable principle applies to the index finger, whose lateral mobility enlarges the common workspace shared with the thumb. When the thumb and index MCP joints can independently modulate flexion and spread, the hand gains a markedly larger set of feasible precision pre-shapes and can achieve more reliable force closure on small or slender objects [71,72]. In this sense, dexterity is strongly linked to how the kinematic structure supports coordinated workspace overlap rather than to the nominal DOF count alone.

However, fully actuated anthropomorphic kinematic chains entail clear penalties in terms of packaging volume, mass distribution, wiring density, controller complexity, and maintenance. To address these limitations, many robotic hands employ underactuated or synergy-inspired structures in which several joints are mechanically coupled and driven through tendons, differential mechanisms, or adaptive transmission networks [33,34,73]. In such hands, the effective functional DOFs available at the contact level may remain high even when the number of actuators is reduced, because passive adaptation allows the fingers to conform to the object surface during closure. This design philosophy is especially attractive for low-cost or lightweight hands intended for service robotics, prosthetics, and grasp-centered manipulation. Fil3D-Hand, for instance, uses a tendon-driven underactuated arrangement with coupled distal joints to achieve 17 DOFs using 12 servo motors, while the BRL/Pisa/IIT SoftHand exploits adaptive synergies to combine mechanical simplicity with robust grasp adaptation [61,74]. The limitation of these architectures is that the final contact configuration is influenced by passive mechanics and object geometry; therefore, repeated fingertip placement and independent contact-point regulation are generally less direct than in fully actuated hands, which can be disadvantageous for highly accurate precision manipulation or within-hand regrasping.

Between these two extremes, hybrid kinematic structures have emerged as a practical compromise. In hybrid designs, proximal joints are often linkage-driven to provide accurate motion transmission and bidirectional control, whereas distal joints are tendon-driven, spring-loaded, or otherwise compliant to improve adaptation at contact. The MCR-Hand III exemplifies this direction by integrating four-bar linkages, springs, and tendons in a single anthropomorphic architecture. Its mechanical compliance is intentionally embedded in the transmission path so that the hand can tolerate geometric uncertainty, distribute contact forces more evenly, and stabilize pinch-like grasps without sacrificing the basic anthropomorphic joint arrangement [1]. Similar ideas are found in recent work on biomimetic distributed compliance, where compliance is not treated merely as a safety feature but as a structural resource that reduces sensitivity to modeling errors and contact misalignment during manipulation. For precision grasping, this point is crucial: small pose errors or local shape variations can destabilize a pinch, and moderate compliance at selected joints may preserve contact without requiring excessive controller authority.

Another important dimension of kinematic design is the location of actuators and sensors relative to the finger chain. When actuation is moved away from the fingers and palm,

the distal links become lighter, inertia is reduced, and the hand can achieve more favorable mass distribution for rapid reorientation and safer interaction. The concept demonstrated by Saliba and Axiak is representative in this regard: the hand retains multiple finger DOFs while placing actuation and sensing devices remotely, thereby enabling a more compact and lightweight terminal structure [75]. Tendon-driven systems naturally benefit from this approach, but they also introduce routing friction, backlash, elastic deformation, and calibration challenges that can compromise kinematic repeatability. By contrast, integrated or intrinsically actuated hands simplify transmission paths and may improve controllability, but at the cost of increased distal mass and tighter packaging constraints [76]. Therefore, the evaluation of kinematic structure for precision grasping should not be limited to joint topology alone; it must include the interaction between joint arrangement, transmission route, moving mass, and sensing accessibility.

Overall, the literature indicates that successful kinematic structures for precision grasping share several recurring traits: a thumb with sufficient opposition capability; at least partial lateral mobility in the MCP region; controllable or predictably coupled distal flexion; overlapping workspaces among the thumb, index, and middle fingers; and a transmission design that balances low inertia with acceptable positional fidelity. Gifu Hand III assigns three controllable DOFs to each finger and four independently controlled DOFs to the thumb [62]. Hoshino and Kawabuchi showed that adding a thumb-twist DOF improved fingertip-pad alignment and increased pinching stability [24]. Sun et al. further demonstrated that a five-fingered hand with only two actuators could perform self-adaptive pinching and enveloping, limited in-hand manipulation by actuating the thumb independently and driving the four fingers synergistically [72]. Taken together, these results indicate that selective independent mobility at the thumb and task-critical finger joints can be more consequential for precision function than nominal DOF count alone.

While kinematic structure determines the reachable contact geometry of the hand, precision grasping also depends on how accurately motion and force can be delivered to those contact locations. This shifts the discussion from joint topology to transmission and actuation.

2.2. Transmission Systems and Actuation

The performance of a robotic hand depends not only on the kinematic structure of its fingers, but also on how faithfully motion and force are transmitted, how compliance is distributed, and how readily sensing and control can compensate for the remaining uncertainty. Recent reviews consistently identify transmission design, actuation principle, and the distribution of compliance as central determinants of manipulation performance, particularly in tasks that require accurate pinch formation, stable fingertip force regulation, or gentle handling of fragile objects [59,77,78].

For precision grasping, the central engineering challenge is to reconcile several requirements that are often in tension with one another: low distal inertia, sufficient fingertip force, compact packaging, low backlash and hysteresis, controllable compliance, and robustness to contact uncertainty. The dominant design families used to address this trade-off are tendon-driven transmission, rigid-link and four-bar architectures, underactuated or differential mechanisms, pneumatic actuation, and hydraulic or other fluidic actuation. In practice, many high-performance hands combine elements of more than one family, so the boundaries between transmission and actuation are intentionally blurred [79,80]. Additional transmission solutions, including ultrasonic-motor fingers with elastic elements, torque-limiter mechanisms, biologically inspired parallel actuation, and geometry-optimized underactuated tendon routing, further confirm that precision-oriented design requires a careful balance among compactness, compliance, and controllability [38,39,81].

2.2.1. Tendon-Driven Systems

Tendon-driven hands place most actuators away from the distal joints and transmit motion through cables or synthetic tendons. This arrangement is attractive for precision grasping because it reduces distal mass and rotational inertia, preserves a slender finger envelope, and leaves space for fingertip sensing or anthropomorphic phalanx geometry. Classic cable-driven hands such as the Utah/M.I.T. hand established the value of routing force along anatomically inspired paths, while later designs emphasized modularity, low weight, and easier integration with robot arms or prosthetic sockets [82–84]. Representative tendon-driven anthropomorphic hands that adopt this proximal-actuation, distributed-cable arrangement are shown in Figure 2.

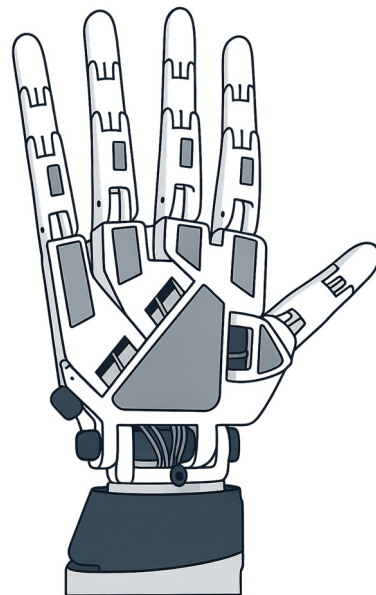


Figure 2. Representative tendon-driven anthropomorphic hands with proximal actuation and distributed cable transmission. The different gray shades are used only to visually distinguish the structural components and do not represent different materials or functional categories. Redrawn by the authors based on [60], licensed under CC BY 4.0.

From a biomechanical viewpoint, tendon transmission remains the most direct engineering analogue of the human musculotendon system. It is therefore widely used when a robotic hand aims to reproduce anthropomorphic finger proportions or human-like flexion trajectories. Several tendon-driven fingers preserve an independently oriented metacarpophalangeal joint while using cable routing to generate flexion at the more distal joints, thereby retaining the opposition and fingertip orientation needed for precision pinch. This biomimetic arrangement also facilitates the decoupling of the joints that dominate grasp formation from those that primarily contribute to local object conformity [83,85].

The main mechanical benefit of this architecture is the separation of actuator placement from joint placement. When motors, gearheads, and encoders are relocated to the palm, wrist, or forearm, the finger links can remain narrow and lightweight, which improves collision tolerance and makes accurate fingertip placement easier. This design principle is particularly relevant to fine grasping because the digits can approach small objects with reduced inertia and a lower risk of overshooting. Hybrid implementations further exploit this advantage by directly driving the joint that determines finger splay or thumb opposition while transmitting distal flexion by stainless-steel tendons or cables. Representative examples include low-cost anthropomorphic hands with a directly driven proximal degree of freedom and tendon-actuated distal joints, as well as compact hands with remotely located actuators and sensors [75,86,87].

Tendon transmission is also naturally compatible with under-actuation. In synergy-based or underactuated hands, one tendon can drive multiple joints in sequence, allowing distal links to keep closing after a more proximal link encounters the object. The Pisa/IIT SoftHand concept and its low-cost BRL/Pisa/IIT implementation show how carefully routed tendons can combine under-actuation with adaptive synergies, thereby reducing actuator count while preserving stable object enclosure and robust grasp acquisition [33,74]. More recent humanoid-scale designs such as CasiaHand confirm that palm-integrated tendon actuation remains a competitive strategy for achieving anthropomorphic dimensions and task-level dexterity without excessive structural weight [2].

These advantages, however, come with well-known limitations. Cable stretching, friction in sheaths and pulleys, pretension drift, dead zones, and maintenance demands can degrade repeatability and force transparency. In precision tasks, such effects are especially critical because a small amount of hysteresis at the transmission level can become a large position error at the fingertip. Tendon-driven hands therefore require careful routing, minimized path length, stable pretension, and low-friction guidance if they are expected to support accurate manipulation rather than only robust gross grasping. Modular and back-drivable cable-driven hands partially mitigate these issues, but the trade-off between independent joint control and mechanical simplicity remains fundamental [82,88].

Overall, tendon-driven systems are most compelling when a design must preserve a human-like form factor, keep distal inertia low, and retain some degree of mechanical compliance at contact. For precision grasping, they perform best when the joints responsible for opposition and fingertip orientation are either directly controlled or assigned priority in the routing strategy, while distal coupling is used selectively to improve conformity rather than as a substitute for all independent control.

2.2.2. Linkage-Based Architecture

Linkage-based transmissions use rigid members, four-bar couplers, crossed linkages, or other articulated mechanisms to prescribe finger trajectories mechanically. Compared with cable-driven designs, rigid-link architectures generally exhibit lower transmission compliance, fewer tendon-related hysteresis effects, and more predictable kinematics. These properties make them especially attractive in hands intended for accurate fingertip placement, repeatable tool use, or forceful pinch actions, where geometric fidelity is often more important than passive adaptability. Representative linkage-driven layouts are illustrated in Figure 3, and their precision-relevant attributes are summarized in Table 2.

The integrated linkage-driven dexterous anthropomorphic hand (ILDA) is a particularly influential example because it demonstrates that rigid-link transmission can be used without sacrificing a high degree of dexterity. ILDA integrates all actuation and sensing components inside the hand, provides 15 active degrees of freedom across 20 joints, reaches a fingertip force of 34 N, weighs about 1.1 kg, and fits within a human-scale envelope. Mechanically, it combines parallel and serial link structures to realize a two-degree-of-freedom metacarpophalangeal joint and a one-degree-of-freedom proximal interphalangeal joint while coupling distal motion through linkages. The result is a hand with deterministic kinematics, strong force transmission, and good manufacturability, all of which are advantageous for precise and repeatable grasp execution [19].

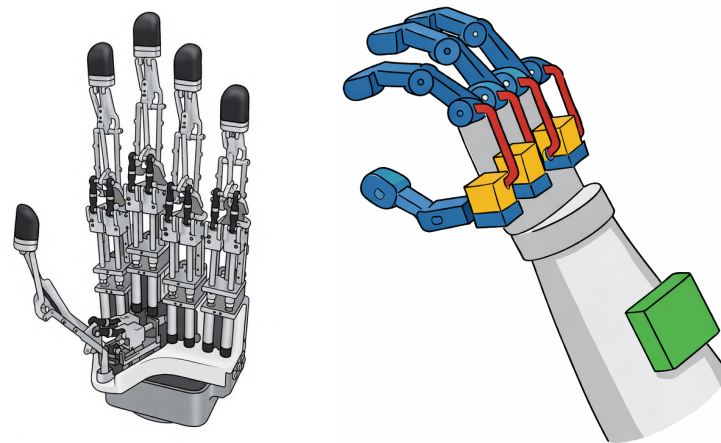


Figure 3. Representative linkage-driven robotic hands and rigid transmission architectures. The different colors are used only to visually distinguish the structural components and do not indicate different materials or functional categories. Redrawn by the authors based on [19,36], licensed under CC BY 4.0.

Other rigid-link hands reach a similar objective with simpler four-bar or hybrid couplers. Four-bar prosthetic or robotic fingers replace cable elasticity with direct link motion, improving durability and reducing the need for pretension management [89]. Underactuated rigid-link designs frequently use torsion springs together with four-bar linkages so that the proximal and distal phalanges follow an anthropomorphic trajectory while still adapting once contact occurs. This strategy is visible in underactuated EMG-controlled anthropomorphic hands and in compact hands that couple twisted-string actuation to a four-bar finger in order to reduce actuator count and packaging volume [90,91]. Feed-screw or linkage-amplified thumb mechanisms have also been used to combine rigid support at the thumb with more flexible transmissions in the remaining fingers, thereby improving opposition stability during fine grasping [92].

The main precision-related strength of linkage-based transmission is its geometric determinism. Because the finger trajectory is largely encoded in the mechanism itself, model-based control becomes more straightforward, fingertip paths are more repeatable, and calibration is typically more stable than in tendon routing. This is why linkage-driven systems are often preferred when the hand must repeatedly approach known grasp points, manipulate tools, or maintain a well-defined fingertip pose under load. In addition, rigid links simplify maintenance and can be more robust in environments where cable damage, tendon creep, or sheath wear would be problematic.

The main limitation is that deterministic kinematics do not automatically provide deterministic contact outcomes. Once the object departs from the nominal size or pose for which the mechanism was tuned, a rigid trajectory may reduce passive self-alignment and increase the burden on sensing and active force control. Rigid-link hands also accumulate manufacturing tolerances through multiple joints and may require additional elastic elements, differential couplers, or compliant fingertips to regain the adaptability that tendon-driven or soft hands obtain more naturally. Consequently, linkage-based designs tend to offer the highest mechanical repeatability, but not necessarily the highest tolerance to geometric uncertainty [93].

A linkage finger may remove tendon elongation, but its fingertip error is still affected by pin-hole clearance, bearing play, joint-axis misalignment, elastic bending of slender links, additive-manufacturing tolerance, and closed-chain assembly error. For an n -joint chain, small angular or translational errors can accumulate along the distal kinematic chain and appear as millimeter-scale fingertip deviations if link length, bearing fit, and joint

stiffness are not tightly controlled. Linkage-based hands are thus most precision-oriented when their joints are manufactured as low-clearance, high-stiffness transmission paths and when compliant pads absorb object uncertainty.

Table 2. Summary of robotic hand designs using four-bar linkage mechanisms for precision grasping.

Name of Robotic Hand	Degrees of Freedom of Each Finger	Finger Actuation Mechanism	Advantages	Disadvantages
ILDA robotic hand [19]	3 DOF (2 DOF at MCP, 1 DOF at PIP; DIP coupled)	Rigid linkage mechanism combining parallel Prismatic–Spherical–Spherical chains and a serial Prismatic–Spherical–Universal chain with four-bar linkages	High accuracy and repeatability due to rigid link mechanisms; eliminates errors caused by tendon elongation; clear kinematic model enabling precise trajectory control	Limited passive adaptability; grasping complex objects requires accurate tactile sensing and active force control
Four-bar linkage hand [36]	One controlled flexion DOF per finger	Rigid four-bar linkage driven by one servo per finger; the joint motion is mechanically coupled.	High durability; stable force transmission; improved motion accuracy by eliminating cable elasticity.	No independent joint control within each finger; fixed coupling limits passive adaptation and dexterity.
EMG-controlled anthropomorphic hand [90]	3 DOF per finger (3 joints), but underactuated	One motor drives three joints through an underactuated mechanism with torsion springs and a four-bar linkage	Adaptive grasping when contacting objects; biomimetic finger motion; more stable grasp due to synchronized PIP–DIP motion	Lower independent joint position accuracy due to underactuation; several fingers share a motor
TSA hand [91]	1 DOF per finger (thumb: 2 DOF)	TSA combined with a four-bar linkage for synchronized joint motion	Lightweight design; reduced number of motors; optimized nonlinear joint motion similar to human finger flexion.	Limited dexterity due to coupled joints; low DOF restricts complex manipulation

In summary, linkage-based architectures are particularly well suited to precision grasping when the task rewards kinematic repeatability more strongly than passive compliance. Their performance can be further improved when rigid transmission is combined with compliant fingertips, selective under-actuation, or tactile feedback so that deterministic finger trajectories do not become a liability in the presence of object uncertainty.

2.2.3. Underactuated Mechanisms

Under-actuation refers to mechanical arrangements in which the number of independent actuators is lower than the number of kinematic degrees of freedom. In robot hands, this principle is not merely a cost-saving measure; it is a deliberate strategy for redistributing motion and force passively when contact occurs. Reviews of dexterous and prosthetic hands consistently show that under-actuation reduces hardware complexity, supports object conformity, and often improves grasp robustness when object pose or geometry is uncertain [34,94].

Differential mechanisms are one of the most common ways to implement under-actuation because they distribute actuator travel or torque among several digits or joints without requiring active coordination at every contact. The dual-actuated hand proposed by Sun et al. exemplifies this idea: a palm-integrated differential synergistically drives the four long fingers, while the thumb is actuated independently to provide opposition and manipulation capability. This configuration preserves a broad repertoire of grasp postures with a very small number of actuators, and it shows how under-actuation can be organized around the functional asymmetry between the thumb and the remaining fingers [72].

Under-actuation is also central to synergy-driven hands. Adaptive synergy concepts and the SoftHand family treat object acquisition as a mechanically assisted coordination problem rather than a fully commanded joint-by-joint trajectory. The result is that the hand often reaches a stable grasp with little sensing or computational overhead, because the object itself helps determine the final configuration. Extremely low-actuation designs, including hands with one actuator for many joints, demonstrate the same principle even more starkly: the fingers close until the environment defines the remaining degrees of freedom [33].

For precision grasping, the benefit of under-actuation is not maximal positional determinism but rapid self-alignment. When the object location is imperfectly known or the target geometry varies between grasp attempts, a passively redistributable mechanism can recover contact more reliably than a fully rigid, fully actuated hand with similar sensing quality. This is especially valuable in service and assistive settings, where object placement is often uncertain and safety is at least as important as repeatability. Early prosthetic designs such as MANUS-HAND and more recent self-adaptive hands confirm that compliant under-actuation can improve stable contact formation without a proportional increase in actuator count or control complexity [95,96].

The limitation is that the final finger posture becomes contact dependent. This property is advantageous for robust grasp acquisition but problematic for tasks that require arbitrary phalanx positioning, exact fingertip force distribution, or repeatable in-hand gaiting. Once the object drives part of the configuration, the controller loses some direct authority over individual joints. Underactuated hands therefore tend to excel at adaptive enclosure and gross stabilization while fine manipulation benefits from additional sensing, regrasp strategies or a selectively actuated thumb and index finger pair that recovers some of the missing controllability.

Accordingly, under-actuation should not be interpreted as the opposite of precision. Rather, it shifts the source of precision from exact joint tracking toward reliable contact organization. In applications where contact uncertainty dominates the error budget, such a shift can be beneficial. In applications that demand repeatable fingertip trajectories in free space, under-actuation must usually be combined with strategically placed independent actuation or richer tactile feedback.

2.2.4. Pneumatic Actuation

Pneumatic actuation generates motion from pressure differentials in compliant chambers, bellows, or artificial muscles. In robot hands, its main appeal lies in the combination of low mass, inherent compliance, and impact safety. Unlike rigid transmissions that must add compliance explicitly, pneumatic hands obtain much of their adaptability directly from material deformation. This property is highly valuable for precision grasping of fragile, deformable, or pose-uncertain objects, because contact forces can be distributed over a larger area and small alignment errors can be absorbed mechanically rather than corrected purely by feedback control.

Deimel and Brock's compliant hand based on a novel pneumatic actuator established an influential benchmark by showing that a soft, compliant hand could achieve robust grasping with substantial mechanical simplicity [97]. Subsequent work extended this principle toward more structured soft hands. Feng et al. developed a soft robotic hand in which each finger is partitioned into multiple pneumatic chambers, enabling richer bending behavior and sEMG-based operation [98]. In a related but application-specific direction, Wang et al. proposed a dual-mode soft gripper that combines PneuNet-style bending with fingertip suction through separated air paths, thereby improving reliability when handling thin, flat, or fragile targets in food packaging [99].

An important shift in recent years is that soft pneumatic devices are no longer limited to simple enveloping grasps. Soft hands have been progressively equipped with adaptive palms, reconfigurable fingers, variable stiffness interfaces, and in-hand manipulation functions. Examples include soft grippers with passive or active palms for better object adaptation, dexterous soft hands aimed at delicate in-hand manipulation, and particle-jamming or hybrid stiffness mechanisms that allow the fingers to remain compliant during acquisition and become more supportive once the object has been secured [43]. These developments are significant because they move soft hands closer to the requirements of precision grasping, where stable contact must coexist with controlled object motion after first touch.

The main challenge is that air is compressible. Pneumatic hands therefore face limits in motion bandwidth, static position accuracy, and force controllability that are less severe in rigid electromechanical transmissions. Hysteresis in elastomeric materials, valve dynamics, chamber coupling, and sensitivity to pressure regulation all make exact fingertip placement difficult, especially when motions are fast or when the object must be manipulated after initial grasp acquisition. For this reason, pneumatic hands often achieve precision indirectly, through morphological adaptation and large, forgiving contact areas, rather than through sub-millimetric open-space positioning.

Even so, pneumatic actuation is particularly advantageous when the object is delicate or the environment is poorly structured. Soft reef-sampling grippers, food-handling devices, and compliant manipulation platforms demonstrate that precise outcomes can emerge from safe, adaptive contact rather than from rigidly imposed trajectories. In such settings, the best performance often arises when pneumatic compliance is supplemented by proprioception, tactile sensing, suction assistance, or temporary stiffening strategies [100].

2.2.5. Hydraulic Actuation

Hydraulic actuators are less common than tendon-driven or pneumatic systems in anthropomorphic robotic hands, but they remain important in applications where high force density and compliant force transmission must coexist. Because liquids are far less compressible than air, hydraulic systems can, in principle, provide more direct and higher-force actuation within soft or semi-soft structures. This characteristic makes them attractive for significant external loads, where soft fingers must retain their ability to conform to objects [101]. Galloway et al. developed underwater soft grippers that were mechanically impedance-matched to fragile benthic organisms and were capable of nondestructive sampling in situ [102]. For applications requiring greater force, Mori et al. reported a hydraulic artificial-muscle hand in which the fingers combined rigid metal links with hydraulic McKibben muscles [103].

However, the need for pumps, reservoirs, hoses, seals, and valves, together with the risk of fluid leakage, complicates the integration of hydraulic systems into compact anthropomorphic hands. Consequently, hydraulic actuation is rarely the first choice for lightweight, human-scale hands intended for routine fine-manipulation tasks, although it remains highly attractive for specialized soft-robotic applications. Nevertheless, hydraulic transmission is a specialized but valuable option, particularly when force density or compliant load-bearing capability is prioritized, but less advantageous when miniaturization, low weight, and low-maintenance integration are the primary design requirements.

2.2.6. Hybrid and Emerging Actuation Strategies

The most capable contemporary robot hands often avoid a single pure transmission philosophy. Instead, they combine rigid and compliant elements, direct and remote actuation, or high- and low-dimensional control within the same device. This hybridization

reflects a practical observation: the requirements for approaching an object, establishing first contact, aligning the fingertips, and stabilizing the object are not identical, so different joints can profit from different transmission properties. MCR-Hand III is an explicit example of a linkage–spring–tendon-integrated compliant hand, while other integrated hands use direct proximal drive together with tendon-actuated distal joints to balance packaging, controllability, and compliance [1,86]. Hybridization can also reach beyond the actuator into the digit structure itself. Stokes et al. introduced a four-fingered gripper whose digits combine directly actuated rigid segments with pneumatically driven continuum sections built from McKibben muscles, so that the rigid links provide load-bearing strength and stable anchoring while the compliant continuum portions conform to and secure large or delicate objects; direct DC-motor drive of the opposable digit and pneumatic actuation of the continuum sections thus coexist within a single hand [104].

Compact alternatives also continue to broaden the design space. Twisted-string actuation offers high transmission ratio in a small package and has been paired with four-bar fingers to synchronize joint motion economically. Piezoelectric hands open a very different pathway by enabling motion manipulation from micro to macro scales [105]. Shape-memory-alloy-driven fingers and embedded SMA actuator arrays remain attractive for miniature or quiet hands, even though their thermal response and control bandwidth still limit broad adoption in precision manipulation [47,106,107].

For precision grasping, the key lesson from these emerging designs is not that a new type of actuator will replace all older ones, but that selective hybridization is increasingly the dominant strategy. High-bandwidth positioning can be concentrated in the thumb or index finger, while compliant or underactuated transmission is reserved for the joints that mainly serve self-alignment and force distribution. In this sense, mechanism selection should be task-led rather than anthropomorphism-led. Hands intended for tool use and repeatable pinch typically benefit from low-hysteresis rigid or tendon transmission, whereas hands for uncertain geometries and fragile materials benefit from under-actuation or soft fluidic contact interfaces [59]. The resulting actuation-level trade-offs are consolidated in Table 3.

Table 3. Comparative summary of transmission and actuation strategies for precision grasping.

Mechanism	Advantages of Precision Grasping	Main Limitations and Best-Fit Use Case
Tendon-driven	Low distal inertia, slender fingers, flexible actuator placement, and compatibility with anthropomorphic and adaptive designs. Representative examples include the Utah/M.I.T. hand [84], modular cable-driven hands [88], and CasiaHand [2].	Cable stretching, friction, pretension drift, and maintenance can reduce repeatability and force transparency. Best suited to hands that need human-like form factor and low moving mass, provided routing is carefully optimized.
Linkage-based	Deterministic kinematics, robust force transmission, and high repeatability for fingertip positioning and tool use. Representative examples include ILDA [19], four-bar fingers [36,89], EMG underactuated hands [90]	Passive adaptability is lower than in softer hands unless compliance is added elsewhere. Best suited to tasks that reward repeatable fingertip pose and mechanically encoded trajectories.
Underactuated/differential	Passive contact redistribution, reduced actuator count, and reliable grasp acquisition under object uncertainty. Representative examples include adaptive synergies [34], single-actuator hands [73], and dual-actuated differential hands [72].	The final posture is contact dependent, and individual joint control is limited. Best suited to adaptive grasp acquisition and stabilization when object pose or shape is uncertain.

Table 3. *Cont.*

Mechanism	Advantages of Precision Grasping	Main Limitations and Best-Fit Use Case
Pneumatic	Intrinsic compliance, safety, and large-area contact for delicate or deformable objects. Representative examples include compliant pneumatic hands [97], segmented soft hands [98], dual-mode soft grippers [99].	Position bandwidth and exact force regulation are harder to achieve because of air compressibility and material hysteresis. Best suited to fragile objects and contact-rich environments where safe adaptation matters more than rigid free-space accuracy.
Hydraulic/fluidic	High force density and compliant load bearing, especially valuable in wet or specialized environments. Representative examples include deep-reef soft grippers [102], hydraulic McKibben hands [103], and electro-conjugate-fluid concepts [108].	Pumps, hoses, sealing, leakage risk, and bulk complicate compact anthropomorphic integration. Best suited to underwater, high-load, or specialized soft-robotic applications rather than small human-scale hands.
Hybrid	Selective combination of rigid and compliant transmission can assign high-accuracy positioning and controlled compliance to different joints. Examples include MCR-Hand III [1], direct-plus-tendon integrated hands [86], and TSA-linkage hybrids [91].	Design, calibration, and control become more involved because multiple transmission behaviors must be coordinated. Best suited to precision hands that must balance exact positioning with controlled contact adaptation.

The comparative picture that emerges is that no single mechanism dominates all aspects of precision grasping. Tendon-driven and linkage-based architecture remain the most common choices when anthropomorphic packaging and accurate fingertip placement are both required. Underactuated mechanisms improve robustness by exploiting passive self-organization at contact. Pneumatic and hydraulic systems shift the design toward safe, adaptive interaction, although they generally sacrifice some free-space positional determinism. Hybrid hands are increasingly attractive because they allow these complementary properties to be distributed strategically across the hand rather than imposed uniformly on every joint.

Therefore, transmission and actuation should be evaluated together with sensing and control, not in isolation. A mechanically precise hand with insufficient compliance may still fail on delicate objects, whereas a highly adaptive soft hand may struggle with repeatable fingertip placement unless supported by proprioceptive or tactile feedback. For flexible robot hands intended to perform precision grasping in real environments, the most promising design direction is likely a hybrid architecture that preserves low distal mass and high geometric fidelity while embedding compliance only where contact uncertainty is greatest. Representative hardware provides quantitative support for this mass-force trade-off. ILDA integrates its actuation and sensing components within a 1.1 kg hand and produces a 34 N fingertip force [19], whereas the 19-DOF SMA prosthetic hand relocates the actuators and driving hardware to the forearm, has a wrist-to-fingertip mass of 0.22 kg within a 0.37 kg total system, and lifts a 2.5 kg payload [64]. Although the two platforms use different actuation principles and report different performance metrics, these values provide objective evidence of the design tension between integrated force transmission and low distal mass.

However, transmission performance cannot be evaluated independently of the structural body that carries it. Material selection and fabrication route strongly affect stiffness, mass distribution, compliance, wear behavior, and integration feasibility, all of which ultimately condition transmission fidelity at the fingertips.

2.3. Structural Materials and Fabrication

Structural materials and fabrication routes are not secondary implementation choices in dexterous robot hands; they define the attainable balance among stiffness, inertia, compliance, durability, and geometric fidelity at the contact interface. This relationship is especially important for precision grasping, where stable pinch and tripod grasps depend on accurate joint alignment, low lost motion, repeatable fingertip geometry, and a controlled distribution of compliance rather than on high squeezing force alone. Reviews of anthropomorphic and prosthetic hands consistently show that the most capable platforms do not rely on a single material class; instead, they combine rigid load-bearing members, compliant contact layers, and manufacturing processes that support small features, embedded components, and rapid iteration [3,16,109].

From this perspective, recent robotic hands can be interpreted as material systems rather than only as kinematic mechanisms. Rigid polymers, aluminum alloys, titanium alloys, carbon-fiber shells, silicone elastomers, urethane rubbers, fiber-reinforced composites, and smart materials such as shape memory alloys (SMAs) are each selected to serve a specific structural function, for example carrying tendon loads, preserving joint geometry, tailoring friction, directing deformation, or embedding actuation and sensing. Likewise, fabrication methods such as fused deposition modeling (FDM), selective laser melting (SLM), selective laser sintering (SLS), laser cutting, molding/casting, and hybrid machining are increasingly combined within one hand to reach the dual objective of precise manipulation and practical manufacturability [46,74,110–113].

- Rigid load-bearing skeletons and hybrid hard-soft interfaces.

Low-cost polymer additive manufacturing remains one of the most influential enablers of precise yet affordable robotic hands. In the BRL/Pisa/IIT SoftHand, the underactuated tendon-driven architecture is implemented through additively manufactured finger segments and a mechanically simple synergy-based transmission, allowing rapid iteration of the finger geometry while preserving adaptive closure around objects [74]. A similar fabrication philosophy appears in the open-source HRI Hand, where complex anthropomorphic components are primarily realized by 3D printing to simplify manufacturing and replacement, while higher-strength versions can substitute selected printed members with machined metal parts such as SUS304 stainless steel in the fingers and palm [114]. For precision-oriented platforms, the value of such strategies lies not only in cost reduction but also in the ability to repeatedly tune tendon routing, joint offsets, stopper positions, and fingertip shape without redesigning an entirely machined assembly.

At the same time, polymer-dominant hands illustrate an important principle: precision grasping does not require uniform rigidity throughout the hand. The base phalanges, palm, and tendon anchor regions benefit from higher stiffness to maintain kinematic consistency under load, whereas distal regions may intentionally retain modest compliance to accommodate contact uncertainty.

When structural mass becomes a limiting factor, particularly in prosthetic or highly back-drivable hands, high-performance metallic materials and design optimization become more attractive. Buccino et al. showed that finger structures can be systematically light-weighted while preserving mechanical integrity by combining geometric optimization with candidate materials such as AlSi10Mg and Ti6Al4V, supported by additive and subtractive manufacturing routes including SLM, SLS, and precision machining [110]. The broader implication for precise grasping is that material selection should be tied to local stress paths and inertia constraints. Excessively heavy structures may improve static alignment but degrade dynamic response, whereas optimized metallic or composite members can preserve stiffness-to-weight ratio and reduce the energetic cost of rapid postural reconfiguration [94,110].

- Compliant elements as precision-enabling structures.

Controlled compliance is equally important at the subassembly level. In underactuated differential mechanisms, passive elastic elements can improve precision by redistributing forces across fingers rather than merely absorbing error. Gao et al. embedded urethane–rubber elements within adaptive differentials so that the mechanism could equalize grasping loads and conform to geometric variation while remaining mechanically compact [115]. In this context, elastomeric components act as structural elements rather than passive add-ons: their stiffness directly influences load sharing, contact sequence, and the stability margin of pinch or enveloping grasps. This design logic is closely related to kinetostatic analyses of underactuated fingers, where small changes in elastic or transmission properties propagate into large differences in fingertip behavior [35].

In soft anthropomorphic fingers, the material system itself defines the kinematic trajectory. Zhou et al. demonstrated a soft-robotic route to hand dexterity in which molded pneumatic chambers, constraint layers, and reinforcement elements are arranged to prescribe bending shape and force output without relying on conventional revolute joints [112]. The fabrication sequence—mold design, chamber layout, reinforcement placement, and tubing integration—becomes equivalent to mechanism synthesis. Such approaches are particularly attractive for precision grasping of irregular or fragile items because they reduce sensitivity to pose uncertainty and spread the contact load over a larger area. However, they also require careful structural programming so that compliance appears in the desired direction while lateral collapse, torsional drift, or excessive volumetric expansion are suppressed [78].

Recent soft fingers achieve this structural programming through composite or multi-material construction. In the soft-robotic gripper of Zhou et al., the elastomeric body is combined with anisotropic reinforcement, including a fiberglass strain-limiting layer and a nylon network, to bias deformation and enhance grasp reliability [32]. Yang et al. further advanced this idea through hybrid jamming, where a compliant silicone matrix is combined with particulate and layered constituents to create a variable-stiffness artificial bone-joint analogue [116]. For delicate in-hand manipulation, Abondance et al. used multi-material casting and pneumatic chamber design to couple a sufficiently stable finger body with ultra-soft contact regions, indicating that dexterity can benefit from a deliberately tuned material gradient between the structural core and the contact surface [43]. Collectively, these studies suggest that precision increasingly depends on material architecture and anisotropy rather than on rigid-link miniaturization alone. An alternative morphological approach is illustrated by the pin-array soft hand, in which an array of slidable pins covered by an elastomeric membrane conforms to the object profile through discrete structural adaptation and vacuum-driven enclosure, achieving shape-dependent contact without conventional articulated joints [41].

Fingertip friction engineering provides another route by which material design directly supports precise manipulation. Spiers et al. introduced variable-friction finger surfaces in which a rigid low-friction ABS core is suspended within a high-friction urethane layer, thereby modifying tangential contact behavior as normal force increases [28]. This result is relevant to precision tasks because surface material pairing affects whether controlled micro-slip, pivoting, or grasp stabilization can be achieved at the fingertip. Early low-cost hands such as the iCub hand similarly highlight the importance of rigid polymer fabrication for fine surface shaping and economical replacement of contact-relevant parts [117]. Taken together, these studies show that distal structural design cannot be separated from tribological behavior: material pairing at the surface determines whether the hand can execute the controlled tangential adjustments required during in-hand manipulation.

Compliance may also be beneficial beyond the fingers themselves. Recent work on actuated or soft palms suggests that precision handling can improve when the palm participates actively in shaping the contact manifold instead of remaining a passive rigid base. Related variable-stiffness strategies based on soft actuation and particle jamming show that the transition between conformal capture and rigid support can be encoded at the structural level [45]. Although these architectures are more common in soft grippers than in fully anthropomorphic hands, the underlying principle is highly relevant to dexterous robot hands intended for precise grasping: local stiffness should be state-dependent, and different regions of the hand should be free to switch between compliant accommodation and stable support as the task evolves. The broader implications of such embodied grasp behavior are discussed further in Section 2.4.

- Fabrication routes and sensor–structure integration.

A clear trend across rigid and soft hands is the shift from monolithic fabrication toward hybrid manufacturing workflows that combine printed, molded, machined, and laser-cut components. Additive manufacturing is no longer limited to covers or demonstrator shells; it is now routinely used for tendon-routing rings, wrist mounts, gears, cable spools, actuator housings, and other mechanically active features, as shown in low-cost rehabilitation and anthropomorphic hand systems [36,111,114]. Earlier work on rapid fabrication of non-assembly robotic hands with embedded components anticipated this direction by using fabrication itself to reduce assembly complexity and integrate subsystems directly into the hand structure [113]. For precise grasping, the consequence is significant: fewer joints, fasteners, and alignment steps often translate into lower cumulative tolerance stack-up and more repeatable fingertip motion.

Soft hands follow a parallel but equally sophisticated fabrication logic. Multi-stage molding from 3D-printed molds allows internal cavities, constraint layers, embedded tubes, and multi-durometer contact zones to be created with relatively high geometric repeatability [32,43,112]. In the SMA-driven soft hand of She et al., 3D-printed molds are used to position actuators and sensors during casting, after which the fingers are assembled to a laser-cut acrylic palm [46]. Homberg et al. also showed that soft finger fabrication routes can be made compatible with embedded sensing, so that bend and force measurements are incorporated into the structure rather than mounted as separate modules [31]. For precision tasks, this is important because sensing quality depends not only on the sensing principle itself, but also on the mechanical path through which strain or contact force is transmitted to the sensing site.

Sensor integration is therefore increasingly inseparable from material and fabrication selection. Hands with integrated nanocomposite strain sensors [61], embedded force or bend sensors [31,46], and fully 3D-printed piezoresistive strain/tactile arrays [48] illustrate a shift toward structurally integrated perception. From a fabrication viewpoint, this means that sensor placement must be considered early, together with wall thickness, reinforcement layout, and cable routing. Such co-design reduces parasitic compliance between the contact interface and the measurement site, improves observability of incipient slip or deformation, and enables more compact fingertip structures. In this sense, material architecture is expected to serve both manipulation and sensing, not just load bearing. Functional implications for control and contact-state estimation are discussed further in Section 3.1.

Nevertheless, the manufacturing route must still be selected with the intended grasp error budget in mind. High-precision machining and careful assembly remain advantageous when backlash, concentricity errors, or wear at compact transmissions dominate fingertip accuracy, as observed in dexterous rigid hands and specialized underwater systems [118]. Yet fully machined solutions are expensive and often difficult to customize at scale. The

most pragmatic tendency in recent hands is therefore selective precision: machining or reinforcing only the locations that define kinematic accuracy—such as bearing seats, joint pins, bevel gear interfaces, or tendon anchors—while leaving housings, covers, routing guides, and soft contact structures to additive or molding-based processes [110,114]. This selective strategy is one of the clearest fabrication responses to the needs of precise grasping.

- Shape-memory-alloy-integrated architectures.

Among smart materials, SMAs occupy a distinctive position because they reshape the relationship among structure, actuation, and fabrication. Instead of attaching bulky motors and transmissions to a rigid finger skeleton, SMA wires, springs, or strips can be embedded directly into the hand structure, allowing the actuator to coincide spatially with the deforming member [46,47,64]. Earlier anthropomorphic designs used SMA arrays to realize compact, muscle-like actuation in miniature or human-scale hands [49,119–121], while more recent work indicates that this approach can be extended to highly dexterous prosthetic systems [64]. This embedded-actuation paradigm is particularly attractive where anthropomorphic size, low mass, and reduced mechanical clutter are critical design constraints. A broader perspective on compact actuation principles, including pneumatic and dielectric-elastomer alternatives, is provided by recent reviews of robotic artificial muscles [101].

The fabrication workflow for SMA hands is correspondingly distinctive. In She et al., SMA strips are trained to a desired shape, combined with insulated heating elements, positioned within molds, and encapsulated in silicone-based fingers that include both soft body regions and stiffer anchoring zones; the resulting fingers are then assembled to a lightweight acrylic palm [46]. The structural benefit of this process is not merely miniaturization. Because the actuator is fabricated as part of the finger, transmission backlash can be reduced, routing can be simplified, and the final hand can exploit compliance rather than suppress it. Yang and Gu earlier showed that embedded SMA actuators could be integrated directly into robotic fingers, highlighting the feasibility of highly compact mechatronic packaging [47]. Such fabrication routes suggest that SMA hands should be interpreted as integrated material systems rather than as conventional rigid mechanisms retrofitted with smart actuation.

From the standpoint of precise grasping, SMA-based architecture offers several appealing advantages. Their high power-to-weight ratio and compact form factor can enable hands with human-like scale and many locally distributed actuators, reducing the need for remote transmissions or heavy forearm-mounted drives [49,107]. In addition, the material itself can contribute to sensing, since the electrical resistance of SMA elements varies during phase transformation and can be exploited for position estimation or state monitoring [47]. These features are valuable for precision manipulation, where both geometric compactness and low reflected inertia help the hand approach cluttered objects and modulate small contact forces more effectively.

These benefits, however, are accompanied by well-known structural and control trade-offs. SMA actuators exhibit thermal hysteresis, limited cooling rate, and configuration-dependent stroke-force behavior, all of which can reduce bandwidth and repeatability unless the finger structure and control strategy are co-designed [120]. Straight wires, coiled springs, and strips also involve different compromises among recoverable strain, force output, and bending moment [47,107,121]. Consequently, successful SMA hands often incorporate additional structural measures—such as antagonistic layouts, compliant fingertips, or embedded auxiliary sensors—to compensate for actuation uncertainty and improve manipulation accuracy [46,120]. The recent 19-DOF lightweight prosthetic hand driven by 38 SMA springs highlights both the maturity and the remaining integration challenges of this approach [64].

- Implications for precise grasping.

Across the material and fabrication strategies reviewed above, a consistent design rule emerges: precise grasping is rarely achieved by maximizing rigidity or softness alone. More effective hands distribute rigidity, compliance, frictional properties, and sensing capability according to functional need. The palm, tendon anchors, proximal phalanges, and transmission interfaces generally require dimensional stability and wear resistance, whereas distal phalanges and contact pads benefit from compliant, high-friction materials. The transition zones between these regions often determine whether an object can be both acquired and stabilized without excessive squeezing. Differential mechanisms [115], composite soft fingers [32,43,116], variable-friction fingertips [28], and hybrid rigid-soft skeletal frames [22,122] therefore support the same conclusion: material architecture is a primary determinant of precision rather than a post hoc packaging decision.

Accordingly, the most promising fabrication strategy for next-generation dexterous hands is hybrid rather than monolithic. Additive manufacturing is well suited to rapid geometric iteration, internal routing, sacrificial molds, and customized lightweight components; high-performance metallic or composite inserts should be reserved for critical load paths that define accuracy and durability; and sensing or actuation elements should be embedded as early as possible in the structural design process [31,46,48,61,110,113,114]. Representative systems illustrate this hybrid logic. Carrozza et al. combined a carbon-fiber palm shell with silicone-rubber padding to provide a lightweight, dimensionally stable structure with compliant contact interfaces [22]. She et al. embedded SMA actuators and PZT flexure sensors within silicone fingers, producing a complete five-finger hand with a mass of 282 g [46]. Mohammadi et al. combined PLA and aluminum structural components with silicone-coated, force-sensitive fingertips [122]. Together, these examples show that functionally distributed materials can reduce mass, integrate sensing and actuation, and tailor contact compliance while preserving structural support. Such a workflow supports lower cost and easier customization while aligning mechanical behavior more closely with the requirements of precision grasping. Future progress in structural materials and fabrication is therefore likely to depend on deliberately graded designs in which stiffness, compliance, friction, and sensing density vary spatially within an integrated hand architecture rather than being assembled as disconnected subsystems [21,61,78].

2.4. Mechanical Intelligence

Mechanical intelligence, as used in this review, refers to the capacity of a mechanism's physical architecture—its topology, compliance distribution, passive dynamics, and kinematic couplings—to encode task-relevant behavior directly in structure, thereby reducing the computational burden or active actuation effort required to achieve stable precision contact.

- Concept and scope.

Mechanical intelligence in a robotic hand can be defined as the capacity of morphology, compliance distribution, transmission topology, and passive constraints to encode useful grasp behavior directly in the hardware. Part of the grasp strategy is realized physically: link geometry, tendon routing, joint elasticity, frictional interfaces, palm configuration, and material deformation bias the way contacts are formed, stabilized, and released [77]. For dexterous hands intended to perform precision grasping, this concept is especially relevant because of small alignment errors, contact instabilities, or transmission losses rapidly degrade pinch quality, induce slip, or destabilize in-hand manipulation. The decisive question is therefore not simply how to maximize the number of actuators or degrees of freedom, but how to distribute stiffness, compliance, and coupling so that the hand acquires, stabilizes, and manipulates objects with the minimum necessary control burden.

This idea is consistent with grasp-reflex-inspired strategies for unknown objects, in which contact triggers mechanically meaningful closure responses, and with dynamic in-hand sliding studies that treat controlled tangential motion as a manipulable resource rather than as a failure mode [123,124].

Mechanically intelligent hands exploit contact-driven self-organization. When an early link or fingertip touches the object, the remaining joints or digits reconfigure passively rather than enforcing a fully predetermined trajectory. Importantly, unlike fully soft hands that obtain adaptation mainly through bulk deformation, anthropomorphic hands for precise work often combine selective rigidity with selective compliance. Comparative reviews across robot hands, prostheses, and orthoses show that useful performance emerges from balancing positional accuracy, adaptability, integration density, and transmission complexity rather than from any single design extreme. This is also why mechanical intelligence remains important in the era of tactile sensing and learning. Rich perception can compensate for uncertainty only within the limits imposed by contact mechanics, actuator bandwidth, and reachable opposition space.

- Under-actuation, adaptive synergies, and differential transmission.

Under-actuation and adaptive synergies are the clearest expression of mechanical intelligence in robot hands. In these architectures, the number of independent actuators is smaller than the number of joints, and the missing control dimensionality is compensated for by tendon differentials, elastic elements, compliant joints, or kinematic couplings. The benefit of under-actuation is not actuator reduction alone, but the fact that contact itself becomes a mechanical selector: once one joint or phalanx is constrained by the object, motion and force are redistributed to unconstrained joints, allowing the hand to envelop or oppose the object without solving a full contact-planning problem online. This principle underlies the long-standing idea that simplicity in hardware can generate functional richness at the level of grasp execution.

The 15-DOF single-actuator hand of Gosselin et al. remains emblematic of this approach [73]. By combining tendon transmission, passive return elements, and object-dependent closure, the hand achieves a broad range of grasp postures through a highly compressed actuation space. Synergy-based descendants extended the same logic by embedding dominant human grasp patterns into mechanical couplings, thereby preserving adaptive grasp acquisition while improving anthropomorphic behavior [33,74]. Differential mechanisms further show that torque distribution is a first-order design variable. To make the category-level differences explicit, Figure 4 compares three four-output architectures implemented in the same prosthetic-hand platform [115]. The whiffletree differential distributes displacement through tendon-loaded translating bars; the four-output geared differential uses rigid gears, concentric shafts, and pulleys to provide continuous rotary outputs; and the series-elastic differential inserts compressible urethane–rubber elements (Smooth-On PMC-780) between the main body and each output attachment. Because the hand frame, number of outputs, and locking concept are comparable across the panels, the figure isolates the load-sharing element that defines each category rather than presenting unrelated examples. The reported prototypes weighed 46, 169.8, and 22.5 g and produced maximum total output forces of 171, 156, and 215 N (rigid mode), respectively [115]. Thus, the whiffletree favors low mass but requires translation space, the geared architecture provides continuous motion at the cost of greater mass and complexity, and the series-elastic architecture provides compact compliance but limits adaptive travel through elastic compression.

In a related direction, Sun et al. demonstrated that a dual-actuated hand with an independently driven thumb and a synergistically driven finger group can reproduce a large repertoire of anthropomorphic grasps and representative manipulation tasks with

only two actuators [72]. These examples emphasize that mechanical intelligence depends less on minimizing actuator count than on assigning independence where it matters most and passive coordination elsewhere.

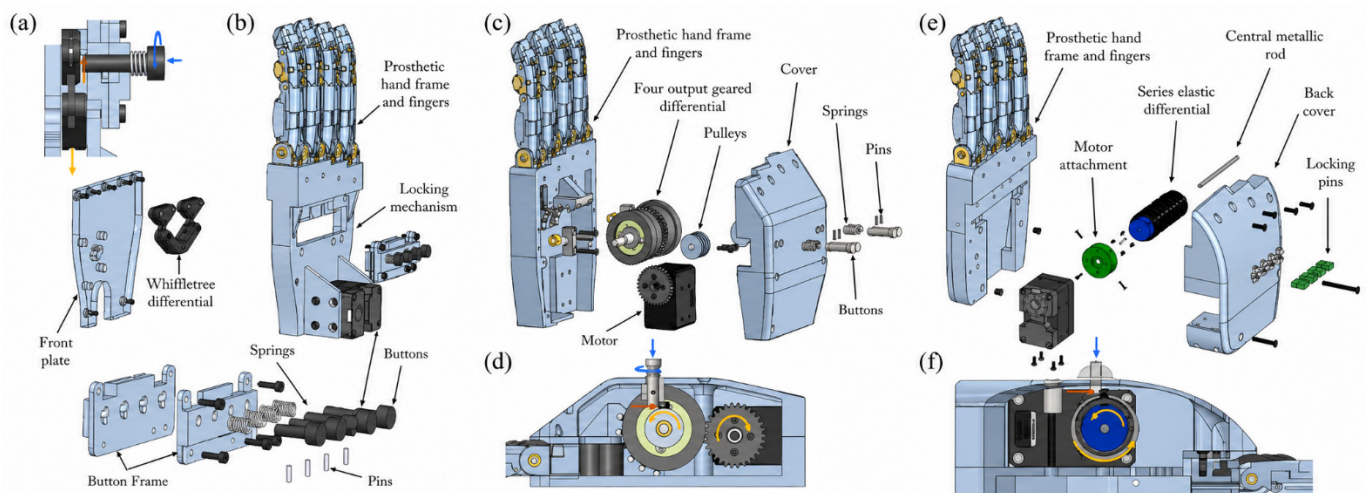


Figure 4. Comparative integration of three underactuated differential architectures in the same prosthetic-hand platform: (a,b) a whiffletree differential based on tendon-loaded translating bars; (c,d) a four-output geared differential based on rigid gears, concentric shafts, and pulleys; and (e,f) a series-elastic differential incorporating compressible urethane-rubber elements (Smooth-On PMC-780) and a central metallic rod. The blue arrows indicate the actuator-input motion, whereas the yellow arrows indicate the resulting output or rotational motion. The different colors are used only to visually distinguish and highlight the principal components and do not represent different material properties unless explicitly labeled. The common hand frame and locking principle make the differences in load distribution, spatial requirement, compliance, and output motion directly comparable. Redrawn by the authors based on [115], licensed under CC BY 4.0.

For precision grasping, under-actuation must therefore be deployed selectively. Strong coupling improves acquisition robustness, yet excessive coupling reduces the ability to place distal contacts accurately or to regulate small pinch forces. Precision-oriented hands tend to preserve greater independence at the thumb and terminal joints while using under-actuation mainly at proximal joints or across non-dominant fingers. The mechanical intelligence required for enveloping and the mechanical intelligence required for precise pinching are thus related but not identical. The former benefits from passive conformity over large contact areas, whereas the latter requires predictable local kinematics, controllable contact normals, and reduced backlash at the final contact interface.

- Precision-oriented mechanisms: thumb opposition, locking, and contact management.

Among all structural variables, thumb morphology exerts the strongest influence on precision grasping. The thumb determines whether the hand can generate stable opposition, align fingertip pads, and regulate moments around small objects. Design guidelines synthesized from anatomy and manipulation studies stress that the thumb should not be treated as an ordinary finger simply placed in opposition; instead, base placement, rotational orientation, and the availability of twist during opposition are decisive for obtaining human-like contact conditions [70]. This interpretation is consistent with the experimental observations of Hoshino and Kawabuchi, who showed that fingertip pinching improved significantly when the hand incorporated a twisting degree of freedom at the thumb, together with independently actuated distal motion at the fingertips [24]. Mechanically, these freedoms allow the thumb pulp and counter-finger pulp to align their local contact planes, thereby reducing parasitic moments and improving control of very small grasp forces.

The same logic applies to linkage-driven or hybrid rigid-soft hands. When the distal phalanges and thumb are guided by well-constrained linkages, positional repeatability can be improved without requiring direct actuation at every joint. This is one reason why recent anthropomorphic hands preserve carefully designed linkage paths even when compliance is introduced elsewhere in the structure [88]. For precision grasping, mechanical intelligence is therefore not equivalent to softness. Rather, it lies in deciding which joints should be mechanically deterministic and which should remain adaptive.

A second important strategy is posture locking or grasp-state locking. Precision pinches often fail not at acquisition but during holding, when tendon relaxation, actuator creep, or small external perturbations induce drift at the fingertips. Joint-locking mechanisms address this problem by mechanically decoupling posture maintenance from continuous actuator effort. Shin et al. introduced an electromagnetic joint-locking concept to increase the effective workspace of underactuated finger modules and to improve grasp stability [125]. In a complementary direction, Saharan and Tadesse proposed a locking mechanism driven by twisted-and-coiled polymer (TCP) muscles, enabling the hand to maintain posture with low sustained energy expenditure [126].

Mechanical intelligence can also be embedded at the contact interface. Variable-friction finger surfaces, for example, can switch between gripping and sliding regimes to support within-hand repositioning without fully releasing the object [28]. For precision manipulation, this means that the hand can intentionally exploit controlled slip rather than merely resist it. In practice, the architecture becomes capable of transitioning between a high-friction stabilization phase and a lower-friction reorientation phase, which is valuable for tasks such as cap screwing, edge alignment, or object rolling.

- Soft, compliant, and variable-stiffness embodiments.

Soft and compliant hands realize mechanical intelligence through material behavior rather than through rigid kinematic closure alone, building on the material and fabrication foundations discussed in Section 2.3. Their primary advantage is that deformation enlarges contact area, accommodates shape uncertainty, and lowers the risk of damage when interacting with fragile objects. This logic is beneficial in unstructured environments where object geometry, pose, and stiffness are not known precisely before contact. However, the same deformation that enhances robustness can degrade endpoint accuracy, complicate calibration, and introduce hysteresis. For precision grasping, the relevant question is therefore not whether soft hands are preferable to rigid hands in general, but which compliant functions can be exploited without sacrificing repeatable local contact formation.

Although developed for food handling, the dual-mode gripper of Wang et al. illustrates a transferable design principle: by combining soft bending fingers with fingertip suction pads [99], the device integrates frictional enclosure and adhesion-based contact into a single mechanical body. Because the fingers are fabricated by casting soft rubber materials and operating through pneumatic deformation, the device can conform safely to delicate or irregular targets while also switching grasping mode through suction. From the standpoint of mechanical intelligence, the key contribution is not only softness but the integration of multiple contact principles—frictional enclosure and suction—into the mechanical body. Pagoli et al. advanced this direction by proposing a soft gripper with an active palm and reconfigurable fingers, in which a stiff internal rod changes the effective bending location of each finger [44]. This architecture partially compensates for the positional indeterminacy of soft bodies by enabling morphological reconfiguration before or during manipulation. The result is a hybrid design in which workspace and contact topology can be tuned mechanically rather than by means of a fully articulated rigid hand.

Variable-stiffness mechanisms offer a second major route for reconciling adaptability and precision. In the gripper of Wei et al., a soft bending actuator is combined with particle jamming so that the finger remains compliant during shape acquisition but stiffens after conforming to the object [45]. Such a grasp sequence is highly relevant to precision tasks. During the approach and first-contact phase, softness absorbs alignment error and distributes pressure more evenly. During the holding phase, stiffness increases to resist deformation, improve load-bearing capability, and suppress configuration drift. In effect, the hand changes its mechanical role as the task evolves from acquisition to stabilization. This phase-dependent behavior is one of the clearest examples of hardware acting as an adaptive controller.

Soft architecture can also support manipulation rather than only safe grasp acquisition. Abondance et al. showed that soft fingers can execute robust in-hand motion primitives, including rolling and finger-gait-like reorientation, while maintaining reliable grasping under uncertainty and without relying on complex local feedback [43]. Likewise, the RBO compliant hand demonstrates how mold-based pneumatic fingers and a compliant palm can achieve robust shape matching through a fabrication approach that remains simple and inexpensive [97]. Taken together, these studies suggest that the main limitation of soft hands is not an absence of dexterity per se, but the difficulty of mapping continuous body deformation to repeatable fingertip pose and force at the level required for precision pinch.

Recent research further suggests that compliance should be spatially distributed rather than confined to isolated soft joints. Junge and Hughes demonstrated that compliance distributed across the skin, fingers, and wrist can produce self-organized grasp behaviors, robust open-loop pick-and-place performance, and object-dependent grasp types that resemble human grasp selection [21]. Their findings reinforce an important point for this review: mechanical intelligence is strongest when compliance is structured, directional, and task aware. Random softness merely introduces uncertainty, whereas distributed compliance designed to guide contact evolution can enhance robustness without requiring a proportional increase in sensing and control complexity.

The role of the palm is especially important. Human grasping and in-hand manipulation depend not only on fingers but also on palm shape change and active support surfaces. Reviews of actuated palms [127] show that palm motion can modify the relative orientation of fingers, alter reachable opposition regions, and create additional support constraints that stabilize in-hand manipulation. In soft or hybrid hands, an actuated palm is therefore more than a packaging feature; it is a mechanical intelligence element that changes the topology of the grasp itself. The active-palm design of Pagoli et al. and the balloon-actuated palm concept of Yamaguchi et al. both illustrate this principle, although through very different technologies [44,108]. In the electro-conjugate-fluid hand of Yamaguchi et al., balloon-type actuators embedded in the palm generate flexion and thumb-opposition-related motion, allowing the hand to adapt to object shape without a complex controller [108].

- Comparative implications and design outlook.

When the principal mechanical strategies are compared side by side, it becomes clear that no architecture is uniformly superior for all precision-grasping tasks. Each strategy distributes mechanical advantages and limitations differently: rigid-link systems favor deterministic fingertip placement, tendon-driven systems improve packaging flexibility, underactuated mechanisms enhance adaptive conformity, soft fluidic hands increase safety and shape accommodation, and SMA or compact hybrid systems improve integration density. These differences motivate a rubric-based comparison that makes the underlying trade-offs explicit rather than treating the architectures as directly rankable alternatives.

To reduce subjectivity in the comparative assessment, the trade-off matrix was re-constructed using a criterion-based ordinal rubric. The matrix does not rank individual robotic hands as absolute benchmarks. Instead, it summarizes architecture-level tendencies under precision-grasping conditions by linking each score to observable mechanical characteristics reported in the reviewed literature, including DOF allocation, actuator location, tendon length, reported force, repeatability evidence, sensing layout, and benchmark task evidence. Because all five criteria are expressed as favorable design capabilities, the scoring direction is consistent across the matrix: higher scores indicate stronger support for precision grasping, while lower scores indicate weaker support. Therefore, the scores should be interpreted within each criterion and should not be summed, averaged, or treated as equal-interval numerical data. Under this convention, a score of 5 always means stronger precision-grasping support, whereas a score of 1 means weak support. The general interpretation of the five-point ordinal scale is summarized in Table 4.

Table 4. General interpretation of the five-point ordinal scoring scale.

Score	General Interpretation	Capability-Oriented Criteria (Positional Accuracy, Adaptive Conformity, Integration Density)	Capability-Oriented Criteria (Transmission Transparency, Design/Control Practicality)
1	Lowest category	Very weak contribution to the desired capability.	Very low transmission transparency or design/control practicality.
2	Limited/low category	Some favorable features are present, but the capability remains below a clearly moderate level.	Limited transmission transparency or design/control practicality; favorable features remain below a clearly moderate level.
3	Moderate/implementation-dependent category	The capability depends strongly on implementation, task, calibration, or operating conditions.	Moderate transmission transparency or design/control practicality; performance is strongly implementation-dependent.
4	High category	The capability is generally favorable, but residual constraints prevent assignment of the maximum score.	Generally favorable transmission transparency or design/control practicality, but residual constraints prevent assignment of the maximum score.
5	Highest category	Very strong contribution to the desired capability.	Very high transmission transparency or design/control practicality.

In this convention, all five criteria follow the same direction: a score of 5 indicates stronger precision-grasping support, whereas a score of 1 indicates weaker support.

When direct quantitative values are reported, the relevant physical indicators should be prioritized, such as fingertip repeatability (mm or deg), backlash or lost motion (deg or mm), tendon elongation, pressure delay, material hysteresis, actuator/sensor packaging volume, number of independently controlled variables, calibration demand, and assembly sensitivity. These indicators provide evidence for transmission transparency and design/control practicality. When such values are not consistently available across studies, the architecture-level score is assigned by the anchor logic in Table 5.

Table 5. Criterion-specific anchors for applying the ordinal rubric.

Criterion	Direction	Score 1	Score 2	Score 3	Score 4	Score 5
Positional accuracy	Lower fingertip error, stronger repeatability evidence	Poor repeatability; weak fingertip placement control; large lost motion.	Limited repeatability under constrained conditions.	Moderate or task-dependent accuracy; sensitive to tuning and load.	Generally repeatable fingertip placement with residual nonidealities.	Highly deterministic kinematics and low lost motion for fingertip placement.
Adaptive conformity	Better object-shape accommodation without losing contact localization	Minimal passive adaptation to object shape.	Limited local compliance or contact accommodation.	Moderate adaptation; strongly task-dependent.	Good adaptation over many shapes, but with some loss of independent pose control.	Strong passive shape accommodation and contact redistribution.
Integration density	More compact packaging of actuation, routing, and structure	Bulky implementation; poor packaging efficiency.	Partial integration, but substantial external or distributed components remain.	Moderate packaging with clear size, routing, or sensor trade-offs.	Compact packaging through remote actuation or embedded elements, with auxiliary components.	Very compact integration of actuation, transmission, structure, and/or sensing.
Transmission transparency	More predictable transfer; lower backlash, hysteresis, stretch, lost motion, and friction	Very low transparency; transmission error, pressure delay, thermal hysteresis, or lost motion dominates fine positioning.	Low transparency; high transmission uncertainty requires frequent compensation or calibration.	Moderate transparency; usable for many grasps but sensitive to routing, pretension, friction, or material hysteresis.	Good transparency; low lost motion and predictable transfer under most precision-grasping conditions.	Very high transparency; predictable motion transfer with minimal backlash, hysteresis, or lost motion.
Design/control practicality	Easier design, calibration, control, and assembly	Very low practicality; complex calibration, fragile assembly, and high-dimensional control.	Low practicality; precise operation requires careful fabrication, tuning, and compensation.	Moderate practicality; task-dependent mechanical and control tuning is needed.	Good practicality; limited tuning, calibration, or coordination is required.	Very high practicality; simple, robust implementation and low calibration demand.

Based on this scoring convention, Table 6 synthesizes the architecture-level trade-offs among representative mechanical strategies for precision grasping. The purpose is to show how each architecture distributes favorable capabilities across the five criteria under precision-grasping conditions. Of particular relevance to mechanical intelligence is the observation that the most adaptable systems are not always the most precise, whereas the most deterministic systems are not always the most forgiving under uncertainty.

Table 6 shows that no single architecture provides the best behavior across all precision-grasping criteria. Rigid-link and linkage-based hands provide deterministic fingertip placement and very high transmission transparency when joints and linkages are manufactured precisely, but these advantages are accompanied by limited passive adaptability and low design/control practicality. Tendon-driven hands provide good positional capability and

favorable integration density through remote actuation, but their transmission transparency and design/control practicality remain constrained by tendon routing, pretension, friction, stretch, calibration, and compensation requirements.

Table 6. Rubric-based qualitative trade-off matrix for representative mechanical strategies in precision grasping.

Architecture	Positional Accuracy	Adaptive Conformity	Integration Density	Transmission Transparency	Design/Control Practicality
Rigid-link/linkage-based	5	2	3	5	2
Tendon-driven	4	3	4	3	2
Underactuated differential	3	5	4	4	3
Soft pneumatic/hydraulic	2	5	3	1	3
SMA/hybrid compact	3	3	5	1	2

Note: All five criteria are capability-oriented and follow the same scoring direction, so higher scores are more favorable. Color shading distinguishes ordinal categories only and should not be interpreted as a universal good-to-bad heatmap. Scores represent relative ordinal assessments derived from the mechanical trends reviewed in Sections 2.1–2.4 and from comparative studies on robotic hand architectures and benchmarking methods [3,109]. Representative evidence includes linkage-driven, tendon-driven, underactuated, soft, and smart-material-based hands [19,33,43,46,115]. The scores support design-level comparison among architectures and should not be interpreted as measured values, equal-interval numerical data, or absolute rankings across all robotic hands and grasping tasks. The architecture-level rationale for the scores assigned in Table 6 is provided in Table 7.

Table 7. Rationale for the architecture-level scores assigned in Table 6.

Architecture	Score Rationale
Rigid-link/linkage-based	Adaptive conformity is limited (2) because passive shape accommodation is weaker than in underactuated or soft hands. Design/control practicality is low (2) because precise multi-joint rigid hands require tight tolerances, alignment, actuation coordination, and calibration. Integration density is moderate (3) because rigid joints, bearings, and linkages increase packaging volume. Positional accuracy is very high (5) because rigid kinematic chains and linkage constraints provide deterministic fingertip placement. Transmission transparency is very high (5) because properly manufactured joints and linkages provide predictable motion transfer with low lost motion.
Tendon-driven	Design/control practicality is low (2) because stable precision grasping requires tension management, routing optimization, calibration, and compensation for transmission nonlinearities. Adaptive conformity is moderate (3) because compliance and routing can support contact accommodation but do not guarantee passive adaptation. Transmission transparency is moderate (3) because tendon stretch, friction, routing curvature, pretension variation, and sheath effects introduce uncertainty. Positional accuracy is good (4) because properly tensioned tendons can provide repeatable fingertip placement. Integration density is good (4) because remote actuation reduces distal mass and enables compact fingers.
Underactuated differential	Positional accuracy is moderate (3) because individual contact positions are not fully independently controlled. Design/control practicality is moderate (3) because reduced actuator count simplifies some aspects, but contact sequencing and precision regulation remain task-dependent. Integration density is good (4) because multiple joints can be driven with fewer actuators. Transmission transparency is good (4), although it depends on whether the differential is gear-, linkage-, tendon-, or compliance-based. Adaptive conformity is strong (5) because differential and underactuated couplings redistribute motion and contact forces over object shapes.
Soft pneumatic/hydraulic	Transmission transparency is very low (1) because material hysteresis, fluid compressibility, pressure delay, and nonlinear deformation reduce predictable motion transfer. Positional accuracy is limited (2) because structural compliance and pressure-mediated dynamics reduce repeatable fingertip placement. Integration density is moderate (3) because soft fingers can be compact but require pumps, valves, tubes, reservoirs, or pressure regulation. Design/control practicality is moderate (3) because safe grasp acquisition is simple, but accurate force and position regulation requires modeling, sensing, and compensation. Adaptive conformity is strong (5) owing to safe passive deformation and large contact-area redistribution.

Table 7. *Cont.*

Architecture	Score Rationale
SMA/hybrid compact	Transmission transparency is very low (1) because thermal hysteresis, temperature-dependent strain recovery, slow cooling, and cycle-dependent behavior reduce predictable motion transfer. Design/control practicality is low (2) because precision grasping requires thermal management, calibration, feedback compensation, and careful material integration. Positional accuracy is moderate (3) because compact thermal actuation is affected by hysteresis and cooling dynamics. Adaptive conformity is moderate (3), depending on whether compliant structures are integrated. Integration density is strong (5) because actuation can be embedded directly into compact fingers.

Underactuated differential mechanisms improve adaptive conformity and grasp diversity per actuator, but they reduce independent control of individual contacts and therefore remain moderate in positional accuracy; their transmission transparency is generally good, while design/control practicality remains implementation-dependent. Soft pneumatic and hydraulic hands provide high safety and shape adaptability, yet their transmission transparency is very low because pressure-mediated dynamics, structural compliance, and material hysteresis reduce repeatable fine positioning. SMA and compact hybrid hands offer very high integration density, but their transmission transparency and design/control practicality remain low because of thermal latency, hysteresis, cooling constraints, and calibration requirements.

Overall, the matrix should be read as a design trade-off map rather than as a universal ranking. Precision grasping is unlikely to be achieved by maximizing a single architectural property. Hybrid combinations are often required to balance deterministic fingertip placement, adaptive acquisition, compact integration, transmission transparency, and design/control practicality. In particular, distal contacts, thumb opposition, and local transmission paths should be sufficiently deterministic for fine manipulation, whereas proximal joints, palm motion, and pre-contact acquisition can remain more adaptive to absorb uncertainty.

From the perspective of precise grasping, mechanical intelligence should be regarded as an architectural principle that redistributes complexity from software into structure. Under-actuation, adaptive synergies, active palms, selective thumb freedoms, posture locking, variable friction, soft joints, and variable stiffness are all concrete ways of embedding task-relevant behavior in the body of the hand [24,108,127]. The key challenge is not to maximize any one of these ingredients in isolation but to coordinate them so that acquisition is tolerant, holding is stable, and manipulation remains controllable. Future dexterous hands for precision work will likely combine mechanically guided pinch interfaces with distributed compliance in the palm and proximal joints, together with reconfigurable or lockable transmissions that change the hand's effective mechanics across task phases. Such systems will be soft where uncertainty is high, stiff where contact location matters, and mechanically reconfigurable when the task transitions from grasp acquisition to fine manipulation.

The mechanical intelligence framework developed above is best illustrated by examining how it manifests across actual hand platforms. To consolidate the design trends discussed across Sections 2.1–2.4, Table 8 compares representative hand platforms that are most relevant to precision grasping in terms of kinematic allocation, transmission strategy, actuation placement, structural material, sensing, and reported task evidence.

Table 8. Representative dexterous robotic hand platforms most relevant to precision grasping.

Hand/ Platform	Year	Finger Number	Total DOF	Actuator Number	Thumb Configuration	Transmission Type	Actuation Type	Actuator Location	Structural Material	Sensors Integrated	Reported Precision Task	Main Advantage	Main Limitation
Gifu Hand II [128]	2002	5	16	16	4-DOF opposable thumb	Built-in geared/rigid joint transmission	Electric servomotors	In fingers + palm	Rigid frame	Distributed tactile sensor; magnetic encoders; optional 6-axis fingertip force sensors	Grasping with human-grasp-reflex strategy; dexterous object manipulation	Sensorized anthropomorphic benchmark with full-finger tactile feedback	High distal integration, mass, and mechatronic complexity
CEA Dexterous Hand [88]	2014	5	20 DOF; 24 degrees of mobility	20 actuated DOF	5-DOF anthropomorphic thumb	Tendon-driven transmission in a modular backdrivable architecture	Backdrivable electric motorized actuation	Integrated within the hand/forearm structure	Modular rigid mechatronic structure	Position/proprioceptive sensing; no dense tactile array reported	Dexterous finger motion and manipulation-oriented experiments	Fully modular, backdrivable, and mechanically simple design suitable for dexterous manipulation	High mechatronic complexity; less tactile-rich than sensorized hands
KITECH-Hand [63]	2017	5	15	15 (5 forearm + 10 palm motors)	Anthropomorphic opposable thumb; roll-pitch MCP concept	Tendon-driven	Electric motors	5 in forearm, 10 in palm	NR	NR	Pinch, tripod, lateral grasps	Roll-pitch MCP enlarges shared workspace and improves contact reorientation	Higher packaging complexity and many actuators
Pisa/IIT SoftHand 2 [33]	2018	5	NR	2	Synergy-based opposable layout	Tendon-driven augmented adaptive synergies	Electric motors	Proximal	Soft/compliant embodied hand	NR	Rotating objects, opening a jar, pouring coffee	Strong grasp + basic in-hand manipulation with only 2 DoA	Lower local determinism than fully actuated rigid hands

Table 8. Cont.

Hand/ Platform	Year	Finger Number	Total DOF	Actuator Number	Thumb Configuration	Transmission Type	Actuation Type	Actuator Location	Structural Material	Sensors Integrated	Reported Precision Task	Main Advantage	Main Limitation
BCL-26 soft hand [112]	2019	5	26 inde- pendent DOF	NR	Strong thumb dexterity; metacarpal extension	Soft-robotic compliant architecture	Proprietary actuation/ control	Distributed	Soft/compliant anthropo- morphic body	NR	Full scores on grasp taxonomy, thumb dexterity, in-hand manipula- tion/writing	Most ambitious soft anthropomor- phic dexterity among the platforms reviewed	Actuation/ control chain is less standardized and less transparent than rigid hands
HRI Hand [114]	2020	5	6	6	2-DOF thumb (MCP + CMC/ab-ad)	Two four-bar linkage, un- deractuated	Linear electric actuators	Integrated in hand/palm	3D-printed polymer; optional SUS304 sub- stitutions reported in related build notes	NR	Pre-shaping before object contact; collaborative end-effector use	Low cost, open-source, modular; good as research baseline	Low DOF, limited fine in-hand manipulation
ILDA hand [19]	2021	5	15 active (20 joints)	15	Anthropomorphic, precision- oriented thumb/index workspace	Linkage- driven rigid transmission	Electric motors	Fully integrated in hand	Rigid linkage architecture	Tactile sensing	Tool-use tasks (e.g., scis- sors/tweezers); pinch/tripod/ lateral grasping	Very high repeatability, deterministic kinematics, fingertip force up to 34 N	Lower passive adaptability; structure/ control more complex
MCR-Hand III [1]	2021	5	NR	NR	Anthropomorphic thumb with opposability- oriented design lineage	Hybrid linkage- spring- tendon	Electric actuation	Hybrid integrated/ proximal	Rigid links + springs + compliant elements	NR	Cutkosky grasps, deformable- object lifting, piano manipulation	Good compromise between repeatability and passive compliance; low cost	Calibration/ control more involved than pure rigid hands

Table 8. Cont.

Hand/ Platform	Year	Finger Number	Total DOF	Actuator Number	Thumb Configuration	Transmission Type	Actuation Type	Actuator Location	Structural Material	Sensors Integrated	Reported Precision Task	Main Advantage	Main Limitation
Mini X-hand/ dual- actuated hand [72]	2022	5	NR	2	Thumb independently driven; manual ab/ad function	Differential palm + synergistic finger transmission	Electric actuation	Palm- integrated	Rigid differential mechanism	NR	Self-adaptive pinch/envelop grasps; in-hand ball manipulation; screwing bottle cap	Exceptional actuator economy with broad grasp repertoire	Fine independent joint control remains limited
CasiaHand [2]	2025	5	15	NR	Human-like an- thropomorphic thumb	Tendon- driven	Electric mo- tor/tendon actuation	Palm- integrated tendon actuation	NR	NR	Human-like grasping dexterity; object manipulation demonstra- tion	Human-scale 15-DOF tendon- driven platform with low structural weight	Tendon fric- tion/stretch and calibration still limit repeatability
Fil3D-Hand [61]	2025	5	17	12 servo motors	Humanoid thumb configuration	Tendon- driven underactu- ated	Servo motors	Hand + forearm assembly	3D-printed filament structure	14 nanocom- posite filament strain sensors	Grasping evaluation with real-time finger-motion monitoring	Strong embedded propriocep- tion + low cost (<\$350)	Larger/heavier than strict human scale; precision still depends on tendon under- actuation
Lightweight prosthetic hand [64]	2025	5 + wrist	19	38 SMA actuators	Biomimetic multi-DOF thumb	Embedded SMA-based actuation/ transmission	Shape- memory alloy	Distributed in fingers + wrist	Lightweight biomimetic prosthetic structure	NR	ADL-oriented human-level functions	Very high dexterity at very low mass (~370 g)	SMA thermal dynam- ics/hysteresis complicate precise high- bandwidth control

Note: NR indicates the information was not reported in the cited source.

3. Control-Oriented Design

3.1. Sensor–Structure Integration

Sensing is a fundamental enabler of precision grasping in dexterous robotic hands because accurate manipulation depends not only on the mechanical design of the fingers but also on continuous access to internal state and contact information. As discussed in Section 2.3, the fabrication route and material architecture of the finger directly affect where sensors can be placed and how faithfully contact signals reach the measurement site. Recent reviews broadly divide sensing in dexterous manipulation into intrinsic/proprioceptive sensing, which measures the state of the mechanism itself, and extrinsic/exteroceptive sensing, which measures interaction with the object and environment [52,76]. In practice, precision grasping emerges when these sensing channels are co-designed with the actuation and transmission architecture. Accordingly, sensor-mechanism integration is a primary architectural variable. The same co-design logic appears in hands, where joint position sensing and torque sensing were integrated directly into each finger unit [129].

At the control level, studies show that precision depends not only on morphology, but also on how effectively the controller compensates for coupling, friction, and transmission uncertainty [130,131]. The CyberHand combined joint-angle sensing, motor-side position sensing, and cable-tension sensing with contact and force sensing [22]. Likewise, the sensorized biomechatronic hand reported by Edin et al. emphasized task-relevant events such as touch onset, lift-off, load transfer, and slip-related transients [23]. This perspective remains highly relevant for present-day review work: the best sensor suite for precision grasping is not always the densest one, but the one whose measurements are most informative for contact-rich control. Figure 5 presents a representative mechanism-embedded proprioceptive architecture, in which sensing elements are integrated into the finger structure rather than attached as an external tactile skin. CNT-based nanocomposite filament strain sensors are secured in dedicated housings within the 3D-printed resin phalanges, while fixed data-output points define repeatable sensing regions. The enlarged finger and full-hand views clarify local sensor placement and system-level integration; this architecture monitors finger deformation and posture rather than contact pressure.

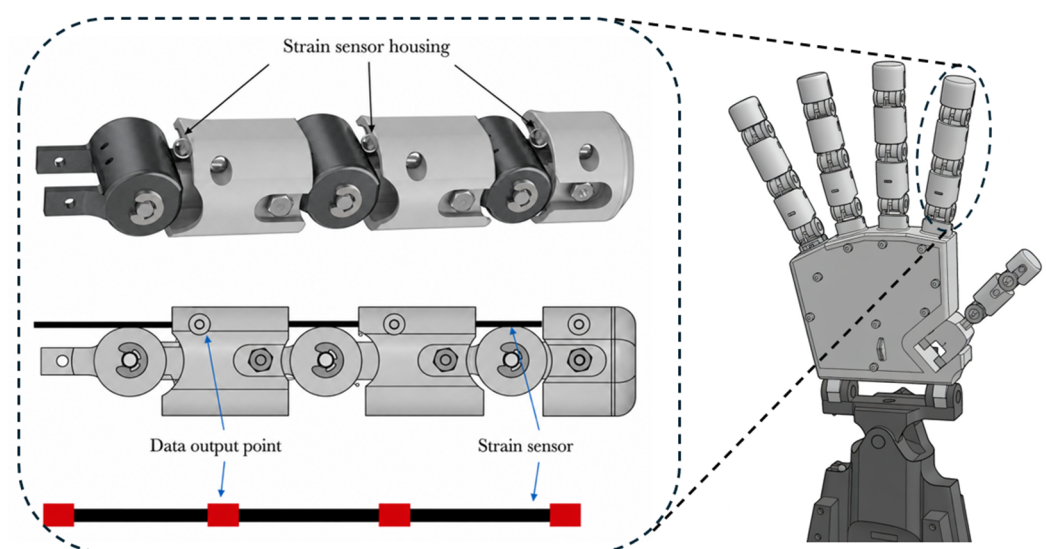


Figure 5. Representative integration of CNT-based nanocomposite filament strain sensors in the Fil3D robotic hand. The enlarged finger views identify the sensor housings, sensing segments, and data-output points along the 3D-printed resin phalanges, whereas the full-hand view locates the sensorized finger within the complete architecture for proprioceptive posture monitoring. Redrawn by the authors based on [61], licensed under CC BY 4.0.

- Proprioceptive sensing embedded in the mechanism

For precision grasping, the first sensing layer is typically embedded within the actuation chain. Encoders, Hall-effect sensors, potentiometers, motor current feedback, cable-tension sensors, and strain or bend sensors are used to reconstruct finger posture, actuator displacement, and, in some cases, transmitted force [31,132]. They also support repeatable preshaping before contact, which is especially important in multi-finger pinch and in-hand alignment tasks.

Grossard et al. reported that coupling a Maxon Encoder MR to the motor yielded a linear position resolution of 0.001 mm at the actuator output, and the low-level controllers estimated joint angles from motor-angle measurements [50]. This case illustrates an important design principle: encoder performance cannot be assessed independently of transmission mechanics. High encoder resolution does not automatically translate into precise finger motion if tendon routing, backlash, or friction degrade the correspondence between motor motion and joint motion.

In the DLR multisensory articulated hand and its successors, joint sensing was also tightly integrated into the active joints to enable torque/position control within a compact, human-sized structure [51]. Modular lightweight hands have followed similar strategies by embedding motor-position sensing and contact-force sensing into the hand body rather than relying on bulky external instrumentation [133]. In hands designed for rehabilitation or compact wearable systems, potentiometers or simplified position sensors are sometimes selected because they fit constrained spaces more easily than larger rotary encoders, although this may come at the expense of robustness or long-term repeatability [132].

For compliant and soft hands, proprioceptive sensing becomes even more critical because the finger configuration may deviate substantially from nominal kinematic models during object contact. Homberg et al. showed that internal bend and force sensors can be used to infer both hand configuration and object interaction state, allowing a soft hand to perform proprioceptive grasping and remain robust to object-pose uncertainty [31].

Another pathway to reduce hardware complexity is sensorless or quasi-sensorless estimation. For example, contact force can be approximated from actuator current and transmission models in highly back-drivable tendon-driven hands, thereby reducing the need for dedicated fingertip transducers [29]. However, such estimates are strongly model-dependent and degrade when friction, hysteresis, or unmodeled contact conditions vary. Consequently, they are useful as complementary feedback channels but rarely sufficient on their own for high-precision grasping of diverse objects.

- Tactile, force, and slip sensing at the contact interface

While proprioceptive sensing determines how the hand moves, exteroceptive sensing determines how the hand is interacting with the object. For precision grasping, the most influential measurements are usually contact location, pressure distribution, normal and tangential force components, and incipient slip cues. Their role is to close the loop after contact has occurred: tactile and force sensing allow the controller to confirm whether the intended grasp has actually been achieved, to refine finger closure, and to regulate grip force without crushing or dropping the object [30].

Distributed tactile sensing across the hand surface is one of the most established strategies. Gifu Hand II is a classic example in which tactile sensing was distributed over the anthropomorphic hand to obtain pressure information during grasping and object handling [128]. Later developments extended this idea by designing tactile systems as modular construction kits for fingers and palms, together with signal-processing pipelines capable of interpreting large numbers of sensing elements on curved surfaces [134]. As

summarized in the review by Kappasov et al., distributed tactile skins are valuable because they capture spatial patterns of contact rather than isolated point measurements [26].

Edin et al. embedded a low-noise three-axis force sensor in the fingertips of a biomechatronic hand and combined it with surface contact sensors to detect the mechanical events that organize grasp-and-lift behavior [23]. More recently, Kim et al. developed a six-axis force/torque fingertip sensor that can be installed inside a human-sized robotic fingertip, allowing direct measurement of the contact wrench without substantially compromising finger size or mobility [18].

Nevertheless, resultant force measurements alone do not fully describe the contact state. Vision-based tactile sensors such as DIGIT have demonstrated that high-resolution contact imaging can be miniaturized to fit multi-fingered hands and used for in-hand manipulation tasks [135]. Compared with conventional force sensors, these devices provide substantially richer geometric and textural information about the contact area.

Slip sensing is especially important because grasp stability is often limited not by gross positioning error but by the onset of local sliding at the contact interface. James and Lepora showed that tactile slip detection can be used to trigger reactive grip adjustment and stabilize grasps across a range of objects and grasp types [27]. These studies support a broader conclusion: in precision grasping, tactile sensing is most valuable when it is tightly integrated into a fast reflex-like control loop rather than treated merely as a post hoc measurement channel.

Recent sensing work also includes barometer-based tactile skins, pressure-sensor design specifically targeted to robotic hands, active tactile exploration strategies, robust sensor-based grasp primitives, and custom soft sensor skins for haptic object visualization [136–140].

The fusion of tactile and kinematic data is also crucial. Dang et al. formulated blind grasping as stable grasp perception using tactile feedback together with hand kinematics [141]. Their approach highlights that contact sensing and mechanism state are complementary. For this reason, multimodal fusion is generally more informative than either modality alone for grasp evaluation.

- **Multimodal architecture and physical sensor placement**

The performance of a sensorized hand depends not only on the sensing principle but also on where the sensors are physically located and how well they are mechanically integrated. In most dexterous hands, tactile or pressure sensors are concentrated at the fingertips and distal phalanges [134]. Proprioceptive sensors, by contrast, are usually placed near motors, joints, transmissions, or tendons. This division of placement is consistent with the intrinsic/extrinsic sensing taxonomy and also reflects packaging reality: fingertip volume is scarce and should be reserved for sensors that must be collocated with the contact interface.

A growing trend is to realize these multimodal networks on flexible or monolithic substrates. Soft robotic hands have demonstrated the value of embedding actuators and sensors within the same compliant body, thereby shortening transmission paths and simplifying state estimation. Wang et al. further reported a thin-film robotic platform that monolithically integrated piezoresistive, pyroelectric, and piezoelectric sensing modalities, enabling simultaneous perception of deformation, force, and temperature in a highly compliant structure [142].

However, integrating large numbers of sensors onto curved fingertips and within narrow finger volumes remains a major engineering challenge. In many cases, a smaller number of strategically placed sensors may be preferable to a full-surface skin if it yields higher bandwidth, better durability, and simpler control integration.

- Implications for precision grasping and remaining challenges

Proprioceptive sensing supports accurate preshaping but cannot fully determine contact stability, whereas tactile signals are difficult to interpret without a reliable estimate of finger posture and actuation state. The most effective architectures therefore combine encoder- or strain-based internal-state estimation with localized tactile and force sensing at the contact interface. An ultra-precision example is illustrated in Figure 6. The piezo robotic hand developed by Zhang et al. uses direct-drive piezoelectric ceramic actuators to achieve extremely high motion resolution, fast response, and low hysteresis, which are advantageous for micro-to-macro manipulation and micro-grasping [105]. During characterization, external displacement measurement was used to quantify positioning accuracy, demonstrating that high actuator resolution must still be experimentally measured and verified. However, in practical grasping scenarios, contact uncertainty and object variability still require local sensing at the hand.

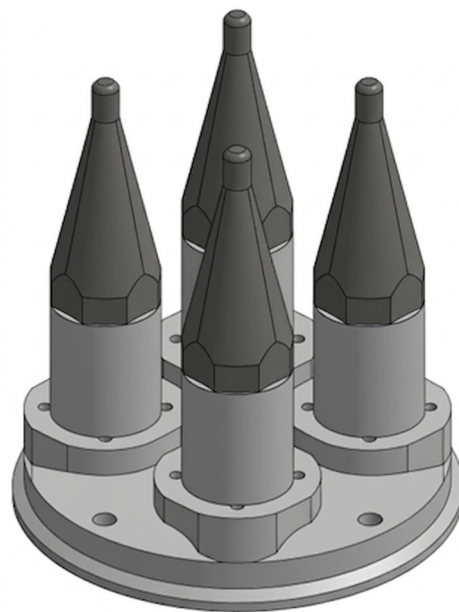


Figure 6. Piezoelectric-ceramic-actuated robotic hand for ultra-high-resolution manipulation. Redrawn by the authors based on [105], licensed under CC BY 4.0.

Several design issues therefore remain open. First, sensor integration must be considered from the earliest design phase because it strongly affects finger dimensions, cable routing, distal mass, and maintainability. Second, multimodal data fusion remains difficult: robotic hands can now generate rich streams of kinematic, force, and tactile data, but transforming these measurements into robust contact-state estimates and reliable grasp actions is still an active challenge [76]. Third, compact sensor packaging introduces calibration and drift problems. Finally, dense multimodal sensorization increases hardware and software complexity.

Overall, the literature suggests that precision grasping is best served by a task-driven multimodal architecture rather than by indiscriminate sensor proliferation. Encoders, Hall sensors or embedded strain sensors should provide a robust estimate of finger configuration; fingertip or palmar tactile and force sensors should capture contact state; and the two layers should be fused within a fast closed-loop controller capable of adjusting force and posture online [27,30,141]. Under this perspective, sensor-mechanism integration is not merely a supporting feature of dexterous hands; it is one of the main determinants of whether a robotic hand can grasp precisely, compliantly and reliably in unstructured environments.

3.2. Hardware Challenges for Control

Achieving precise grasping with dexterous robotic hands remains fundamentally a hardware-constrained control problem. Even when model-based, robust, or learning-based controllers are available, closed-loop performance is still bounded by the transmission, actuator, structure, and sensing architecture of the hand itself. In practice, grasp inaccuracy is rarely caused by a single defect; rather, it emerges from a coupled chain of mechanical and sensory nonidealities that accumulates between the motor output and the fingertip contact. For review purposes, these limitations can be organized into five recurrent and strongly coupled sources of control difficulty: (i) transmission friction, backlash, and hysteresis; (ii) under-actuation and mechanical coupling; (iii) the stiffness-compliance trade-off; (iv) actuation-specific nonlinearities; and (v) incomplete observability of contact and fingertip state [3,16,54].

From the viewpoint of precision grasping, these issues matter because fingertip tasks operate in a narrow tolerance band: small position errors change local contact geometry, small force errors can trigger slip, and small delays can destabilize contact transitions. Accordingly, the literature increasingly treats control performance as the outcome of hardware-software co-design rather than controller design alone. This perspective is especially important for anthropomorphic and tendon-driven hands, where compact form factors, human-like kinematics, and distributed actuation introduce the very nonlinearities that the control system must subsequently overcome.

- Transmission nonidealities: friction, hysteresis, and backlash

Tendon-driven architecture remains attractive because they relocate actuators away from the fingertips, reduce distal inertia, and enable compact anthropomorphic fingers. However, these benefits come at the cost of routing-dependent friction, tendon elasticity, pretension sensitivity, and motor-to-joint hysteresis [143]. Liu et al. showed on the DLR multisensory articulated hand that friction and tendon elasticity create a measurable discrepancy between commanded and realized motion, making motor-side sensing alone insufficient for precise control [51]. In such systems, the controller does not act directly on the joint; it acts through a compliant and frictional transmission whose properties vary with routing geometry, loading condition, and wear.

A similar conclusion emerges from control-oriented hand design studies. Grossard et al. designed the CEA dexterous hand so that tendon routing minimized static and kinematic coupling, reduced the number of idle pulleys and direction changes, and enabled robust decentralized control of mechanically quasi-decoupled axes [50]. The importance of transmission transparency is likewise emphasized by highly back-drivable designs such as RoboRay, in which reducing friction and reflected impedance improves both compliance and the observability of contact forces from actuator-side measurements [29]. In other words, a significant part of control robustness is decided before controller synthesis begins, through choices in routing, gearing, and bearing interfaces.

Differential and pulley-based mechanisms introduce additional control-relevant effects. Gao et al. note that cable-pulley friction reduces transmission efficiency, floating pulleys require stable cable tension to prevent slippage or derailment, and friction-based locking mechanisms accelerate wear when used to hold grasp configurations [115]. These effects are especially critical for precision pinch and fingertip grasps, where small transmission losses or dead zones are amplified into visible pose drift and unstable force application at the contact interface. For this reason, low-friction routing, appropriate pretension, and durable rotational elements should be regarded as prerequisites for precise and repeatable grasp control rather than merely as good mechanical practice.

Table 9 compares representative tendon-driven hands from the standpoint of precision control. The comparison suggests that reported fingertip force alone is not a sufficient

predictor of controllability. Tendon material, routing length, and the degree to which elongation and pretension are managed are equally important, because deformation in the transmission directly degrades fingertip positioning and force repeatability during grasp execution.

Table 9. Comparison of tendon-driven robotic hands from the viewpoint of precision grasping.

Robotic Hand/Source	Reported Tendon/Transmission Length	Reported Fingertip Force (N)	Assessed Finger/Module	Tendon Material	Implication for Precision Control
BRL/Pisa/IIT SoftHand [74]	NR	5.5	Small finger	NR	Adaptive synergy design prioritizes simplicity and morphological adaptation; however, the limited reported fingertip force suggests that precise force regulation depends strongly on contact strategy and task selection.
HR-hand index finger [85]	175 mm	20	Index finger	Dyneema DB-8HE	Illustrates that low-elongation tendon materials can support higher output force, but routing length still affects stretch, pretension sensitivity, and repeatability.
CasiaHand [2]	NR	16.43	Index and middle fingers	PTFE-coated nylon	Shows that palm-integrated tendon actuation can preserve anthropomorphic size and dexterity; coating and routing quality remain important to reduce friction and transmission variability.
CEA Dexterous Robot Hand [50]	A few centimeters	4.2	Modular finger unit	NR	A clear example of control-oriented design: shorter routing and mechanically quasi-decoupled axes simplify decentralized control even when absolute fingertip force is moderate.
Differential hand [115]	280 mm	45	Middle finger	Dyneema	High force output is achievable, but long routing length and differential cable tension increase sensitivity to friction, pretension drift, and wear.

Note: NR indicates the information was not reported in the cited source.

Overall, the tendon-driven literature converges on three practical points. First, low-elongation materials such as Dyneema and coated nylon help, but they do not eliminate routing-dependent compliance. Second, stable pretension is essential, because loss of cable tension degrades both kinematic accuracy and force transmission. Third, short and mechanically transparent routing paths are consistently easier to control than long, heavily redirected transmission paths.

- Under-actuation, coupling, and the dimensionality of grasp control

The second major challenge is that the number of controllable inputs is often smaller than the nominal kinematic dimension of the hand. To achieve anthropomorphic size, acceptable mass, and practical cost, designers routinely couple joints, distribute one actuator across multiple phalanges, or exploit differential and synergy-based architectures [35]. Bicchi described this design philosophy as a road toward simplicity: fewer actuators and sensors can produce more practical hands, but only by shifting complexity from hardware

count to mechanical coupling and control design [16]. From a control perspective, this means that fingertip motion and force cannot be specified independently at every joint; instead, the controller operates inside a constrained, transmission-dependent manifold.

This challenge is not merely theoretical. Physical constraints in anthropomorphic hands, especially those associated with thumb opposition, finger crowding, and limited joint independence, reduce the subset of grasp postures that are both mechanically feasible and controllable with high precision. Cordella et al. demonstrated that human grasp behavior contains invariant features that can be exploited to constrain the search for stable grasps, while Provenzale et al. further showed that postural synergies combined with stochastic optimization can reduce the high-dimensional planning problem to a lower-dimensional posture subspace [71,144]. Such approaches are highly relevant for control because they reduce computational burden and keep planning inside configurations that the hardware can plausibly realize.

Nevertheless, dimensionality reduction does not remove the hardware constraints themselves. In precision grasping, overly strong mechanical coupling can limit the independent fingertip adjustments needed to stabilize small objects, align contact normals, or modulate tangential force during incipient slip. The resulting trade-off is therefore fundamental: more coupling usually simplifies actuation and planning, whereas less coupling generally improves local dexterity but increases hardware complexity and control burden.

Linkage-driven hands represent an alternative response to this problem. By replacing long tendon paths with closed-chain finger mechanisms, they can reduce elongation and make the static relation between actuator motion and finger posture more repeatable, albeit at the expense of increased joint friction, assembly tolerances, and geometric constraints.

Tables 9 and 10 show that tendon-driven and linkage-driven hands fail in different ways from a control standpoint. Tendon-driven hands tend to suffer more from stretch, routing friction, and pretension drift, whereas linkage-driven hands are more sensitive to joint clearances, manufacturing tolerances, and local friction at revolute pairs. Neither architecture is universally superior; the decisive question is how consistently the mechanical design preserves the relation between commanded actuator motion and realized fingertip motion under load.

Table 10. Comparison of representative linkage-based robotic hands in relation to mechanical configuration and precision-oriented grasping capability.

Robotic Hand/Source	Mechanism Configuration	Actuation Mechanism	Representative Precision-Grasping Evidence	Reported Force Performance	Implication for Control
HRI Hand [114]	Two four-bar linkages	Linear motor	Precision grasp experimentally verified	Fingertip force: 8.76 N	Linkage transmission reduces tendon stretching, but tracking accuracy remains sensitive to revolute-joint friction and manufacturing tolerances.
ILDA hand [19]	Integrated linkage-driven fingers	Electric motor and ball screw	Manipulation with scissors or tweezers	34 N (flexed), 28 N (extended)	Closed-chain kinematics support strong and repeatable force transmission for tool use, although mechanical complexity and local backlash still require careful compensation.

Table 10. Cont.

Robotic Hand/Source	Mechanism Configuration	Actuation Mechanism	Representative Precision-Grasping Evidence	Reported Force Performance	Implication for Control
Four-bar prosthetic hand [36]	Planar four-bar linkage	Mini servo motor with solid coupler linkage	Range of motion: 70–98%	Medium load: 1.6 kg	Demonstrates efficient motion transmission, but servo backlash and additive-manufacturing tolerances remain important limitations for fine manipulation.
Gifu II [128]	Planar four-bar linkage	DC servo motors	Grasping a soft sphere and a hard cylinder	Fingertip force: 4.9 N	An early example showing that linkage-driven anthropomorphic fingers can generate stable fingertip forces when combined with distributed sensing.

- Compliance, soft structures, and actuation nonlinearity

A third hardware challenge arises from the need to balance kinematic accuracy against passive adaptation. Stiff structures are beneficial for repeatable geometry, higher control bandwidth, and faithful force transmission. Compliance, in contrast, improves tolerance to pose uncertainty, reduces impact loads, and enhances contact robustness when object shape or alignment is imperfect. The difficulty is not whether compliance is useful, but where it should be placed. Compliance at the fingertip or palm can improve robustness, whereas compliance in tendons, joints, or support structures generally introduces pose drift, delayed force buildup, and nonlinear saturation that the controller must continually compensate [143,145].

This issue is amplified in soft and hybrid robotic hands. Tan et al. emphasized that the highly deformable nature of soft fingers complicates simultaneous calibration of hand kinematics, sensor tip location, and robot-world geometry, because deformation cannot be treated as a small perturbation around a rigid nominal model [146]. When the object is also deformable, the state dimension grows further: the controller must reason not only about finger motion and contact force, but also about the evolving deformation of the grasped body itself [147]. As a result, precise grasping with soft hands is frequently limited less by nominal dexterity than by the difficulty of maintaining a reliable state estimate under deformation.

Actuation technology introduces another layer of nonlinearity. High-ratio electric transmissions can provide large force density, but they reduce back-drivability and attenuate the contact cues available to force-control algorithms. Soft muscles, pneumatic actuators, and related artificial-muscle technologies offer attractive compliance and low weight, yet their behavior is strongly nonlinear, rate dependent, and often bandwidth limited [85,101]. In pneumatic systems, valve dynamics, compressibility, and pressure losses make fine force modulation difficult, especially during rapid transitions between free motion and contact [148]. Even in conventionally actuated rigid hands, electromechanical effects may appear as overshoot, residual vibration, and tracking error that require careful sensing and controller tuning to suppress [149].

These observations suggest that control precision depends not only on the nominal mechanism type, but also on whether the dominant nonlinearity sits in a part of the system that can be sensed and compensated. Friction and elasticity embedded deep in the transmission are particularly problematic because they are only indirectly observable. By contrast, compliant contact surfaces or variable-friction pads can sometimes be ex-

exploited constructively to enlarge the stable grasp region, provided that their behavior is sufficiently repeatable.

- Sensing limitations and the observability of precision grasping

Precise grasp control requires more than actuation fidelity; it requires reliable observability of contact, local geometry, and incipient slip. Reviews of dexterous manipulation consistently identify tactile sensing as a key missing element between gross grasp acquisition and stable in-hand manipulation [26]. Tactile information is needed to estimate where contact occurs, how force is distributed across the pad, whether tangential loading is approaching the friction limit, and whether micro-slip has begun. Without this information, the controller often relies on conservative force margins or rigid motion assumptions that reduce both efficiency and dexterity.

Despite major progress, integrating tactile sensors into compact anthropomorphic fingers remains difficult because of space limitations, wiring density, fragility, calibration drift, and manufacturing variability [26,48]. DIGIT is notable precisely because it was designed to simultaneously improve compactness, ease of manufacture, reliability, and spatial resolution for multi-fingered in-hand manipulation [135]. The paper therefore illustrates a broader point for this review: the bottleneck is not simply sensing principle, but sensor system integration. A sensor may be accurate on the bench yet still be impractical if it cannot be mounted robustly on a small fingertip or replaced without re-calibration of the full control pipeline.

Proprioception faces analogous issues. Motor encoders do not fully capture the behavior of a compliant transmission, while camera-based state estimation suffers from occlusion during closed grasps and from uncertainty in contact-rich transitions. This is one reason why recent control strategies increasingly combine motor-side sensing, joint-side sensing, tactile feedback, and slip detection instead of relying on any single modality. The emerging consensus is that precise grasping is only weakly observable if sensing remains physically remote from the contact interface.

- Implications for control-oriented hand design

The coupled nature of the preceding challenges can be summarized as a mechanical error chain. Actuator nonlinearity, tendon or linkage friction, structural compliance, and contact uncertainty accumulate until they appear at the fingertips as position drift, force overshoot, micro-oscillation, slip, or unstable grasp transitions. Figure 7 illustrates this error chain together with mitigation routes repeatedly reported across the literature. The purpose of the figure is not to propose a single architecture, but to emphasize that the observable grasp error is the end product of multiple hidden hardware stages rather than a direct reflection of the controller alone.

Three design implications recur across different hand architectures. First, control performance improves when transmission transparency is maximized through low-friction routing, stable pretension, minimized backlash, and, where possible, back-drivable actuation [29]. Second, distributed sensing substantially improves the controller's ability to compensate for hidden transmission errors; joint-side sensing in addition to motor encoders, as well as tactile and slip sensing near the contact, directly addresses the observability gap introduced by compliant transmissions [27]. Third, passive adaptation should be localized and intentional: compliance is most useful at the object interface, whereas uncontrolled compliance in tendons, joints, and support structures degrades precision [21].

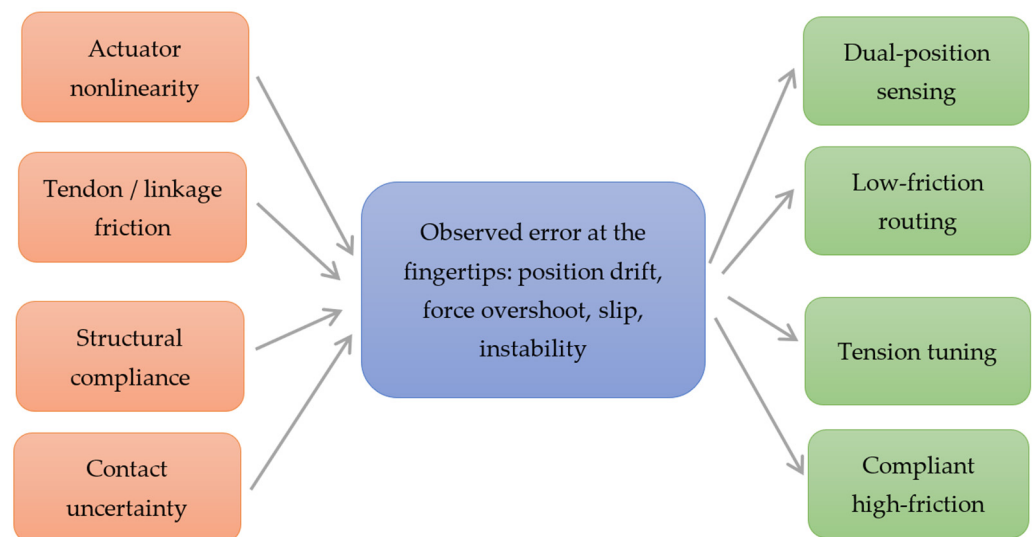


Figure 7. Mechanical error chain and mitigation path for precision grasping. Orange boxes indicate the sources of mechanical error, the blue box represents the observed fingertip errors, and green boxes indicate the corresponding mitigation strategies. The arrows show the direction of influence from the error sources to the observed errors and from the observed errors to the mitigation strategies.

Therefore, future progress in precision grasping is unlikely to come from ever more sophisticated controllers applied to unchanged hardware. Rather, it will come from control-oriented hardware co-design in which transmission layout, actuator choice, sensing architecture, and contact engineering are selected with explicit regard to the requirements of closed-loop manipulation. From this viewpoint, the hardware challenge for control is not a peripheral issue in dexterous robotic hands; it is the central reason why precise grasping remains difficult despite substantial progress in planning and control algorithms [145,150].

4. Discussion and Future Directions

4.1. Top Three Engineering Paradoxes in Precision-Oriented Dexterous Hand Design

The literature reviewed in this paper indicates that precision grasping should not be interpreted as a single performance index of a robotic hand. Rather, it emerges from a coupled design chain linking morphology, kinematic determinism, transmission fidelity, compliance distribution, sensing observability, and control architecture. This coupling explains why improving one component of a hand frequently creates a limitation elsewhere. For example, placing high-resolution sensors or actuators near the fingertips can improve local measurement and motion authority, but it also increases distal volume, inertia, wiring density, and packaging difficulty, thereby reducing the speed, smoothness, and robustness of fine positional control. Therefore, the Discussion should not present kinematics, actuation, sensing, and compliance as isolated technologies. It should synthesize the recurring engineering trade-offs that determine whether precision grasping is repeatable in practice.

Accordingly, the present review organizes the main design tension into three engineering paradoxes: (i) kinematic complexity versus control robustness, (ii) remote actuation/tendon routing versus frictional hysteresis, and (iii) compliance or soft mechanical intelligence versus precise force transduction. These paradoxes do not imply that one side of the design space is universally superior. Instead, they show that successful dexterous hands must allocate determinism, compliance, sensing, and actuation authority according to the task. In this view, the most effective hand is not necessarily the most anthropomorphic or the most densely actuated platform, but the one that introduces mechanical complexity only where it improves contact formation, force regulation, and repeatable manipulation. Table 11 summarizes these three paradoxes as a structured trade-off matrix.

Table 11. Top three engineering paradoxes shaping precision-oriented dexterous robotic hand design.

Engineering Paradox	Design Benefit	Hidden Penalty	Precision-Oriented Design Implication
Kinematic complexity versus control robustness	Additional joints, independent actuation, and human-like geometry expand reachable workspace, thumb opposition, and potential manipulation modes.	They increase controller dimensionality, calibration burden, distal packaging difficulty, inertia, wiring complexity, tolerance sensitivity, and failure modes.	Use selective anthropomorphism: reserve independent actuation for the thumb, index finger, and task-critical joints; use controlled coupling or underactuation for joints mainly responsible for envelope formation or support.
Remote actuation/tendon routing versus frictional hysteresis	Remote motors and tendon or differential transmission reduces distal mass and allow compact, slender, anthropomorphic fingers.	Long routing paths, friction, tendon stretch, backlash, and pretension drift introduce hysteresis and reduce fingertip repeatability, especially when only motor-side sensing is available.	Prioritize transmission transparency: short tendon paths, low-friction routing, stable pretension, minimized backlash, joint-side sensing, and repeatable calibration routines.
Compliance/soft intelligence versus precise force transduction	Compliance improves safety, object-shape adaptation, impact tolerance, and grasp acquisition under pose uncertainty.	Excessive or poorly localized softness makes fingertip pose, contact force, contact normal, force bandwidth, and slip onset harder to predict and regulate.	Use spatially graded compliance: rigid load-bearing structures and joints, compliant pads at contact interfaces, and variable stiffness for acquisition and holding phases.

The first paradox, kinematic complexity versus control robustness, explains why increasing the number of degrees of freedom does not automatically improve precision. More joints and actuators can enlarge the reachable workspace and permit more human-like postures, but they also increase the number of variables that must be calibrated, sensed, and controlled. In compact anthropomorphic fingers, this additional complexity is accompanied by tighter packaging constraints, higher distal inertia, more wiring, and greater sensitivity to manufacturing tolerances. Conversely, strongly coupled or underactuated fingers simplify hardware and can improve adaptive enclosure, but they reduce direct authority over local contact placement and internal force distribution. A practical implication is that independent actuation should be concentrated at the thumb, index finger, and other joints that directly determine pad-to-pad contact, while controlled coupling can be used in joints whose role is mainly envelope formation or object support [70].

The second paradox is remote actuation/tendon routing versus frictional hysteresis. Remote motors, tendon drives, and differential transmissions are attractive because they remove mass from the distal phalanges and preserve compact anthropomorphic geometry. However, the same routing that improves packaging can introduce friction, backlash, tendon stretch, and pretension drift. These effects are often not fully observable from motor-side encoders and can cause the actual fingertip trajectory and contact force to differ from the commanded motion. For this reason, precision grasping is often limited less by peak actuator force than by transmission transparency. Low-friction routing, short tendon paths, stable pretension mechanisms, minimized backlash, joint-side sensing, and repeatable calibration should therefore be treated as core design requirements rather than secondary implementation details [50]. At the system-integration level, lessons from lightweight soft robotic arms and compact surgical-robot design further reinforce that packaging, safety, workspace management, and maintainability should be considered early rather than after the hand mechanism has already been fixed [151].

The third paradox is compliance or soft mechanical intelligence versus precise force transduction. Soft structures, underactuated mechanisms, and compliant pads are valuable

because they absorb pose uncertainty, protect fragile objects, and organize contact passively during approach and first contact. Nevertheless, excessive or poorly localized compliance can reduce the predictability of fingertip pose, contact normal direction, force bandwidth, and slip onset. The design challenge is therefore not to make the hand globally soft or globally rigid, but to distribute stiffness, damping, friction, and sensing density spatially. Rigid structures are needed at joints, bearing seats, tendon anchors, and load-bearing links; compliant materials are more appropriate at contact pads and distal interfaces; and variable-stiffness elements can allow the hand to be compliant during acquisition but stiffer during holding and manipulation [1,21,33,34,74,127].

These three paradoxes are strongly coupled. Increasing kinematic complexity often requires more compact transmission and sensing, which can intensify friction, wiring, and calibration problems. Adding compliance can reduce the demand for exact positioning during grasp acquisition, but it increases the need for tactile sensing and deformation estimation during post-contact regulation. Similarly, using remote actuation reduces distal inertia, but if transmission hysteresis is not controlled, the advantage in compactness may be lost through poor fingertip repeatability. The central lesson is that precision grasping is not achieved by maximizing any single design variable. It is achieved by balancing mechanical determinism where accuracy matters, compliance where uncertainty is greatest, and observability where contact cannot be inferred reliably from motor commands alone.

4.2. *Toward Mechanically Intelligent Embodiment and Hybrid Actuation*

The above paradoxes suggest that future robotic hand design should move from human-like appearance toward task-relevant biomechanical abstraction. For precision grasping, the most influential structural variables are not only the total number of fingers or degrees of freedom, but also thumb opposition, the common workspace between the thumb and the index-middle finger complex, controllable distal flexion, palmar support, and the ability to regulate contact normals during small-object interaction. The thumb cannot be treated as a simple additional finger placed in opposition. Wrist posture and palm geometry also influence whether the hand can approach an object from a favorable direction before the fingers close [152,153]. Thus, precision grasping should be understood as a whole-hand design problem rather than a finger-level problem alone.

This perspective also clarifies the increasing importance of active palms, reconfigurable palm surfaces, and spatially distributed compliance. Palm motion can enlarge the opposition workspace, modify contact topology, and compensate for limitations of the fingers, particularly in soft or underactuated hands. Similarly, biomimetic compliance can improve contact organization without requiring every joint to be independently actuated, provided that the compliance is directional and mechanically purposeful rather than uniformly soft. A promising architecture is therefore hierarchical: deterministic pinch interfaces between the thumb and index finger, adaptive proximal and palmar structures for object acquisition, and compliant fingertip layers for contact stabilization. Such a hierarchy allows the hand to remain tolerant during approach and first contact while preserving the local rigidity needed for accurate post-contact manipulation [21].

The same hierarchical principle should guide actuation and transmission design. Electric actuation remains a practical backbone for many precision-oriented hands. Tendon-driven or differential transmission can be used where mass reduction and compact geometry dominate, while direct or highly transparent drive should be reserved for pose-critical joints. Pneumatic and soft actuators remain valuable where safety, shape adaptation, and low mass are prioritized, although compressibility and hysteresis can limit precision and force bandwidth [154]. Consequently, future hands are more likely to be electrically driven and mechanically moderated, combining electric actuation with selective cable transmis-

sion, local compliance, variable friction, and posture-holding or self-locking mechanisms, rather than relying on any single actuation philosophy [94,109,125,126].

A parallel implication arises from structural materials and fabrication. The precision of a robotic hand is strongly affected by the spatial distribution of stiffness, compliance, and friction within the structure, not merely by whether the hand is classified as rigid or soft. Therefore, fabrication routes should be selected with the same intentionality as kinematic and actuation strategies. Hybrid manufacturing workflows that combine additive manufacturing for geometric iteration with selective precision machining for kinematically critical paths can reduce tolerance accumulation and support structural integration of sensors rather than treating sensors as external additions.

4.3. Sensing, Learning, and Human-in-the-Loop Control

Precision grasping is also an observability problem. Even a mechanically capable hand cannot regulate grasp quality if it cannot detect the actual contact state. Motor-side encoders are useful for actuator control, but they are insufficient when friction, tendon compliance, backlash, or soft deformation exists between the motor and the contact interface. For precision tasks, the relevant variables include joint position, fingertip pose, contact location, pressure distribution, resultant wrench, incipient slip, and sometimes the deformation state of both the finger and the object. This explains why tactile arrays, fingertip force/torque sensors, optical tactile sensors, and slip detectors have become central to modern precision-grasping research [18,26,52,135].

However, sensing introduces its own trade-off. Dense multimodal sensorization improves observability but increases wiring complexity, packaging burden, calibration requirements, power consumption, and long-term drift, especially in compact anthropomorphic fingers or compliant hands [146,155]. Therefore, future hands should not simply add more sensors. They should use sensing strategically at locations where hidden mechanical uncertainty is greatest: contact pads, distal phalanges, tendon paths, joint outputs, and interfaces where compliance or friction may decouple commanded and actual motion. Self-monitoring should also be interpreted broadly. Next-generation robotic hands should monitor not only objects but also their own transmission health, tactile surface condition, calibration state, and wear. This capability will be essential for long-duration use in prosthetics, service robotics, industrial handling, and rehabilitation.

These sensing issues directly affect the role of artificial intelligence and learning-based control. Deep reinforcement learning, imitation learning, and policy optimization have shown clear promise for contact-rich manipulation [53,150]. Nevertheless, their real-world performance remains bounded by the mechanical and sensing assumptions of the platform. Policies trained on poorly observed or mechanically inconsistent hands will inherit hidden transmission errors, calibration drift, and contact uncertainty. Learning should therefore be viewed as an amplifier of good mechanical design rather than a substitute for it. Future learning systems should be grounded in physically informed embodiments: mechanically transparent transmissions, task-relevant kinematic abstraction, calibrated tactile perception, and retargeting methods that explicitly account for the mismatch between human and robot hand geometry [156–158]. Future progress will also depend on bridging mechanical design with visual grasp planning, task-oriented tool manipulation, and a more critical assessment of when anthropomorphic hands are truly necessary for a given manipulation objective [159–161]. A concrete step in this direction is the vision-guided, per-finger grasp-planning pipeline proposed by Sulaiman et al., in which hand-mounted RGB-D point clouds are segmented using an axis-aligned bounding-box hierarchy, while fingertip contacts are planned independently through trajectory-aware sampling and inverse kinematics. The method achieved a high grasp success rate with millimetre-scale pose errors [162].

For prosthetic and human-in-the-loop systems, tactile feedback and intuitive command interfaces provide an additional design direction. Research on bionic hands indicates that meaningful sensory feedback can improve embodiment, force regulation, and functional interaction when it is delivered through appropriate peripheral or central interfaces [163]. Teleoperation, kinesthetic feedback, haptic gloves, and motion-retargeting studies also show that human demonstrations cannot be transferred directly to robotic hands without considering kinematic mismatch. They require structured mappings between human intent, robot embodiment, and task constraints. Therefore, precision-oriented robotic hands should be developed not only as standalone end effectors, but also as components of broader perception-action loops involving shared autonomy, prosthetic control, or teleoperation [164]. Within such perception-action loops, visual substitutes for physical force feedback are also emerging. Yamamoto et al. rendered the robot hand transparent and overlaid virtual hands that deform under the measured contact force, creating a pseudo-haptic illusion of the operator's own hand deforming. This approach enabled operators to detect contact faster than with no feedback, matching the response of a physical force-feedback device while avoiding the added weight and workspace constraints of bulky haptic hardware [165].

Although outside the core scope of autonomous dexterous robot hands, wearable robotic fingers, haptic gloves, and soft exoskeleton gloves provide transferable insights into intuitive posture control, safe assistance, and user-specific adaptation in contact-rich manual tasks [166–169]. Related rehabilitation and therapist-training systems likewise emphasize the importance of ergonomic alignment, compliant actuation, and repeatable assistance when robotic hand mechanisms operate in close physical interaction with the human body [170–174]. From a broader human-centered perspective, embodiment studies linked to the rubber hand illusion also suggest that morphology and feedback influence how natural and trustworthy robotic hand interaction may feel to users [175].

4.4. Reliability, Evaluation Metrics, and Translation to Applications

The three engineering paradoxes also have direct consequences for reliability and translation. A large fraction of the literature still emphasizes proof-of-concept demonstrations, whereas long-duration repeatability, cable wear, joint wear, seal degradation, sensor replacement, calibration drift, and serviceability are comparatively underreported. These issues are not secondary if dexterous hands are expected to move from laboratories into prosthetics, service robotics, industrial manipulation, and rehabilitation [155]. A design that performs well in a short demonstration may fail in practical use if its tendon pretension cannot be maintained, its tactile sensors drift, its fingertip pads wear rapidly, or its calibration procedure is too fragile. Modular architecture is therefore important. Modular finger units, accessible routing paths, replaceable fingertip pads, open-source electronics, and low-cost or reproducible platforms can reduce maintenance effort and improve cross-laboratory reproducibility [82,114,133,176,177].

Evaluation metrics remains another major bottleneck. Static pinch success, object lift, tool use, tactile slip recovery, in-hand reorientation, disturbance rejection, and contact-force accuracy are often evaluated under incompatible protocols. This makes it difficult to determine whether one hand is mechanically superior or merely better tuned for a particular demonstration. Future evaluation frameworks should move beyond binary success rates and include metrics that reflect the mechanics of precision manipulation: fingertip positioning repeatability, contact-force fidelity, slip onset margin, disturbance recovery time, energy consumption, sensing drift, transmission backlash, and maintenance burden. Open benchmark objects, shared task protocols, and transparent reporting of calibration and sensing conditions would help distinguish genuine mechanical advances from improvements that

depend on unreported tuning or favorable experimental conditions [20,25,178]. Control studies on robust finger motion regulation, together with experimental evaluations and simulation environments for grasping research, suggest that meaningful benchmarking of precision grasping requires both closed-loop performance analysis and comparable testing protocols [130,131,179,180].

At the same time, recent comparative work questions whether strongly anthropomorphic hands are always necessary, suggesting that embodiment should be selected according to manipulation requirements rather than appearance alone [160]. The Anthropomorphic Hand Assessment Protocol (AHAP) provides a structured way to evaluate anthropomorphic and prosthetic hands through common human grasp types and a numerical grasping ability score [181]. AHAP does not replace the hardware-level precision metrics, such as repeatability, force regulation, backlash, and slip margin, but it provides a useful task-level complement because it links mechanical embodiment to standardized grasp execution. This point is consistent with the trade-off perspective developed in this Discussion: anthropomorphism is useful when it creates task-relevant contact geometry, thumb opposition, and manipulation modes, but it becomes a burden when it adds unobservable compliance, friction, calibration difficulty, or unnecessary control dimensions.

As summarized in Figure 8, the future roadmap for dexterous hands aimed at precision grasping can be organized into three converging tracks. The first track is embodiment and actuation. Near-term priorities in this track include low-friction hybrid transmissions, variable-stiffness joints, improved thumb-index kinematic design, and active or reconfigurable palms [21]. The long-term objective is mechanically intelligent embodiment, in which morphology, transmission, compliance, and contact engineering collectively guide the hand toward stable grasps before high-level control intervenes. The second track is sensing and self-monitoring. Near-term work should focus on tightly integrated multimodal sensing, joint-side and contact-side sensor fusion, compact slip-sensitive fingertips, and self-calibration routines. Over the longer term, robotic hands should become self-sensing and self-diagnosing systems capable of monitoring their own state, wear, and calibration quality during operation. The third track is evaluation and reproducibility. In the short term, the field needs unified precision-grasp protocols and more transparent reporting of transmission, sensing, and calibration conditions. In the longer term, benchmark-ready open platforms will be essential for ensuring that reported progress is comparable, reproducible, and transferable across applications.

The proposed trade-off matrix in Table 11 also provides a direct link between design choices and benchmarking requirements. For the kinematic-complexity paradox, evaluation should report not only workspace or degree-of-freedom count, but also calibration stability, controller burden, and repeatability under disturbance. For the tendon-routing paradox, benchmark data should include transmission backlash, hysteresis, pretension stability, and joint-side versus motor-side tracking error. For the compliance paradox, evaluation should include contact-force fidelity, slip margin, deformation recovery, and the ability to transition from compliant acquisition to stable holding. In this way, benchmarking becomes a tool for measuring the consequences of design trade-offs rather than a checklist of isolated task successes. These requirements also show why precision-oriented benchmarking needs open-source or benchmark-relevant hand ecosystems that expose the full mechanical error chain rather than only reporting final task success. Concretely, the mechanical error chain that should be reported maps directly onto the five screening criteria of Table 1, namely sub-1 mm fingertip repeatability, plus or minus 0.1 to 0.5 N micro-force regulation, sub-0.5 mm contact repeatability at one sigma, a 1 to 2 mm compliance range, and a 1 to 2 N slip margin, while the Anthropomorphic Hand Assessment Protocol adds a complementary task-level grasping-ability score [181].

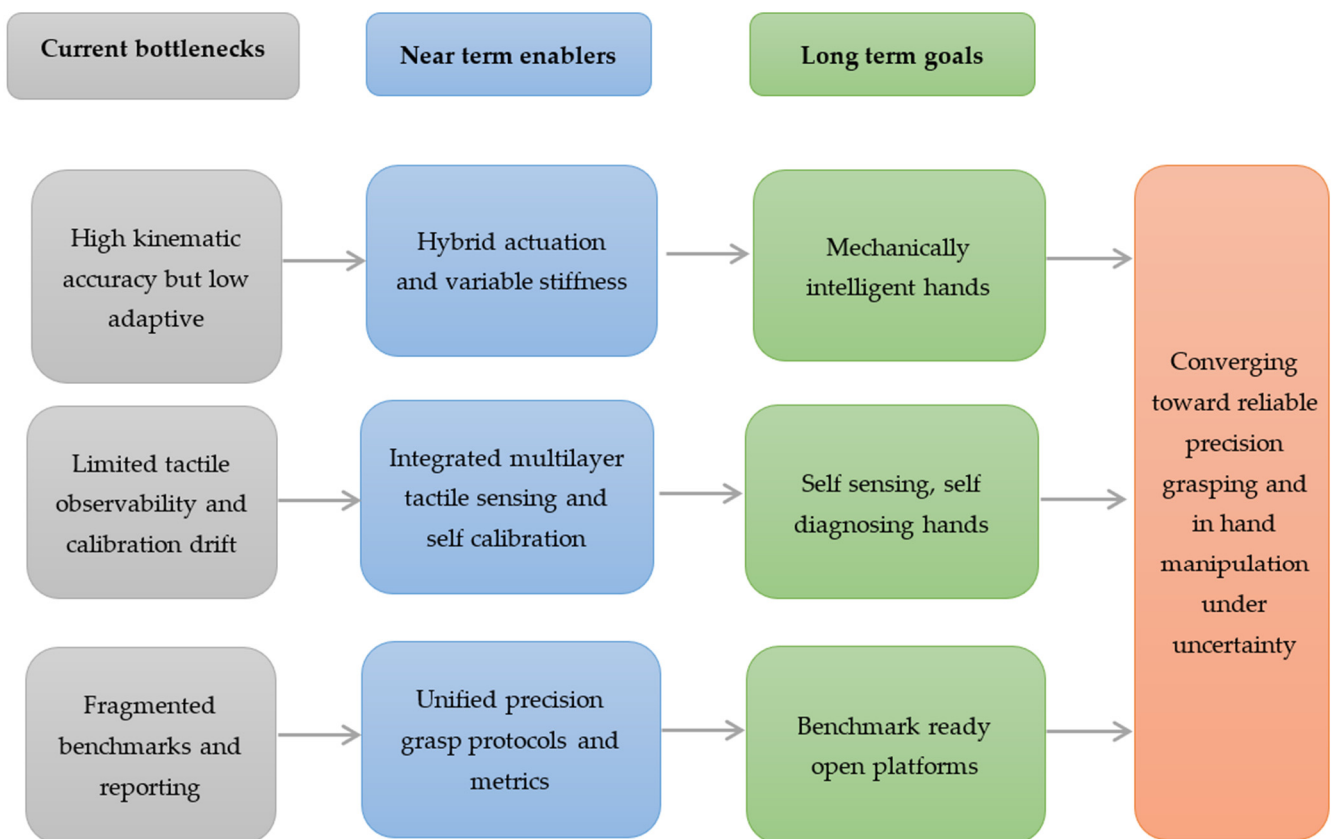


Figure 8. Roadmap for next-generation dexterous robotic hands toward reliable precision grasping and in-hand manipulation under uncertainty. Gray boxes represent current bottlenecks, blue boxes indicate near-term enablers, green boxes represent long-term goals, and the orange box indicates the overarching outcome. The arrows show the directional progression from current bottlenecks through enabling developments and long-term goals toward the final outcome.

4.5. Open-Source Ecosystems and Benchmark-Ready Embodiment for Precision Grasping

Building on the benchmarking and reproducibility issues discussed above, open-source and benchmark-ready robotic hand platforms are increasingly important for precision grasping. Reproducible evaluation is difficult when each study uses a different hand structure, actuation layout, sensing configuration, calibration procedure, object set, and success definition. From a mechanical-design perspective, the main value of open-source platforms is not only that their CAD files can be reused, but also that their mechanical error sources, transmission behavior, sensing layout, and task-level performance can be examined and compared across laboratories. This issue is particularly important for precision grasping, where small differences in fingertip placement, contact-force regulation, tendon stretch, backlash, friction, hysteresis, or tactile-sensor calibration can strongly affect grasp stability and manipulation repeatability.

Existing platforms provide different types of value for the community. Low-cost underactuated hands make mechanical variation, fabrication, and repair accessible; open anthropomorphic hands support education, modular modification, and reproducible hardware studies; widely adopted commercial research hands provide stable baselines for manipulation benchmarks; and recent low-cost dexterous hands reduce the cost barrier for learning-based and sim-to-real manipulation studies. Therefore, the key question is not simply whether a robotic hand is open-source or anthropomorphic, but whether it provides enough hardware, sensing, calibration, software, and task-level information to reproduce

the mechanical conditions required for precision grasping. Representative open-source and benchmark-relevant hand ecosystems are compared in Table 12.

Table 12. Open-source and benchmark-relevant hand ecosystems evaluated through the lens of precision grasping.

Platform/Ecosystem	Reproducibility Assets	Precision-Grasping Value	Remaining Gap
Yale OpenHand variants [182]	Open hand designs, rapid-prototyped components, low-cost fabrication logic, and modifiable underactuated mechanisms.	Strong baseline for studying how underactuation, compliance, tendon routing, and finger geometry influence adaptive contact acquisition.	More standardized reporting is still needed for fingertip repeatability, tendon stretch, hysteresis, sensor placement, and long-term mechanical wear.
HRI Hand [114]	Open-source anthropomorphic system with modular 3D-printed components and a simple actuation layout.	Useful educational and research baseline for low-cost anthropomorphic grasping, pre-shaping, and hardware modification.	Limited DOF and sparse sensing restrict fine in-hand manipulation, high-resolution force regulation, and precision contact evaluation.
BRL/Pisa/IIT SoftHand [74]	Low-cost, 3D-printed, tendon-driven underactuated hand based on soft and adaptive synergies.	Valuable platform for robust grasp acquisition, morphology-driven adaptation, and benchmarking adaptive enclosure of uncertain objects.	Local fingertip determinism is lower than in fully actuated hands; precision-oriented studies should report contact state, slip margin, and fingertip-level repeatability.
Open-source underactuated prosthetic hands with selectively lockable differentials [183]	Affordable anthropomorphic hand concepts with modular structures and selectively lockable differential mechanisms.	Useful for repairable prosthetic-hand studies and low-cost underactuated grasping, where adaptive closure and mechanical simplicity are important.	Precision grasping is limited by sparse sensing and reduced local actuation authority unless tactile feedback, calibration, and standardized precision tests are added.
Allegro-based in-hand manipulation benchmark [184]	Benchmark protocol using a widely adopted multi-fingered research hand, object-level task definitions, and repeatable evaluation of in-hand manipulation performance.	Strong reference for comparing planning, control, and learning methods under a shared manipulation task structure; especially useful for evaluating independent joint actuation, object pose adjustment, and fingertip coordination.	The hand itself is commercial rather than fully open-source; reproducibility still depends on shared calibration files, sensor configuration, control code, object-tracking setup, and actuator-level settings.
LEAP Hand [177]	Low-cost anthropomorphic research hand with released assembly resources, software interfaces, and simulation-oriented development support.	Useful for learning-based manipulation and sim-to-real benchmarking at a lower cost than many commercial dexterous hands.	Community-wide agreement is still required on precision-specific physical metrics beyond task success, policy performance, or qualitative manipulation demonstrations.

From a precision-grasping perspective, open hardware should be treated as a complete experimental package rather than as CAD files alone. A benchmark-ready robotic hand should provide: (i) editable CAD files, a bill of materials, actuator and transmission specifications, and replacement instructions; (ii) joint-side and motor-side calibration data, including backlash, tendon stretch, friction, and hysteresis tests; (iii) documented tactile or force sensor placement, sampling rate, drift behavior, and calibration method; (iv) common precision-grasp tasks involving small rigid, fragile, deformable, and slippery objects; and (v) software interfaces, simulation models, controller parameters, and data logs that allow other groups to reproduce both the controller and the mechanical error chain. These

requirements are essential for moving from impressive single-platform demonstrations toward cumulative and comparable progress in precision robotic grasping.

Based on the reviewed literature, future open-source and benchmark-oriented hand platforms should follow a precision-grasping-oriented reporting framework. First, hardware openness should include not only CAD geometry but also transmission routing, actuator specifications, tolerance-sensitive parts, assembly procedures, and maintenance information. Second, calibration should be reported at both the motor side and joint side, because fingertip error often originates from backlash, tendon elongation, friction, and hysteresis inside the transmission. Third, sensing information should include sensor location, resolution, sampling rate, drift, and calibration method, since precision grasping depends on the observability of contact state and incipient slip. Fourth, benchmark tasks should move beyond binary grasp success and include fingertip placement error, contact-force fidelity, slip margin, in-hand pose adjustment, repeatability over repeated trials, and durability after extended use. Finally, simulation models and physical experiments should be linked through shared parameters and data logs so that sim-to-real manipulation studies can be evaluated not only by task success, but also by whether the mechanical behavior of the hand is reproduced.

This review therefore suggests that the next stage of open-source dexterous-hand development should move from “open CAD” toward “open benchmark-ready embodiment”. For precision grasping, the most useful platforms will be those that make the full mechanical error chain visible, measurable, and repeatable across laboratories. Such platforms would allow the community to compare not only algorithms, but also the mechanical design choices that determine whether stable, accurate, and adaptable fingertip contact can be achieved in practice.

Open-source and benchmark-ready platforms should not be regarded as separate topics from mechanical design, but as necessary infrastructure for evaluating whether mechanical design strategies truly improve precision grasping. By making CAD models, actuation layouts, calibration data, sensing configurations, controller parameters, task protocols, and experimental logs available, future robotic-hand studies can move from isolated demonstrations toward cumulative and comparable progress. Therefore, the next generation of dexterous robotic hands should be evaluated not only by grasp success or anthropomorphic appearance, but also by the reproducibility of fingertip positioning, contact-force regulation, slip resistance, and long-term mechanical reliability across laboratories.

4.6. Limitations of This Review

This review has several limitations. First, it emphasizes mechanical embodiment and control-relevant hardware factors rather than providing an exhaustive survey of grasp-planning algorithms or learning pipelines. Second, quantitative comparison across platforms remains constrained by inconsistent reporting of fingertip accuracy, contact-force fidelity, slip margin, transmission hysteresis, and long-term durability. Third, some representative platforms were included because of their design significance even when their experimental reporting was incomplete. Fourth, the proposed engineering paradoxes are intended as a design-oriented synthesis rather than a strict taxonomy; future experimental work is needed to quantify these trade-offs using common metrics and benchmark tasks. These limitations reflect the current state of the field and further motivate the need for unified benchmarking, transparent reporting standards, and reproducible open platforms.

Overall, the evidence synthesized in this review suggests that the next major advances in dexterous robotic hands will not come from mechanical complexity alone. They will come from coordinated design across morphology, transmission, sensing, control, fabrication, and evaluation. The most promising hands for precision grasping are therefore

unlikely to be simply the most anthropomorphic in appearance or the most heavily actuated in count. Rather, they will be selectively anthropomorphic, mechanically transparent where accuracy matters, compliant where uncertainty is greatest, observable at the contact interface, and reproducible enough to be meaningfully compared across studies. Achieving this balance is challenging, but it is precisely this balance that will determine whether dexterous robotic hands can progress from impressive laboratory demonstrations to reliable precision manipulation in real-world environments.

5. Conclusions

This review assessed dexterous-hand designs using criteria for fingertip placement, low-force regulation, contact repeatability, localized compliance, and slip resistance. These criteria provide a common screening basis, not universal standards. Because tasks, hardware, and measurements vary, comparisons should remain within each criterion.

The evidence shows that precision depends on integrated task-relevant mobility, transmission, compliance, sensing, and fabrication. Gifu Hand III illustrates the value of independent thumb and contact-critical motion, and ILDA demonstrates repeatable rigid-link transmission. CasiaHand illustrates compact palm-integrated tendon actuation; across tendon-driven studies, reduced distal inertia is accompanied by recurrent sensitivity to friction, backlash, pretension drift, and hysteresis. The BRL/Pisa/IIT SoftHand demonstrates adaptive underactuation, while MCR-Hand III combines rigid guidance with localized compliance. These examples link each architectural benefit to a corresponding limitation; no single architecture therefore dominates all precision-grasping requirements.

Precision grasping should therefore be treated as a system-level mechanical outcome. For repeatable small-object tasks, priority should be given to controllable thumb-finger opposition, low-clearance transmission, joint-side sensing, and rigid load paths with compliant fingertips. For fragile or uncertain objects, compliance should be spatially graded and supported by tactile feedback and post-contact stiffening. For low-cost and open-source hands, underactuation and additive manufacturing should be adopted only when transmission errors, repeatability, sensing, and durability are clearly characterized.

Future research should develop hybrid hands that combine precise actuation at pose-critical joints with lightweight tendon or differential transmission elsewhere. Key directions include compact multimodal sensing near the contact interface, variable-stiffness or lockable mechanisms, self-calibration of transmission errors, structurally integrated sensing, and mechanically intelligent components coordinated with predictive or learning-based control. Durability, energy efficiency, maintenance, and long-term stability must also be addressed for operation beyond controlled laboratory trials.

Further progress requires standardized reporting, representative benchmarks, and reproducible hardware. Studies should describe the mechanical error chain, calibration, sensor placement, repeated-trial variability, durability, and operating conditions. A task-level benchmark such as AHAP should be supported by shared objects, procedures, and reporting templates. Releasing editable CAD, bills of materials, fabrication settings, controller parameters, simulation models, and experimental data would enable cross-laboratory comparison and independent replication.

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Abbreviations

The following abbreviations are used in this manuscript:

ABS	acrylonitrile butadiene styrene
ADL	activity of daily living
DC	direct current
DIP	distal interphalangeal
DOF	degree of freedom
DoA	degree of actuation
EMG	electromyography
FDM	fused deposition modeling
ILDA	integrated linkage-driven dexterous anthropomorphic
MCP	metacarpophalangeal
PDMS	polydimethylsiloxane
PIP	proximal interphalangeal
PLA	polylactic acid
PTFE	polytetrafluoroethylene
PZT	piezoelectric
SLS	selective laser sintering
SLM	selective laser melting
SMA	shape memory alloy
SMC	sliding mode control
TCP	twisted-and-coiled polymer
TSA	twisted string actuation

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