# A Novel Type of Compliant, Underactuated Robotic Hand for Dexterous Grasping

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***Abstract*—We built a highly compliant, underactuated, robust and at the same time dexterous anthropomorphic hand. We evaluate its dexterous grasping capabilities by implementing the comprehensive Feix taxonomy of human grasps and by assessing the dexterity of its opposable thumb using the Kapandji test. We also illustrate the hand's payload limits and demonstrate its grasping capabilities in real-world grasping experiments. To support our claim that compliant structures are beneficial for dexterous grasping, we compare the dimensionality of control necessary to implement the diverse grasp postures with the dimensionality of the grasp postures themselves. We find that actuation space is smaller than posture space and explain the difference with the mechanic interaction between hand and grasped object. Additional desirable properties are derived from using soft robotics technology: the hand is robust to impact and blunt collisions, inherently safe, and not affected by dirt, dust, or liquids. Furthermore, the hand is simple and inexpensive to manufacture.**

## I. Introduction

Dexterous grasping, i.e. grasping with postural variability comparable to that observed in human grasping (see, for example, the grasp taxonomies of Cutkosky [7] and Feix et al. [11]), is a prerequisite for task-dependent manipulation of objects of different shapes and sizes. For example: Small objects can be picked up with pincer grasps, large objects with enveloping power grasps. Depending on the task at hand, a sideways cylindrical grasp might be used to pick up a glass for drinking, whereas a disk grasp from above is appropriate to lift it off a cluttered table.

In robotic hands, dexterous grasping capabilities are traditionally realized through complex, multi-jointed structures and sophisticated actuation mechanisms. Such hands are expensive and difficult to design and build, and they also require complex sensing and control. Recently, there has been a trend to build underactuated hands with passively compliant parts. These hands perform certain grasps very robustly, are mechanically simpler than traditional hands, and, due to underactuation, allow for simpler control. However, there is one commonly assumed drawback of compliant hands: underactuation and passive compliance seem to render dexterous grasping difficult or even impossible. The experiments performed with our novel hand indicate otherwise.

We present a novel type of compliant and underactuated hand based on soft robotic technology. This hand is capable of dexterous grasping, it is easy to build, robust to impact, inherently safe, low-cost, and easy to control. These advantages are achieved by building almost the entire hand out of soft,

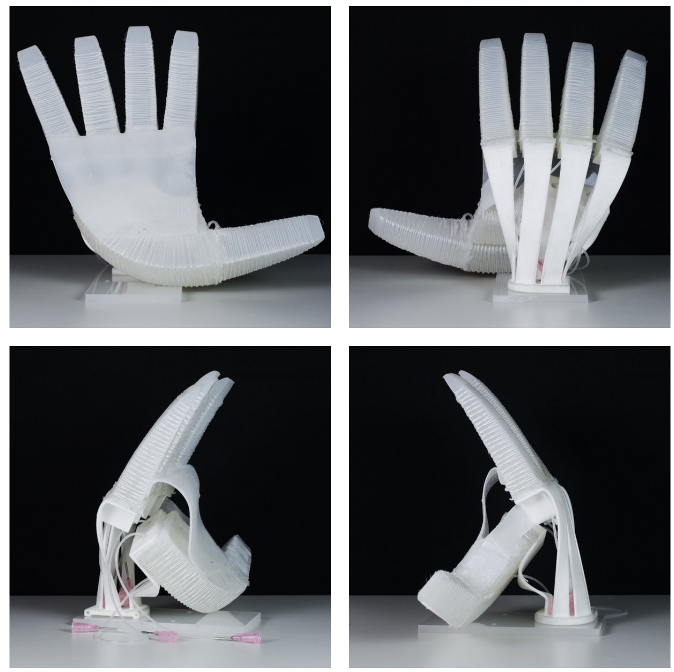


Fig. 1. The RBO Hand 2 is a compliant, underactuated robotic hand, capable of dexterous grasping. It is pneumatically actuated and made of silicone rubber, polyester fibers, and a polyamide scaffold.

inherently compliant materials and structures, rather than of rigid plastic or metal parts. We believe that the combination of dexterous grasping capability with easy manufacturability and low cost make our hand well-suited for enabling high-risk-high-reward research activities and thus progress in dexterous manipulation.

Our design, shown in Figure 1, purposefully maximizes the hand's passive compliance, while ensuring sufficient structural support to lift objects. We believe that this design choice is critical for robust grasping: First, passive compliance facilitates obtaining force closure in power grasps [8]. Second, passive compliance facilitates the use of contact with the environment to aid attaining a grasp, a strategy shown to increase grasp performance in humans and robots [9, 21]. We therefore believe that passive compliance is a key ingredient for robust grasping. In this paper, we want to show that in addition to the two aforementioned advantages, passively compliant hands can also perform dexterous grasping. Further, our results indicate that the benefits of passive compliance even help with dexterous grasping.

We evaluate the dexterity of the proposed hand using the Kapandji test [20], which is commonly used to evaluate dexterity of the thumb in human hands after surgery. The opposable thumb critically enables dexterous grasping in humans as well as in our soft hand. In addition, we show that our hand is capable of re-creating 31 out of 33 grasp postures of the human hand from the Feix grasp hierarchy [11]. We also show that four actuation degrees of freedom suffice to achieve these diverse grasping postures. This implies that the variability of observed grasping posture is only partially generated by the hand's actuation. The remaining variability is the result of interactions between hand and object. These interactions, we claim, are greatly simplified and enriched by the extensive use of passive compliance in the hand's design. These results indicate that dexterous grasping might actually be easier to achieve with passively compliant than with traditional, stiff-linked hands.

## II. Related Work

Many highly capable robotic hands exist. A historical overview, collecting robotic hands from over five decades, was compiled by Controzzi et al. [6]. An analysis of robot hand designs with respect to grasping capabilities was recently presented by Grebenstein [16]. As the notion of compliance is central to our hand design, we will limit our discussion to hands designs that deliberately include this concept.

We distinguish two main approaches for designing compliant hands. Compliance can be achieved using active control, and can be implemented on a fully actuated or even hyper-actuated systems, where every degree of freedom can be controlled (active compliance). Examples of this type of hand are the impressive Awiwi hand [16], the ShadowRobot Shadow Dexterous Hand, and the SimLab Allegro Hand [2]. These hands achieve dexterity through accurate control, which comes at the price of mechanical complexity, making them difficult and costly to build and prone to failure.

An alternative approach is to make hands compliant by including elastic or flexible materials (passive compliance). Building a passively compliant joint is much cheaper than an actively controlled one in terms of costs, volume and system complexity. Passive compliance can easily absorb impact forces — a desirable property for an end-effector designed to establish contact with the world. The cost of adding additional (passive) degrees of freedom is low, compared to actively compliant hands. The resulting ability to better adapt to the shape of an object greatly enhances grasp success and grasp quality. At the same time, the hand can be underactuated, effectively offloading control to the physical body.

A pioneering work in grasping with passive compliance was the soft gripper by Hirose and Umetani [18]. Recently, a whole range of grippers and hands were built using passive compliance, such as the FRH-4 hand [13], the SDM hand and its successor [10, 22, 23], the starfish gripper [19], the THE Second Hand and the Pisa-IIT Soft Hand [17], the Positive Pressure Gripper [1], the RBO Hand [8], and the Velo Gripper [5]. A different source of inspiration was taken by Giannaccini et al. [14], who built an octopus-inspired compliant gripper.

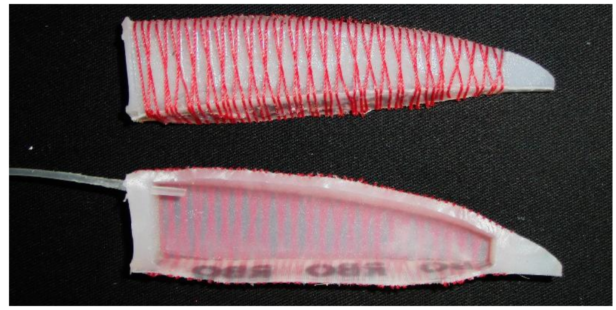


Fig. 2. Cut of a PneuFlex continuum actuator used as finger of the hand. When inflated, the translucent silicone body bends around the bottom side, which embeds an inelastic fabric. The red helical thread stabilizes the actuator cross section around the embedded air chamber.

The practical realization of underactuated hands is matched by theoretical approaches to analyze and evaluate their dexterity [24, 12]. However, these approaches require accurate knowledge of grasp posture, contact point locations and contact forces. Given today's sensor technologies, this information is difficult to obtain in physical implementations.

The inclusion of compliance into the design of robotic hands has lead to significant improvements in power-grasping objects. Very little work has examined the effect of compliance and underactuation on the dexterity of a robotic hand. Closing this gap will be the focus of this paper.

## III. Hand Design

In this section, we describe the components of our soft anthropomorphic hand (RBO Hand 2, see Figure 1). The entire hand weighs $178\,\mathrm{g}$ and can carry a payload of about $0.5\,\mathrm{kg}$. Higher payload can easily be achieved with the same design, as we will explain in Section VI.

*a) Morphology:* The design space of possible hands is very large. For this hand, we chose an anthropomorphic design in shape and size for three reasons. First, we know the human hand form enables dexterous grasping in humans. By attempting to replicate the human hand in our hand design, we therefore are probably not in the worst part of the design space. Second, many objects have been built with manipulation by a human hand in mind, and match the anthropomorphic form factor. Third, we can compare our results to many other anthropomorphic hands, to data on human grasping, and to well-established grasp taxonomies.

*b) Actuation:* The hand uses a highly compliant, pneumatic continuum actuator design, called PneuFlex [8] (see Figure 2). It is actuated by inflating the embedded chamber with air. The pressure forces the hull to elongate along the actuator, the only direction not reinforced by the helical thread. Additional fibers are embedded on one side (passive layer) to stabilize the motion and to make the actuator bend.

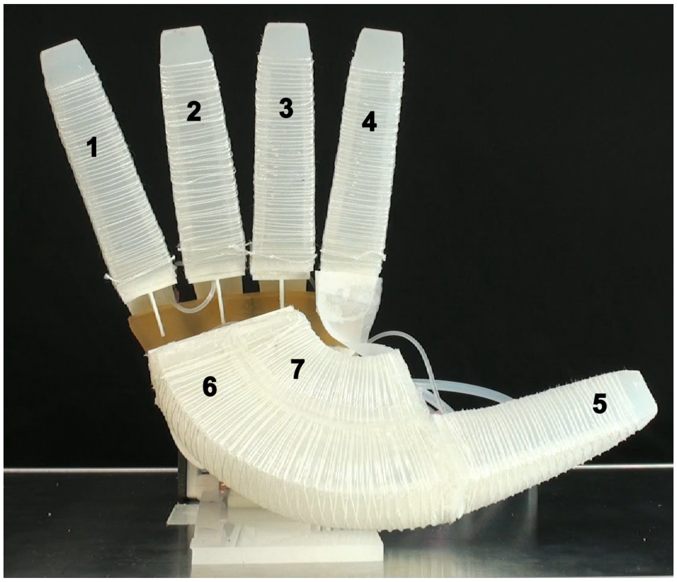



Fig. 3. The seven actuators of the soft anthropomorphic hand: four fingers (1–4), thumb (5), and the palm, consisting of two actuators (6, 7)

PneuFlex actuators are easy to build in one day using a simple procedure [8] with material costs of a couple of dollars. The actuator design space can be explored by varying the shape and size of the actuator, the shape and size of the chamber, the stiffness of the passive layer, the shear modulus and the maximum strain of the silicone. All of these factors affect the bending behavior, stiffness and limits of the actuator. The mold based production process enables intricate designs and reproducible properties. PneuFlex actuators are robust to impact and blunt collisions, are inherently safe and are not affected by dirt, dust, or liquids. However, they can easily be cut or pierced.

Pneumatic control of the PneuFlex actuators is based on a simple linear forward model for valve opening times to achieve a desired channel pressure, corresponding to a desired bending radius or grasping force. We use industrial air valves and an off-board air supply.

Interest in this type of continuum actuators also has spurred advances in modeling and control. Bishop-Moser characterized all basic motions attainable by changing inclinations of the reinforcement helices [3], while approximate numeric models based on twisted, one dimensional beams are formulated by Renda [25] and Giorelli [15].

*c) Fingers:* All fingers of our hand are single PneuFlex actuators (see Figure 3. The index, middle, ring, and little finger are 90 mm long and of identical shape, the thumb actuator is 70 mm long. All fingers get narrower and flatter towards the finger tip. By using actuators as fingers, we can exploit the excellent compliance and robustness of the actuators and greatly simplify the design.

*d) Palm:* A key feature of the human hand is the opposable thumb. We realize this capability by actuating the palm (see Figure 3). The palmar actuator compound consists of two connected actuators and its base shape is a circular section of

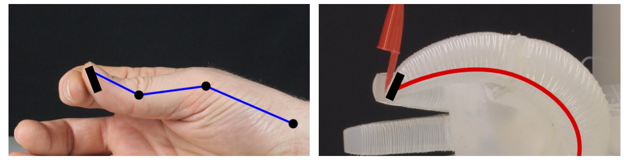


Fig. 4. Difference in thumb configuration and fingertip use during a pincer grasp between a human hand and the robotic hand

$90^\circ$ with 78 mm outer and 25 mm inner radius. The actuator curves perpendicular to the passive layer. Figure 6 provides an impression of the possible thumb motions when the two palm actuators are inflated either together or differentially.

In addition to enabling thumb opposition, the palm also provides a compliant surface that, together with the fingers, is used to enclose objects in various power grasps. To augment this function, the fingers and the palmar actuator are connected by a thin sheet of fiber reinforced silicone, covering the gap between palm actuators and fingers (shown in Figure 1 but removed in in Figure 3 for clarity). This sheet also transmits tensile forces between fingers and palm, and between adjacent fingers. This stabilizes the underlying scaffold during power grasps, or on heavy loads, as shown in Figure 9.

*e) Thumb:* A faithful imitation of how humans use their thumb would require a negative curvature close to the tip, as shown in Figure 4, and would significantly increase complexity of building. We therefore deviate from the human hand design. Instead of the inside of the thumb, we use the backside (dorsal side) as the primary contact surface for pincer grasps. This effectively changes the contact surface orientation by about $45$–$60^\circ$ relative to the orientation found in a human thumb, avoiding the need for negative curvatures. As both sides of the PneuFlex actuator have similar surface characteristics (unlike human thumbs), this choice will not affect grasp quality.

*f) Scaffold:* The fingers and the palm are connected to the wrist by individual, flexible struts as part of a 3-D printed polyamide scaffold (2 mm thick, see Figure 1). Their intentionally flat cross section enables deformation modes, such as arching the palm and spreading the fingers. Space for the respective actuator is provisioned, but was not added to the hand described here. The struts decouple finger motion, further increasing passive compliance of the hand. The flexibility of the struts helps absorb impact forces, while providing sufficient stiffness to transmit forces from heavy payloads without excessive deformation (see Figure 9).

The fingers and the palmar actuator compound are bonded to the supporting scaffold as shown in Figure 1. The palm is supported by parts of the scaffold to increase its torsional stiffness during opposition with the fingers.

*g) Strength between thumb and fingers:* An inelastic band connects the base of the index finger to that of the thumb (see Figure 3). Similarly to a muscle in human hands (adductor Pollicis), it enables increased contact forces between thumb and opposing finger, by reducing torques on the struts at the

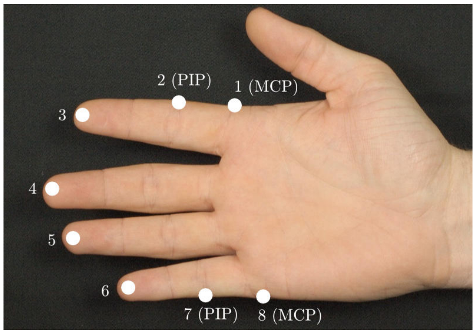



Fig. 5. The Kapandji test counts the number of indicated locations that can be contacted with the thumb tip.

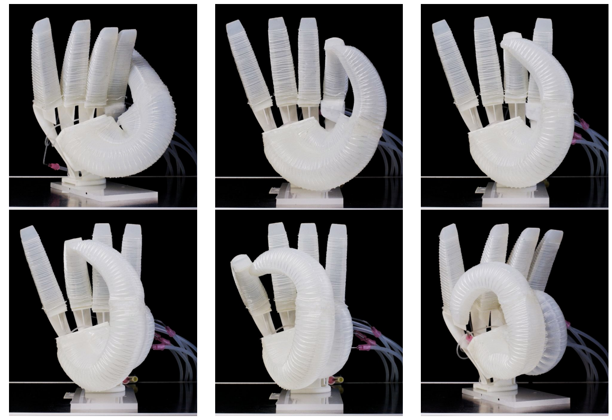


Fig. 6. The thumb reaching for six locations of the Kapandji test (left to right, top to bottom: 1, 3, 4, 5, 6, and 8): The test succeeds for all positions (including 7, not shown), except for position 1 (top left)

wrist.

## IV. Grasp Dexterity

In this section, we evaluate the dexterous grasping capabilities of the proposed hand. The most appropriate evaluation would of course be in full-fledged, real-world grasping experiments. However, this requires the integration of hand and control with perception and grasp planning and would effectively be an evaluation of the integrated system. Here, we focus on evaluating the capabilities offered by the hand. Furthermore, we have to resort to empirical methods. Accurate simulation of the complex, nonlinear deformations encountered in such a heterogeneous and soft structure is difficult to conduct and anyways requires empirical experiments to validate the results.

### *A. Thumb Dexterity*

Medical doctors employ the Kapandji test [20] to assess thumb dexterity during rehabilitation after injuries or surgery. This test was also used by Grebenstein for evaluating and improving the thumb dexterity of the Awiwi hand [16]. For the Kapandji test, the human subject has to touch a set of easily identifiable locations on the fingers with the tip of the thumb. These locations are shown in Figure 5. The total number of reachable locations serves as an indicator of overall thumb dexterity. A thumb is considered fully functional if it is able to reach all locations.

To perform the Kapandji test on our hand, we manually selected actuation pressures that would position the thumb as desired. The six most important postures of the hand performing the test are shown in Figure 6. The thumb tip could reach all but one location. Location 1 was not possible to reach because it would require a backwards bending of actuator 5 (thumb). Still, the hand scores seven out of eight points, indicating a high thumb dexterity.

### *B. Grasp Postures*

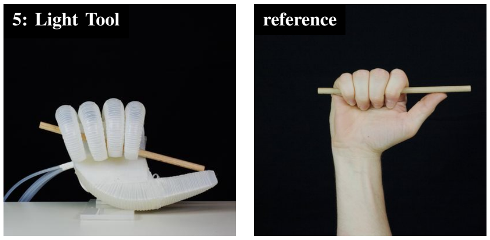
A common way of assessing the dexterous grasping capabilities of hands is to demonstrate grasps for a set of objects. For example, the THE Second Hand was evaluated with 4 objects and 2 grasp types [17], the SDM hand on 10 objects and 1 grasp type [10], the Velo Gripper on 12 objects and 1 grasp type [5], and the Awiwi hand on 8 objects and 16 grasp types [16]. We follow this method of experimental evaluation.

We select grasp types and objects based on the most comprehensive grasp taxonomy to date, the Feix taxonomy [11]. It covers the grasps most commonly observed in humans and therefore is a realistic reference for assessing the dexterity necessary for common grasping tasks. The taxonomy encompasses 33 grasp types, out of which the first 17 are identical to the grasps in the Cutkosky taxonomy [7]. To demonstrate these 33 grasps, the original publication illustrates 17 different object shapes [11]. We therefore used 17 objects and 33 grasp types to evaluate our hand.

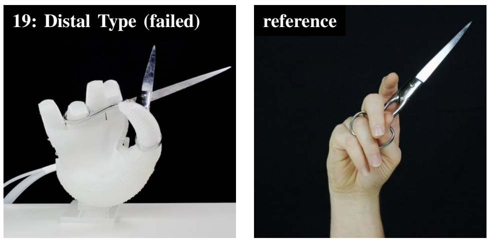
We implemented the grasps from the Feix taxonomy by defining appropriate actuation pressures and actuation sequences. When, due to collisions, simultaneous actuation of all channels was not sufficient to reach the desired posture, we added an appropriate pre-grasp posture. The commanded actuation pattern was then modified and tested iteratively to improve the quality of the grasp in terms of grasp stability and robustness against external forces, and to ensure the proper types and locations of contact. Grasp quality was judged by manually rotating and translating the hand, and by testing several repetitions of the actuation pattern.

To simplify the search for appropriate actuation patterns, we combined the control of the seven actuators into four actuation channels. Channel A drives actuators 1, 2, and 3 (small, ring, and middle fingers), channel B drives actuator 4 (index finger), channel C drives actuators 5 (thumb) and 7 (inner palm), and channel D controls actuator 6 (outer palm). These channels can be understood as the hand's four grasping synergies.

To perform a grasping experiment for a particular grasp type, the experimenter triggers the actuation sequence to attain the pre-grasp posture, holds the object in the seemingly most appropriate location relative to the hand, and then triggers the actuation sequence for the grasping motion. The resulting postures for each empirical actuation pattern are shown in Figure 10. Out of 33 grasp types, the hand is able to perform 31




(a) Failed Light Tool grasp: no force closure




(b) Failed Distal Type grasp: functionally defective

Fig. 7. Grasping postures not successfully attained by the robotic hand

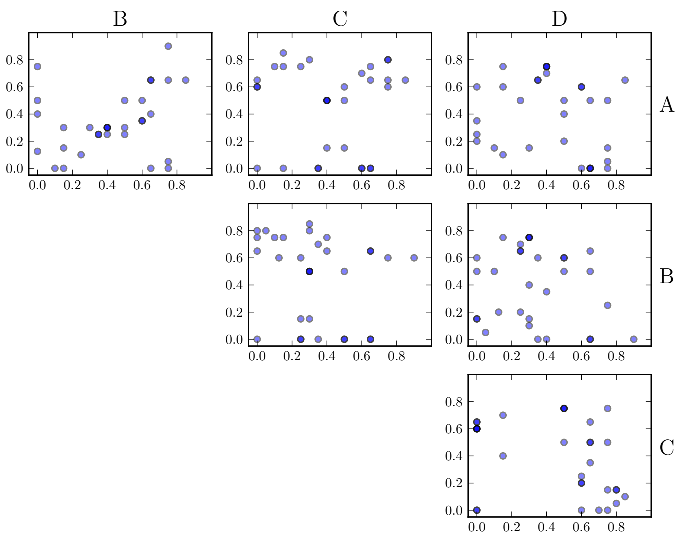


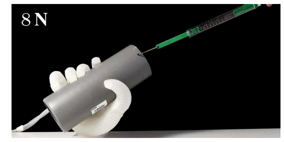

Fig. 8. Scatter plots of the four actuation channels for the actuation patterns of the 31 successful grasps. Darker color indicates overlapping dots.

repeatably (three consecutive successful trials). The two grasps that failed are the *light tool* grasp and the *distal type* grasp.

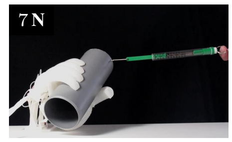
The light tool grasp fails because the hand does not posses finger pulp that fills the cavity formed by the maximally bent fingers, which causes the object to slip. The distal type grasp fails because, while it is possible to force the soft fingers through the scissors' holes, the resulting grasp is nonfunctional with respect to proper use of the scissors. Both grasp failures are shown in Figure 7.

Figure 8 shows a scatter plot of the actuation patterns for the 31 successfully achieved grasp types of the Feix taxonomy. The actuation patterns relate to final grasps, not for the pre-grasp postures. The plots indicate an even distribution of activation for all channels and do not reveal obvious correlations that could be leveraged to further simplify actuation.


(a) Cylinder off center




(b) Tolerated disturbance




(c) Tolerated disturbance


(d) Tol. disturbance


(e) Support strength

Fig. 9. Illustrations of grasping force capabilities: (a) finger strength and palm support strength, (b)–(d) tolerated disturbance forces in different directions for grasp 1, and (e) strength of the support provided by the scaffold

The evaluation presented in this section demonstrates the hand's ability to assume a variety of grasp postures. This ability is comparable with that of other hands presented in the literature. We therefore believe that dexterous grasping and compliance can indeed be combined in a highly capable, compliant, underactuated robotic hand.

### C. Grasping Forces

While grasp quality and grasp strength was not the driving design criterion for the hand, it is important to verify that a compliant hand is capable of lifting objects of reasonable weight. To give the reader an intuition on the capabilities of the hand, we provide a few tests regarding grasping forces.

The heaviest objects used in the Feix grasps were the rectangular plate in grasp 22 (156 g), the metal disc in grasp 10 (181 g), the wooden ball in grasp 26 (183 g), and the circular plate in grasp 30 (240 g). Note that in grasps 26 and 30, the shown posture offers the least structural support of possible hand poses. Figure 9 shows two additional heavy objects, a wooden cylinder (541 g) and a lead ball (1.650 g).Figure 9 also shows three different directional disturbance forces on a cylinder which is power-grasped with grasp 1. The applied forces (6-8 N) are the thresholds beyond which the object will slide in the hand.

### D. Grasping in Realistic Settings

To further illustrate the effectiveness of the proposed hand, we performed experiments of complete grasping sequences, shown in Figure 11. In these experiments, a human operator selects the appropriate grasp, triggers the pregrasp posture of the hand, places the hand in the appropriate location, and then executes the grasp. These experiments demonstrate that the proposed hand, given appropriate perception and grasp planning skills, is able to perform real-world grasps.

## V. Compliance Benefits Dexterous Grasping

In the previous section, we showed that our underactuated and compliant hand is capable of dexterous grasping. We now would like to explore whether compliance and underactuation


Fig. 10. Enacted grasps of the Feix taxonomy, using empirically determined actuation patterns: Grasps are numbered according to the Feix taxonomy [11]; the hand failed to replicate grasps 5 (Light Tool) and 19 (Distal Type, Scissors)

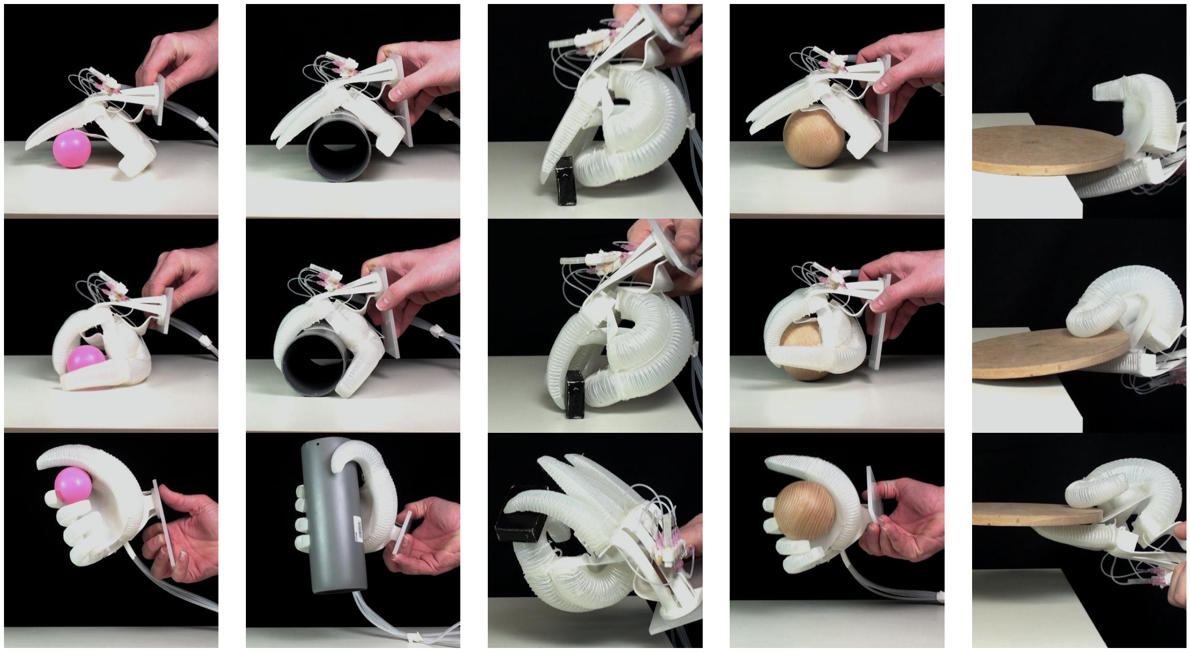


Fig. 11. Performing grasps using the grasp postures 25, 1, 9, 28 and 18: a human places the hand and then triggers the actuation of the appropriate grasp; top: pregrasp posture, middle: executed grasp, bottom: lifting object to show success.

actually are beneficial or detrimental to attaining different grasp postures. If they are beneficial, control should be simpler than the resulting behavior, which can express itself in a grasp posture space larger than actuation space. An increase in dimensionality of the grasp posture space relative to actuation space could arise from the compliant interaction between hand and object.

To assess the intrinsic dimensionality of the grasp posture space spanned by the Feix taxonomy, we would ideally analyze grasp postures of the proposed hand. Since the hand currently is not sensorized, this is not possible. As a placeholder experiment, we analyzed human grasp postures performing the same grasps on the same objects, excluding the two failed ones. We recorded joint angles from four male and two female, right-handed subjects using a Cybersystems Cyberglove II. Subjects were instructed to imitate the grasp demonstrated by the experimenter, holding the object in a convenient pose. They then repeated the same grasp five times, placing the hand flat on a table after each grasp. Subjects were allowed to use the other hand to assist in assuming the grasp posture, but had to achieve a successful grasp in the sensorized hand without additional support. The resulting postures were sampled 50 times within $500\,\mathrm{ms}$ and averaged over samples and episodes. We then performed dimensionality reduction by applying Principal Component Analysis (PCA) for each subject individually.

Figure 12 shows a comparison of the resulting unexplained variances, juxtaposed with the unexplained variances of the hand's empirical actuation patterns shown in Figure 8. We see, for example, that four principle components explain about 80–90% of the variance observed in human subjects.

To be able to draw conclusions for the robotic hand, we are forced to make an assumption not experimentally validated yet, due to the fact that our hand is at this point sensorless. We assume that the dimensionality of the 31 grasp types performed by humans is similar to the dimensionality of the same 31 grasp types performed by the robotic hand. We believe that this assumption is justified, as all hands (human and robotic) attain the same grasps on the same objects with similar hand shape, size, finger count and thumb dexterity. Therefore we expect the dimensionality of exhibited posture to be comparable.

To determine the dimensionality of attained human grasp postures, we set the threshold at $95\%$ of the variability to be explained. This high value is appropriate, as even small variations in grasp posture will have a dramatic influence on grasp quality. Using this threshold, we need on average eight dimensions to accurately represent the human grasp postures. This is considerably higher than the control dimensionality of our robot hand, which is only four. Put differently, we have to remove about $16\%$ of grasp posture variance to attain the same dimensionality as control. Given the sensitivity of grasp quality to slight postural variations, this is an indication that the dimensionality of grasp posture attained by humans and therefore also by our robotic hand is higher than its demonstrated dimensionality of control.

We interpret the discrepancy between the dimensionality of the actuation space and the dimensionality of the grasp posture space to be caused by compliant shape adaptation of the hand to the objects. A similar reduction in control complexity was observed with simulations of Eigengrasps [4], corroborating our interpretation of the available data.

We conclude this analysis with the strengthened belief that

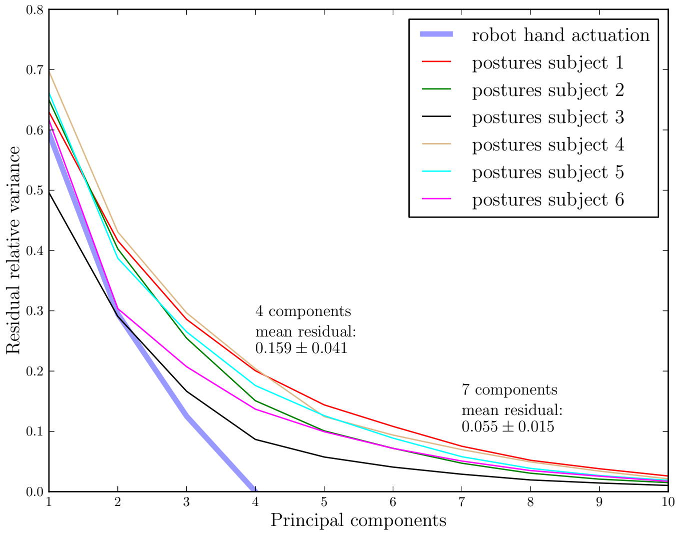



Fig. 12. Residual unexplained variances of PCA for human subjects, compared to the residual variances of the hand actuation patterns: About 16% of postural variance remains unexplained even if control is assumed to account for to the four principal components

compliance and underactuation do not render dexterous grasping difficult, they in fact may simplify the control required to attain it. Given the strong assumption we made to present this argument, we must be careful when drawing definitive conclusions, but we view our results as encouragement to continue investigating compliant, underactuated, dexterous hands.

## VI. Limitations

Using a novel technology in a new application, like continuum actuators in the design of soft hands, opens up new possibilities but also brings new limitations and challenges.

*a) Grasping Forces and Payload:* Continuum actuators, when constructed with reinforced rubber and actuated hydraulically, are in principle capable of exerting extremely large forces. For example, an actuator made out of car tire rubber with a steel-fiber reinforcements and hydraulic actuation would probably be able to exert grasping forces in excess of 100 N. In our hand design, we chose to use very soft rubber, mainly to investigate how much compliance is possible, and to increase safety. We chose pneumatic actuation as it is much simpler and cleaner to operate in a lab environment. Nevertheless, it would be straightforward to make a much stronger hand using the exact same design. Such a hand would also have a higher payload than the hand we presented here.

*b) Pneumatics:* Our hand design uses external pneumatic components for control and an air supply. These components are cheap and readily available in industry-grade quality. However, they are designed for higher-performance applications and are over-sized for the low pressures, small volumetric flow, and size constraints of robotic hands. Miniaturization and integration of electrically actuated valves directly into the hand, possibly even into the actuator, would greatly simplify our design. Long-term autonomy arguably is easier to achieve with pneumatic systems. In contrast to electrical power systems, where no good solution for long-term untethered operation exists, the technology to make small air tanks and mobile compressors is well-understood.

*c) Sensing:* The compliance of the materials makes sensing for proprioception and contact forces very important but also very difficult. While it is easy to integrate air pressure sensors, it would be very desirable to integrate strain and touch sensors. This is a topic of active research.

*d) Modeling:* A mechanical model of the hand is difficult to obtain, due to the nonlinearities and large number of degrees of freedom in the actuators. Obtaining accurate posture information through sensors is also difficult, based on existing sensing technologies. As a result, most existing grasp planners cannot easily be applied to our hand.

## VII. Conclusions

We presented a compliant, underactuated, and dexterous anthropomorphic robotic hand based on soft robotics technology. The hand is able to achieve 31 of 33 grasp postures from a state-of-the-art human grasp taxonomy. To evaluate the dexterity of the opposable thumb, we performed the Kapandji test, in which the hand achieves seven out of eight possible points. We illustrated the hand's excellent payload to weight ratio, as it is able to lift objects nearly three times its own weight. We also presented real-world grasping experiments to demonstrate the hand's capabilities in a realistic setting.

We believe that compliance is crucial to enable robust grasping in robotic hands. We provided support for this hypothesis by showing that the dimensionality of attained grasping postures is significantly larger than the dimensionality of the hand's actuation space. We explain this observation with the hand's ability to adapt to the shape of the grasped object. The final grasping posture is the product of the hand's actuation and compliant interactions between the hand and the object.

In addition to its dexterous grasping capabilities, the proposed hand has other advantages. The use of soft robotic technology renders it robust to impact and blunt collisions, makes it inherently safe and suitable for working environments containing dirt, dust, or liquids. The effort, complexity, and cost of building the hand are significantly lower than for existing hand technologies. The hand presented here can be built in two days using materials worth less than 100 US$. We therefore believe that this novel way of building robotic hands significantly lowers the barrier to entry into grasping and manipulation research.

## VIII. Acknowledgments

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