

# The New Dexterity Adaptive Humanlike Robot Hand: Employing a Reconfigurable Palm for Robust Grasping and Dexterous Manipulation

Geng Gao, Anany Dwivedi, and Minas Liarokapis

**Abstract**—Robots have predominantly been used in automating tasks in structured industrial environments, however, with the advances in technology they are starting to take part in roles in dynamic everyday life scenarios. As a result, the tasks executed by robotic systems will also grow in sophistication. Grasping and dexterous manipulation are critical aspects that allow humans to execute these sophisticated tasks, enabling them to interact with their environment. As such, emulating the human hand can be advantageous for interacting with a world designed for humans. However, directly replicating the anatomical structure of the hand produces designs that are fully actuated, expensive, and which require sophisticated controls and sensing to operate efficiently. In this paper, we present two different versions of the New Dexterity adaptive, humanlike robot hand that is capable of executing robust caging grasps under a wide range of environmental uncertainties (e.g., object pose uncertainties). One of the versions has a classic, fixed thumb base while the second one incorporates an additional degree of freedom at the thumb base, which enables a translational motion for repositioning the thumb and adjusting the aperture. This design choice enhances the in-hand manipulation capabilities of the robot hand, improving also the power grasping capabilities for larger objects. The performances of the proposed robot hand designs are experimentally validated and compared through three different tests: i) grasping experiments involving everyday-life objects, ii) force experiments that evaluate their force exertion capabilities, and iii) in-hand manipulation experiments that demonstrate and compare their dexterity.

## I. INTRODUCTION

As robotics and automation technologies advance, so do the roles they play in our lives, moving from highly structured industrial production lines to unstructured and dynamic environments around humans. For robots to efficiently operate in human-centric environments incorporating anthropomorphic attributes can be advantageous in assisting interactions. A key attribute that enables humans to carry out numerous complex tasks is the use of the human hand, enabling humans to interact through grasping and manipulation of objects and tools. Researchers have aimed to replicate such dexterity within robots by directly modeling the human hands' properties. Although possible, this results in fully-actuated, rigid designs, which require expensive components, complex control algorithms, and sophisticated sensing to create multi-fingered, anthropomorphic, dexterous robot hands [1]–[4]. This design approach also makes it difficult to achieve a dexterous, anthropomorphic robot hand without compromising the weight and form factor of the

Geng Gao, Anany Dwivedi, and Minas Liarokapis are with the New Dexterity research group, Department of Mechanical and Mechatronics Engineering, The University of Auckland, New Zealand. E-mails: {ggao102,adwi592}@aucklanduni.ac.nz, minas.liarokapis@auckland.ac.nz

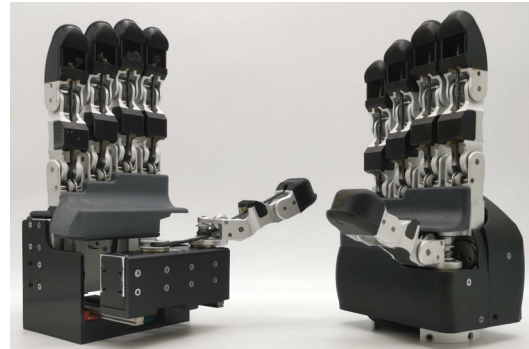


Fig. 1. The humanlike adaptive underactuated tendon driven robot hands with and without an additional DOF for facilitating thumb base translation for adjusting the aperture of the hand.

device because of the many actuators and sensors needed for this approach [5]. To empower robots with higher levels of dexterity in order to conduct tasks of higher complexity, researchers have explored alternative methods to control such devices, such as machine learning methods capable of enabling a robot hand to solve a Rubik's cube one handed [6]. Although machine learning methods provide increased generalizability and reduced complexity of control for highly actuated anthropomorphic robot hands, they require significantly large amounts of data and computational resources in order to learn how to carry out a single task. As a result, many robots in industry are equipped with simple parallel jaw grippers with limited dexterity.

During the last decade, the utilization of compliant elements and underactuation has provided an alternative means of designing lightweight and simple to control robot hands capable of executing robust grasping in unstructured environments with high object pose uncertainty [7]–[9]. By incorporating intrinsic and extrinsic compliance through intelligent material selection and mechanism design, robotic end-effectors can be designed to be mechanically intelligent. This allows such robot grippers and hands to be capable of passively adapting to their environment with intuitive and simple control strategies [10], [11]. The integration of structural compliance has not only allowed for increased adaptability and improved handling of fragile objects, but also facilitates safer interaction between humans and robotic devices [12], [13]. As a result, underactuated and compliant mechanisms have been utilised to develop a wide variety of adaptive grippers capable of grasping and manipulation. The applications range from prosthetic hands [14] giving amputees an improved quality of life to adaptive grippers on

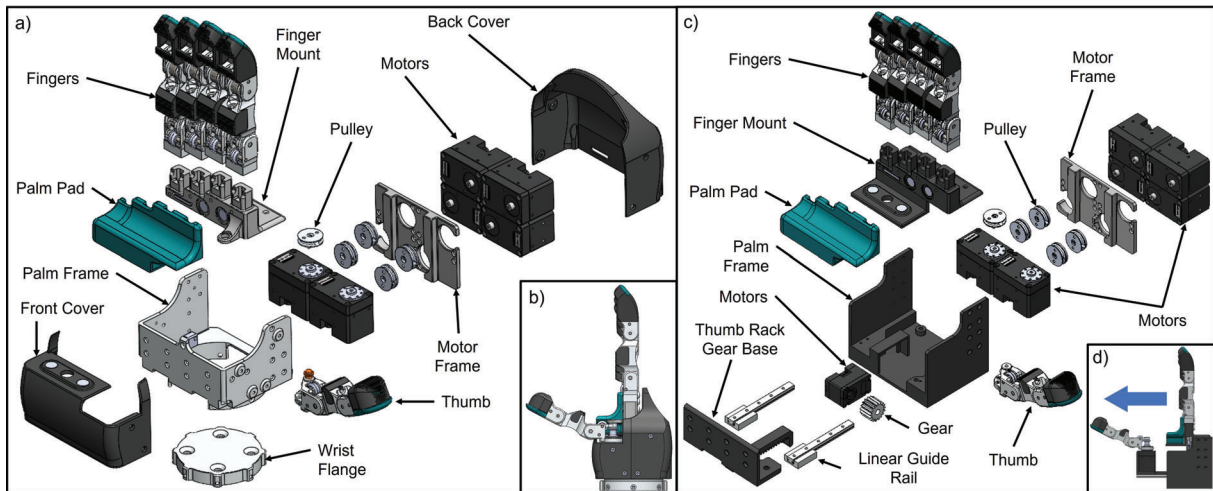


Fig. 2. Exploded views of two different hand structures illustrating the construction and different components within the hand. Subfigure a) shows the structure of the first robot hand with a rotating base frame for the thumb to provide opposition. Subfigure b) presents the maximum aperture of the hand. Subfigure c) depicts the assembly of the robot hand with a base frame capable of both translation and rotation at the thumb. Subfigure d) presents the side view of the thumb when fully extended.

underwater robots [15] for improved interactions between the robot and its surrounding environment. To further improve the capabilities of underactuated compliant grippers, the implementation of reconfigurable finger base frames delivers an efficient allocation of the limited number of actuators so as to increase the dexterous in-hand manipulation capabilities without compromising grasping efficiency [16]–[19]. In [17], authors utilise reconfigurable finger base frames in a three-fingered gripper with each finger having an independent rotational degree of freedom facilitating the execution of pinch, tripod, and interdigitated grasps. In [19], the authors place underactuated adaptive fingers on a translational base allowing the gripper to transform between an adaptive two-finger gripper and a parallel jaw gripper. The reconfiguration of the finger base frame also allows the hand to access different manipulation workspaces.

In this paper, we present two different versions of the New Dexterity adaptive, human-like robot hand. One design has a fixed thumb base frame while the other uses an additional translational DOF at the thumb base to adjust aperture and improve both grasping and the dexterous, in-hand manipulation capabilities of the hand.

The rest of the paper is structured as follows: In Section II, we present the designs of the two different versions of the adaptive, humanlike robot hand, in Section III, we describe the robot hand control interface, in Section IV we present the experimental setup, the methodology used, and the experimental results obtained, and finally in Section V, we conclude the paper.

## II. DESIGN

In this section, we described the design of two different robot hands. The structure of the hand can be seen in Fig. 2. The robot hands are composed of modular fingers, a thumb, and a magnetic palm, which are attached to two different palm designs that differentiate the two hand designs apart.

### A. Palm Design

Many anthropomorphic and robotic hand designs [20]–[24] utilise palms that provide fixed finger base frames to the five fingers of the hand. As a result of using this design paradigm, optimisations are done to find the optimal fixed palm design for all objects. However, for underactuated robot hands to achieve the maximum in-hand manipulation workspace over a range of different objects, different palm sizes, which separate the finger base frames, should be used [25]. More specifically, having a finger base frame separation distance, which is the same as the object width, can provide the maximum object manipulation workspace [25], [26]. This indicates that no one solution will provide the best manipulation workspace for all object sizes, instead, a hand with a changing palm size that can facilitate different finger base frame distances is a more generalisable solution for achieving a highly dexterous end-effector.

Inspired by our previous work focusing on the use of reconfigurable base frames in two-fingered grippers [19], we have designed two different palm designs to compare the improvement in manipulation capabilities. The first design (Fig. 2a) utilises a palm that uses a fixed finger base frame design for all the fingers, while the thumb has a rotating thumb base frame to achieve opposition. The second design (Fig. 2c) is similar to the first design, but consists of an additional DOF in the base of the palm allowing the thumb base frame to reconfigure/translate outwards to increase the aperture of the hand. Contained within the two different palm designs, 6 Dynamixel XM430-W350 motors are stored for actuating each finger and the thumb in order to execute flexion motions. The thumb also uses an additional actuator to perform opposition. The reconfigurable design uses an additional actuator (XC330-T228-T) with a set of linear guide rails and a rack and pinion mechanism to accomplish the translating motion of the thumb.

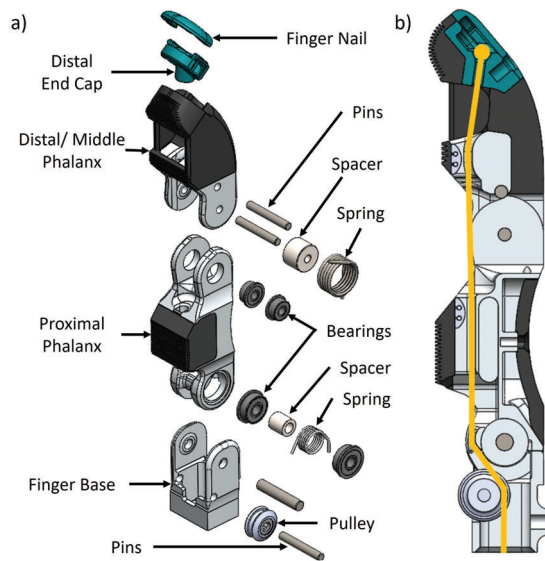


Fig. 3. Subfigure a) depicts an exploded view of the New Dexterity robot hand finger. The finger consists of a finger base, a proximal phalanx, a distal/middle phalanx, a distal end cap, and a detachable fingernail. Additionally, springs within the finger enable passive extension, while bearings reduce friction within the joints. Subfigure b) presents the tendon routing scheme of the hand with the yellow line indicating the tendon.

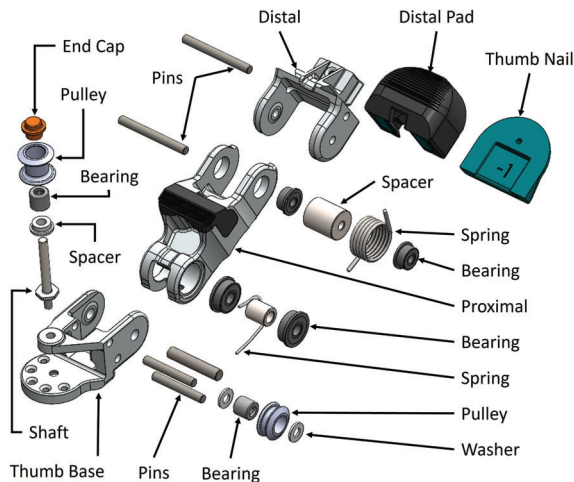


Fig. 4. An exploded view construction of the thumb. A modular distal pad and thumbnail allows the tip of the finger to be easily altered. Bearings are used to reduce friction in the joint, and torsional springs provide passive extension. Pulleys within the thumb reduce friction and enable rerouting of the thumb tendon.

### B. Finger design

The design of the robotic fingers are composed of pin joints at the metacarpal phalangeal (MCP), and proximal interphalangeal (PIP) joints, with the distal interphalangeal (DIP) joint being a flexural joint design. The flexure joint construction not only allows the fingertips to exhibit improved flexibility but also allows the distal and middle phalanges to be constructed as a monolithic structure, increasing the area of the urethane finger pad for improved grasp contact. The monolithic structure is fabricated with

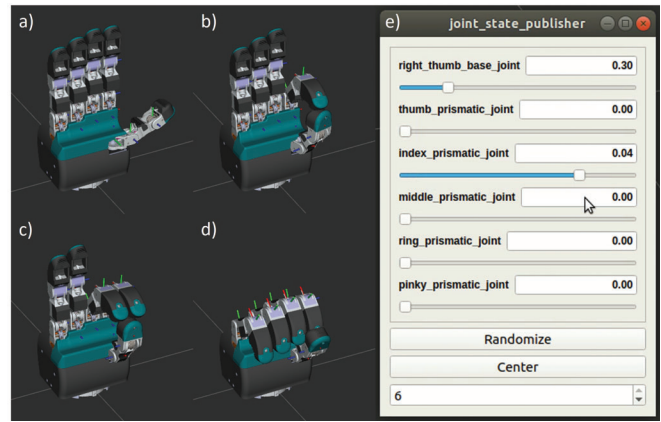


Fig. 5. The robot hand control interface can be used to visualise the hand in simulation and utilised to control the robot hand. Subfigures a) to d) depict the simulated robot hand performing different gestures and grasp types (fully extended, pinch, tripod, and power grasps). Subfigure e) presents the interactive GUI, which can be used to control the robot hand.

a urethane rubber (Smooth On PMC-780) using hybrid deposition manufacturing (HDM) [27] techniques, which allows the combination of rigid and soft materials to be moulded together. This manufacturing technique is also used to construct the proximal phalanx. The finger is composed of a modular fingernail, distal/middle phalanx, proximal phalanx, and a set of bearing and torsional springs at each pin joint. A depiction of the finger is shown in Fig. 3. The torsional spring stiffness was selected such that the flexion profile of the fingers prioritises the bending of the MCP joint before the PIP joint and once the proximal phalanx makes contact or the MCP joint reaches full flexion. The fingers are actuated through low friction polymer tendons, terminated at the fingertips and pulleys of each motor associated with the fingers. The routing of the tendons in the fingers is designed to be positioned as far away from the joints as possible to increase the force exertion capabilities, while still ensuring that the finger pads are not affected. This arrangement allows the tendons to facilitate strong power grasp forces and maximize the applied torque on the joints. The tendon routing scheme is shown in Fig. 3b). Each finger is mounted on an interchangeable base that allows the fingers to be modular and easy to replace.

### C. Thumb Design

The thumb follows a similar design approach as the fingers of the robot hand, but without the inclusion of the flexural joint at the DIP joint. Bearings at the pin joints facilitate low friction bending at the joints and torsional springs at the MCP and DIP joints of the thumb are selected such that the MCP joint flexes before the DIP joint like the fingers of the robot hand, allowing the hand to perform both precision and power grasps. A pulley at the opposition joint of the thumb enables the actuating tendon to be rerouted, housing the actuators in a compact manner. The construction of the robot finger is illustrated in Fig. 4.

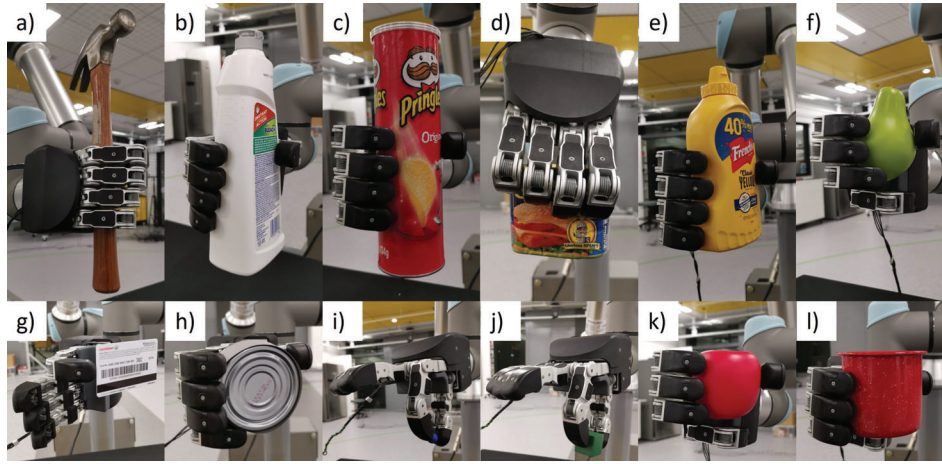


Fig. 6. Grasping experiments were conducted with the YCB object set [28]. Twelve objects from this set were selected to assess the hand: a hammer, a bleach cleanser, a chips can, a potted meat can, a mustard container, a pear, a card, a tuna can, a marble, a small block, an apple, and a metal mug.

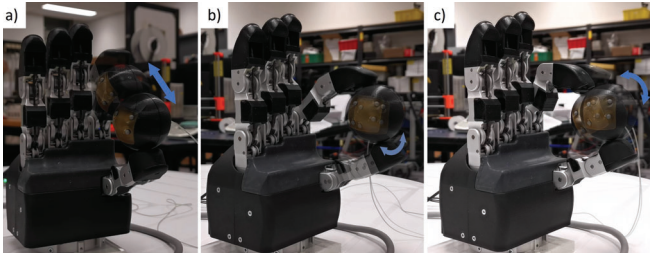


Fig. 7. The hand manipulating a sphere [32]. Subfigure a) presents the hand translating the sphere vertically up and down with a coupled rotation. Subfigures b) and c) demonstrate the hand performing rolling manipulation motions that shift the sphere forward and backward and side to side.

#### D. Robot Hand Control Simulation and Interface

For the control of the proposed hand, a control framework was implemented within the Robot Operating System (ROS) [29], which facilitates communication between different modules and provides testing and visualisation utilities. The developed ROS framework allows the robot hands to be interfaced with external sensing modules (e.g., fingertip force sensors, grip force sensor etc.) or synchronize the motion of the robot hands with other systems (e.g., synchronise arm and hand motion, control the hand gestures based on output from muscle-machine interfaces) [30], [31]. The ROS framework can also be used to test different control algorithms on the robot hands with simulated physics without access to the actual hardware with the help of simulators (e.g., gazebo simulator). The motion of the robot hands can be visualised using rviz visualiser (see Fig. 5) and can also be controlled using an interactive interface (see the video in Section III-D).

### III. EXPERIMENTS AND RESULTS

In this section, we evaluate the performance of the proposed adaptive robot hands using a combination of contact force exertion experiments, grasping experiments (see Fig. 6), and dexterous manipulation experiments (see Fig. 7).

TABLE I  
MAXIMUM GRASP FORCES EXERTED ON THE DYNAMOMETER.

Grasp Type	Dynamometer Diameter	Force (N)	
		Design 1	Design 2
Pinch	70 mm	33.8	32.2
	85 mm	28.2	25.5
	100 mm	26.1	28.3
Tripod	70 mm	50.1	47.7
	85 mm	48.6	22.8
	100 mm	46.1	29.3
Power	70 mm	122.5	90.5
	85 mm	101.8	104.6
	100 mm	87.9	101.2

#### A. Force Exertion Experiment

The first experiment focused on measuring the grasping forces. Three different grasp types were selected and assessed: a pinch grasp, a tripod grasp, and a power grasp. Force measurements were collected with a SS25LA dynamometer attached to a Biopac MP36 data acquisition unit (Biopac Systems, Inc.). The dynamometer diameter was varied between three different sizes: 70 mm, 85 mm, and 100 mm. The National Institute of Standards and Technology (NIST) grasp strength performance metric [33] was used for the experiments, where the dynamometer is grasped in two different orientations: a 0 degree orientation when the load cell axis is parallel with the palm surface, and a 90 degree orientation when the load cell axis is perpendicular to the palm surface. Once the two readings are collected, the euclidean norm is used to calculate the maximum force exertion for a given grasp type. The maximum force exertion capabilities of the proposed adaptive robot hand in different grasp types can be found in Table I. Table I shows that during precision-type grasps, the reconfigurable thumb design exerts forces similar to the fixed thumb design, provided that the

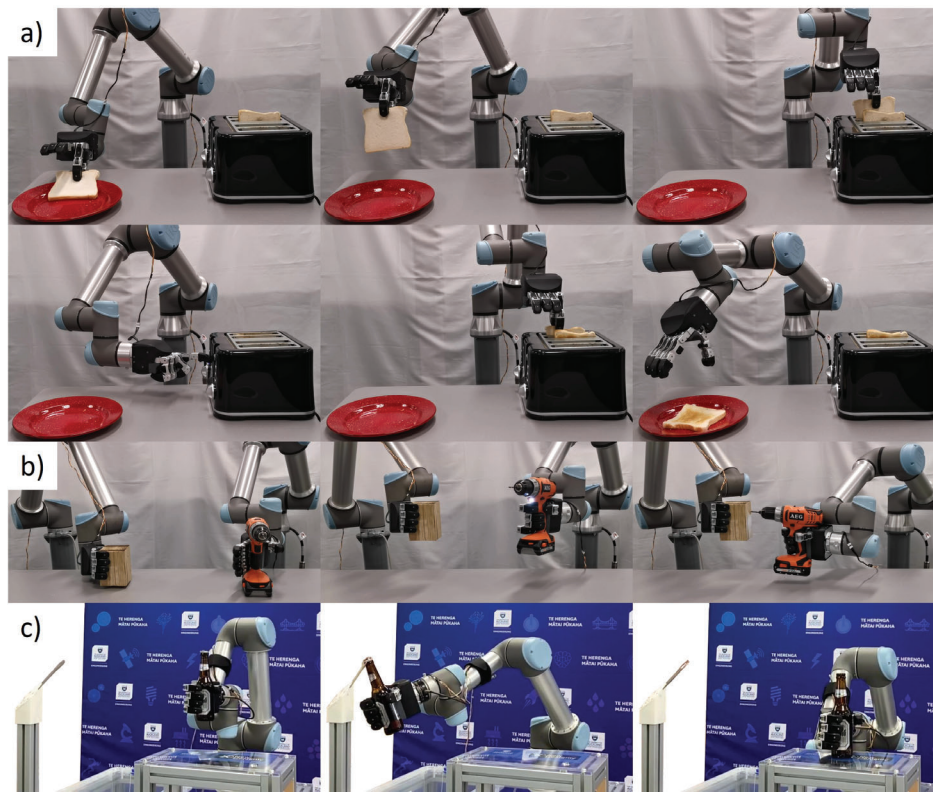


Fig. 8. The hand performing different tasks with the task motions being executed from left to right in sequence. Subfigure a) shows the robot hand executing a cooking task of making toast. Subfigure b) presents the hand performing a bimanual task of drilling a wood block. Lastly, subfigure c) shows the robot hand executing a service task of opening and serving beer.

thumb is positioned identically. This similarity was observed when the hand grasped a 70 mm diameter dynamometer. However, when exerting higher grasping forces, the reconfigurable thumb mechanism's 3D-printed Polylactic acid (PLA) plastic construction was not sufficiently stiff to support the load on the translating mechanism, causing the structure to flex. This flexing, in turn, reduced the maximum achievable force within the hand's grasp since any additional force would cause the structure to flex further, transmitting less force into the object. This can be seen when comparing the pinch and tripod grasps of the 85 mm and 100 mm diameter dynamometers. Although flexing was observed, when power grasping larger objects like the 100 mm diameter dynamometer, a force improvement of 13.3 N was achieved. The reconfigurable palm and changing aperture enable the hand to achieve wider grasps, improve force exertion on the grasped object, and better support objects of varying sizes.

### B. Grasping Experiments

These experiments evaluated the grasping performance of the proposed adaptive robot hand. The grasping capabilities of the hand can be seen in Fig. 6. The YCB object set, an object set composed of a variety of everyday life objects designed to facilitate the benchmarking of grasping and manipulation, was used to assess the robot hands' capabilities. Twelve objects from the object set varying in weight, size, and shape were selected: small block, marble, credit card,

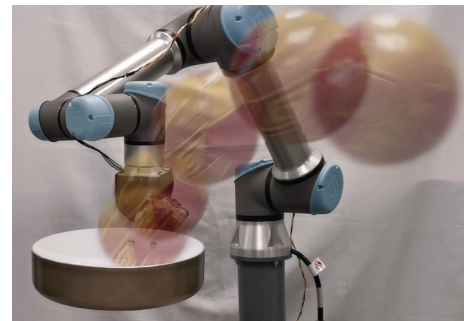


Fig. 9. A grasp robustness test evaluating the hand's ability to hold the pan when experiencing a disturbance (ball being thrown at the pan).

tuna fish can, potted meat can, pear, apple, metal mug, mustard container, chips can, bleach cleanser, and hammer. The objects were placed on a flat surface before being grasped. Additionally, a grasp robustness experiment was conducted where the gripper had to secure firmly and hold a 5 kg pan in full / caging grasp configuration and keep the grasp stable even when a soccer ball was thrown inside the pan as shown in Fig. 9.

### C. Dexterous Manipulation Experiments

A series of experiments were conducted in order to evaluate the dexterous manipulation capabilities of the proposed adaptive robot hand. The achievable in-hand manipulation

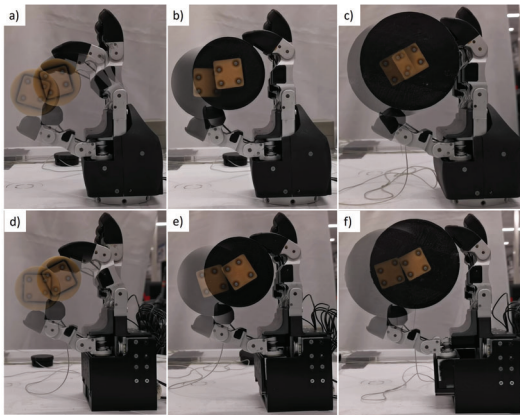


Fig. 10. A comparison of the two different hands manipulation capabilities with and without a translational DOF at the thumb MCP joint. When manipulating smaller objects (subfigure a) and d)) both hands have a similar manipulation workspace as the second hand design uses the translational DOF in its compressed form. However, when manipulating larger objects (as seen in subfigure c) and f)), the translational DOF can be used to extend the thumb base position increasing the manipulation workspace of the object in comparison to the first design.

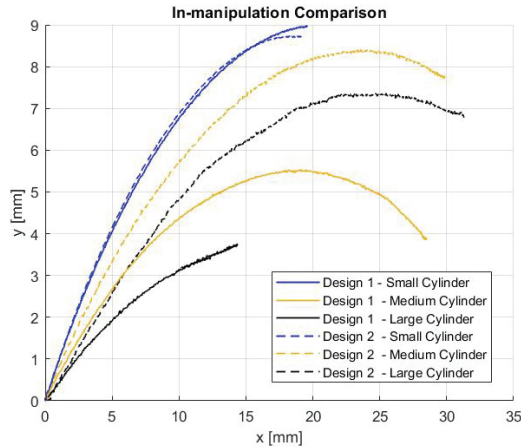


Fig. 11. A comparison of the two different hand designs developed in performing in-hand manipulation of different sized cylinders. The plot presents the different trajectories of the objects when manipulated by the two different designs. Design 1 represents the hand design with a thumb base capable of only opposition, and design 2 represents the hand design with a thumb base that can execute opposition and translation.

motions are presented in detail in Fig. 7 and Fig. 10. To further demonstrate the dexterity of the hand, several manipulation evaluation tests were performed. In these demonstrations, the hand executed pre-programmed manipulation motions with a sphere from the sensorized object set presented in [32] so as to showcase the range of manipulation motions that it can achieve. The sensorized objects were manipulated in two different poses at the borders of the dexterous manipulation workspace so as to demonstrate the hand's ability.

A comparison of the two versions of the proposed adaptive robot hand design was conducted employing three cylindrical objects of various diameters of the object set presented in [32]. The manipulation motion trajectories executed for the

particular experiment are depicted in Fig. 10 while the object trajectories are presented in Fig. 11. The object trajectories were collected with the Polhemus Liberty magnetic motion capture system equipped with a micro-magnetic sensor. When manipulating small objects like the small cylinder (as seen in Fig. 11), the manipulation trajectory that the two versions of the proposed adaptive robot hand are able to achieve is similar. However, for larger objects (see Fig. 10c and Fig. 10f), the addition of the translating DOF at the thumb base (reconfigurable base of the adaptive hand) allowed for adjusting of the aperture of the hand, achieving an increased in-hand manipulation workspace that resulted in a two times larger trajectory length when manipulating the large cylinder. By adjusting the hand aperture of the developed adaptive, humanlike robot hand, the manipulation capabilities of the device can be improved, allowing it to efficiently manipulate a wider range of objects without compromising the grasping performance.

#### D. Applications

To demonstrate the robust grasping and dexterous manipulation capabilities of the proposed adaptive, humanlike robot hand, we conducted a plethora of experiments focusing on the execution of a variety of complex tasks that are related to robotic applications in unstructured and dynamic environments. The tasks considered include: i) opening a beer bottle, ii) preparing toast, iii) drilling, and iv) lastly holding a pan while it experiences significant object disturbances. Images containing instances of the conducted experiments focusing on the different applications can be found in Fig. 8. A video demonstrating the efficiency of the robot hands can be found at the following URL:

[www.newdexterity.org/ndx](http://www.newdexterity.org/ndx)

#### IV. CONCLUSIONS

In this paper, we presented two versions of the New Dexterity adaptive human-like robot hand that are capable of performing robust grasps for a variety of everyday life objects. The first version has a fixed thumb base while the second design utilizes an additional DOF at the thumb base for increasing hand aperture, improving the in-hand manipulation capabilities without compromising grasping efficiency. The proposed reconfigurable palm provided a significant improvement in the dexterous manipulation workspace of the robot hand when manipulating different sized objects. The translating thumb position also allows the hand to adjust its aperture to improve its grasp stability when grasping objects of larger sizes. The force exertion observed in the two designs showed that having a translating thumb facilitates improved contact point selection for larger objects during power grasping allowing the hand to exert an additional 13.3 N on the largest dynamometer. The performances of the two designs were evaluated and compared through: i) force exertion tests using different dynamometer sizes, ii) grasping experiments involving a diverse set of everyday life objects, iii) in-hand manipulation experiments, and iv) execution of different everyday life tasks.

## REFERENCES

- [1] A. Kochan, "Shadow delivers first hand," *Industrial robot: an international journal*, 2005.
- [2] M. Grebenstein, A. Albu-Schäffer, T. Bahls, M. Chalon, O. Eiberger, W. Friedl, R. Gruber, S. Haddadin, U. Hagn, R. Haslinger *et al.*, "The dlr hand arm system," in *2011 IEEE International Conference on Robotics and Automation*. IEEE, 2011, pp. 3175–3182.
- [3] U. Kim, D. Jung, H. Jeong, J. Park, H.-M. Jung, J. Cheong, H. R. Choi, H. Do, and C. Park, "Integrated linkage-driven dexterous anthropomorphic robotic hand," *Nature communications*, vol. 12, no. 1, pp. 1–13, 2021.
- [4] S. Min and S. Yi, "Development of cable-driven anthropomorphic robot hand," *IEEE Robotics and Automation Letters*, vol. 6, no. 2, pp. 1176–1183, 2021.
- [5] A. Billard and D. Kragic, "Trends and challenges in robot manipulation," *Science*, vol. 364, no. 6446, 2019.
- [6] I. Akkaya, M. Andrychowicz, M. Chocieć, M. Litwin, B. McGrew, A. Petron, A. Paino, M. Plappert, G. Powell, R. Ribas *et al.*, "Solving rubik's cube with a robot hand," *arXiv preprint arXiv:1910.07113*, 2019.
- [7] J. Shintake, V. Cacucciolo, D. Floreano, and H. Shea, "Soft robotic grippers," *Advanced materials*, vol. 30, no. 29, p. 1707035, 2018.
- [8] L. U. Odhner and A. M. Dollar, "Stable, open-loop precision manipulation with underactuated hands," *The International Journal of Robotics Research*, vol. 34, no. 11, pp. 1347–1360, 2015.
- [9] L. U. Odhner, R. R. Ma, and A. M. Dollar, "Open-loop precision grasping with underactuated hands inspired by a human manipulation strategy," *IEEE Transactions on Automation Science and Engineering*, vol. 10, no. 3, pp. 625–633, 2013.
- [10] G. Robinson and J. B. C. Davies, "Continuum robots—a state of the art," in *Proceedings 1999 IEEE international conference on robotics and automation (Cat. No. 99CH36288C)*, vol. 4. IEEE, 1999, pp. 2849–2854.
- [11] C. Erdogan, A. Schröder, and O. Brock, "Coordination of intrinsic and extrinsic degrees of freedom in soft robotic grasping," in *2018 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2018, pp. 4251–4256.
- [12] J. M. Gómez-de Gabriel and H. A. Wurdemann, "Adaptive underactuated finger with active rolling surface," *IEEE Robotics and Automation Letters*, vol. 6, no. 4, pp. 8253–8260, 2021.
- [13] M. G. Catalano, G. Grioli, E. Farnioli, A. Serio, C. Piazza, and A. Bicchi, "Adaptive synergies for the design and control of the pisa/iit soft hand," *The International Journal of Robotics Research*, vol. 33, no. 5, pp. 768–782, 2014.
- [14] G. Gao, L. Gerez, and M. Liarokapis, "Adaptive, tendon-driven, affordable prostheses for partial hand amputations: On body-powered and motor driven implementations," in *2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, 2019, pp. 6656–6660.
- [15] O. Khatib, X. Yeh, G. Brantner, B. Soe, B. Kim, S. Ganguly, H. Stuart, S. Wang, M. Cutkosky, A. Edsinger *et al.*, "Ocean one: A robotic avatar for oceanic discovery," *IEEE Robotics & Automation Magazine*, vol. 23, no. 4, pp. 20–29, 2016.
- [16] L. U. Odhner, L. P. Jentoft, M. R. Claffee, N. Corson, Y. Tenzer, R. R. Ma, M. Buehler, R. Kohout, R. D. Howe, and A. M. Dollar, "A compliant, underactuated hand for robust manipulation," *The International Journal of Robotics Research*, vol. 33, no. 5, pp. 736–752, 2014.
- [17] Y.-J. Kim, H. Song, and C.-Y. Maeng, "Blt gripper: An adaptive gripper with active transition capability between precise pinch and compliant grasp," *IEEE Robotics and Automation Letters*, vol. 5, no. 4, pp. 5518–5525, 2020.
- [18] G. Gao, J. Chapman, S. Matsunaga, T. Mariyama, B. MacDonald, and M. Liarokapis, "A dexterous, reconfigurable, adaptive robot hand combining anthropomorphic and interdigitated configurations," in *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2021, pp. 7209–7215.
- [19] N. Elangovan, L. Gerez, G. Gao, and M. Liarokapis, "Improving robotic manipulation without sacrificing grasping efficiency: A multi-modal, adaptive gripper with reconfigurable finger bases," *IEEE Access*, 2021.
- [20] Z. Chen, N. Y. Lii, T. Wimboeck, S. Fan, M. Jin, C. H. Borst, and H. Liu, "Experimental study on impedance control for the five-finger dexterous robot hand dlr-hit ii," in *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2010, pp. 5867–5874.
- [21] L. U. Odhner, R. R. Ma, and A. M. Dollar, "Precision grasping and manipulation of small objects from flat surfaces using underactuated fingers," in *2012 IEEE International Conference on Robotics and Automation*. IEEE, 2012, pp. 2830–2835.
- [22] K. Mitsui, R. Ozawa, and T. Kou, "An under-actuated robotic hand for multiple grasps," in *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2013, pp. 5475–5480.
- [23] A. G. Zisimatos, M. Liarokapis, C. I. Mavrogiannis, and K. J. Kyriakopoulos, "Open-source, affordable, modular, light-weight, underactuated robot hands," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2014, pp. 3207–3212.
- [24] D. Ospina and A. Ramirez-Serrano, "Sensorless in-hand manipulation by an underactuated robot hand," *Journal of Mechanisms and Robotics*, vol. 12, no. 5, p. 051009, 2020.
- [25] N. Elangovan, L. Gerez, G. Gao, and M. Liarokapis, "A multi-modal robotic gripper with a reconfigurable base: Improving dexterous manipulation without compromising grasping efficiency," in *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2021, pp. 6124–6130.
- [26] J. Borràs and A. M. Dollar, "Dimensional synthesis of three-fingered robot hands for maximal precision manipulation workspace," *The International Journal of Robotics Research*, vol. 34, no. 14, pp. 1731–1746, 2015.
- [27] R. R. Ma, J. T. Belter, and A. M. Dollar, "Hybrid deposition manufacturing: design strategies for multimaterial mechanisms via three-dimensional printing and material deposition," *Journal of Mechanisms and Robotics*, vol. 7, no. 2, p. 021002, 2015.
- [28] B. Calli, A. Walsman, A. Singh, S. Srinivasa, P. Abbeel, and A. M. Dollar, "Benchmarking in manipulation research: Using the yale-cmu-berkeley object and model set," *IEEE Robotics & Automation Magazine*, vol. 22, no. 3, pp. 36–52, 2015.
- [29] M. Quigley, K. Conley, B. P. Gerkey, J. Faust, T. Foote, J. Leibs, R. Wheeler, and A. Y. Ng, "ROS: an open-source Robot Operating System," in *ICRA Workshop on Open Source Software*, 2009.
- [30] J. Chapman, A. Dwivedi, and M. Liarokapis, "A wearable, open-source, lightweight forcemyography armband: On intuitive, robust muscle-machine interfaces," in *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2021, pp. 4138–4143.
- [31] D. Shieff, A. Turner, A. Dwivedi, G. Gorjup, and M. Liarokapis, "An electromyography based shared control framework for intuitive robotic telemanipulation," in *2021 20th International Conference on Advanced Robotics (ICAR)*. IEEE, 2021, pp. 806–811.
- [32] G. Gao, G. Gorjup, R. Yu, P. Jarvis, and M. Liarokapis, "Modular, accessible, sensorized objects for evaluating the grasping and manipulation capabilities of grippers and hands," *IEEE Robotics and Automation Letters*, vol. 5, no. 4, pp. 6105–6112, 2020.
- [33] National Institute of Standards and Technology, "Grasping performance metrics and test methods," <https://www.nist.gov/el/intelligent-systems-division-73500/robotic-grasping-and-manipulation-assembly/grasping>, accessed: 2022-15-9.