# LEAP Hand V2: Dexterous, Low-cost Anthropomorphic Hybrid Rigid Soft Hand for Robot Learning

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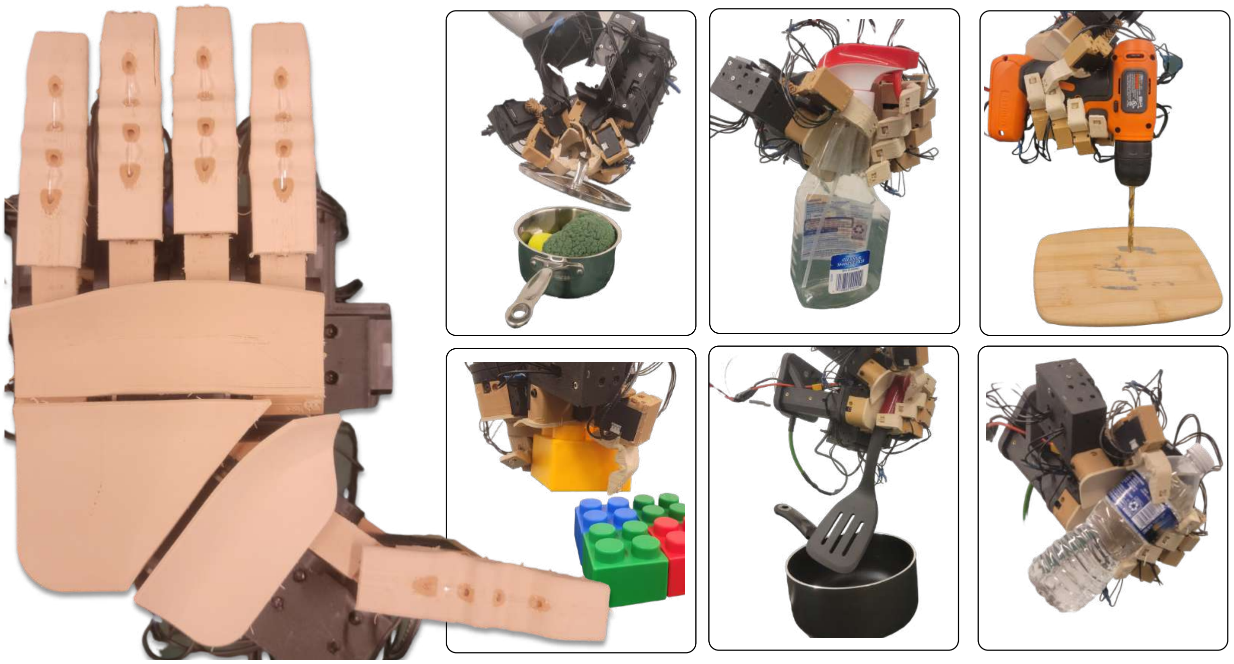

Fig. 1: Presenting DLA Hand, a robot hand designed to emulate the compliance of the human hand. It features a 3D-printed soft exterior skin complemented by a robust internal bone structure. The foldable palm incorporates two powered articulations—one spanning the four fingers and another across the thumb—facilitating human-like grasping. Additionally, a dexterous MCP joint enhances overall dexterity, resembling human hand movements. With its human-like size, straightforward assembly, cost-effectiveness, and open-source attributes, DLA Hand will be useful for dexterous hand research.

***Abstract*—The human hand is a remarkable feat of biology, offering remarkable versatility and precision with many joints and muscles working in tandem. It enables us to adeptly handle intricate tools with great strength. Yet, it retains a soft, secure, and yielding nature for delicate objects. This fusion of formidable strength and gentle compliance renders it an unparalleled manipulative instrument. However, robot hands attempting to emulate this have often fallen into one of two categories: soft or rigid. Soft hands, while compliant and safe lack the precision and strength of human hands. Conversely, while rigid robot hands can match the precision and power of human hands, they are brittle and do not conform to their environment. Our proposed solution is to build a robotic hand that *bridges the gap* between these two categories. We call this hand DLA Hand, a dexterous, $3000, simple anthropomorphic soft hand that is extremely dexterous and versatile. First, it achieves a balance of human-hand-like softness and stiffness via a 3d printed soft exterior combined with a 3d printed internal bone structure. Next, DLA Hand incorporates two powered articulations in the foldable palm: one spanning the four fingers and another near the thumb—mimicking the essential palm flexibility for human-like grasping. Lastly, DLA Hand boasts a dexterous Metacarpophalangeal (MCP) kinematic structure, making it highly human-like, easy to assemble, and versatile. Through thorough real-world experiments, we show that DLA Hand exceeds the capabilities of many existing robot hands for grasping, teleoperated control, and imitation learning. We plan to release 3D printer files and assembly instructions on our website for the dexterous hand research community to use.**

## I. Robot Hand Design

DLA Hand is crafted to closely mimic the intricacies of the human hand and to provide the advantage of both rigid robotic hands, as well as soft ones, while still being easy to produce. This is enabled by three distinctive features not commonly found in readily available robotic hands: (1) The hand exhibits human-like softness and stiffness achieved through the 3D printing of a soft exterior complemented by a rigid internal bone structure. (2) DLA Hand incorporates two powered articulations in the palm, one spanning across the four fingers and another near the thumb, replicating the crucial palm flexibility essential

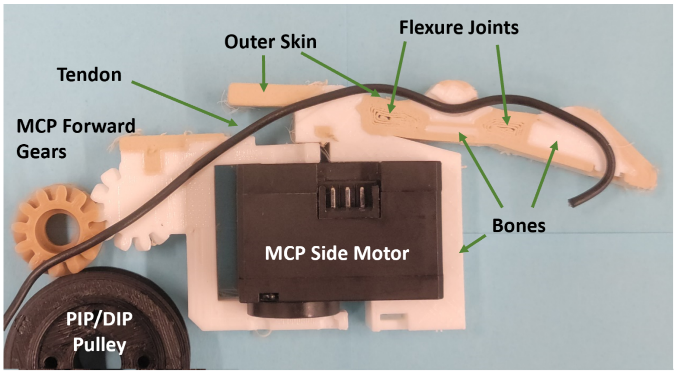

Fig. 3: A cross-section of the 3D printed finger showing the soft rubber joints, hard PLA bones, and resilient, dense outer skin. The MCP forward is connected by gears to a motor, the MCP side rotates using an embedded motor, and the PIP and DIP joints are actuated together by a tendon connected to a pulley. The total range of the MCP forward joint is 90 degrees, the MCP side can move 180 degrees, and the PIP and DIP joints can each fold by 90 degrees.

for human-like grasping. (3) DLA Hand boasts a dexterous Metacarpophalangeal (MCP) kinematic structure, rendering the hand highly human-like, easy to construct, and versatile for a wide variety of tasks. We find that the combination of these three allows for DLA Hand to have all of the advantages of both rigid and soft robotic hands, just like a human hand.

### A. 3D Printed Bones and Skin

The pliability of human hands allows them to adapt to objects and their surroundings during interactions such as grasping. [1, 2] For instance, when reaching for a delicate object, the hand conforms around the object and applies safe pressure. When bumping into a table, our fingers will bend out of the way and not snap. To emulate this, the soft robotics community often uses a casting procedure to make soft robots. [3, 4] However, this often makes robot hands too compliant in under-actuated directions which is undesirable. On the other hand, some robot hands such as LEAP Hand or Shadow Hand are made up of purely rigid joints. While they are strong, they do not conform to their environment like a human hand and exhibit brittleness and a tendency to snap upon contact. Finally, many other hands such as [5, 6] try to make the joints similar to the softness of a human hand but they are incredibly complicated and hard to reproduce. Our goal is to fabricate conformal fingers with stiffness properties closely resembling those of a human finger, aiming to replicate both its softness and rigidity.

Selecting the right materials is very important. For the soft outer skin, Colorfabb Varioshore or Filaflex Foamy is chosen due to its ability to adjust TPU rubber density based on the flow rate and temperature of the 3D printer nozzle. [7] The change of density allows for the change of flexibility of the skin within different parts. Underneath the skin and within the fingers, we opt for PLA, known for its rigidity and smooth texture. The 3D printer used is an Independent Dual Extrusion (IDEX) printer, specifically the $1000 Snapmaker J1S [8]. This printer allows for the simultaneous use of two materials automatically in one seamless print.

### B. Palm Articulation

When human hands grip objects, the palm folds to conform to the specific shape of the object being grasped. This adaptive behavior allows the hand to firmly enclose the object and support it from many angles. Two pivotal articulations contribute to this capability. Firstly, the CMC joint, situated between the thumb and the palm, facilitates both the movement of the thumb towards the rest of the hand and the articulation of the palm itself. Second, the MCP forward joint and CMC joint in the human fingers also apply a downward force on the palm to make it fold. The synergy of these articulated motions improves grasping capabilities and fosters a better closure around objects.

Many robot hands such as Allegro, LEAP Hand, and DASH Hand have flat palms that do not conform to the environment [9, 10, 11]. This means that their grasps against objects are flat and not very stable. Others such as Psyonic [12] only have a few degrees of freedom. Some advanced robot hands such as Shadow Hand [13] have a CMC joint across the palm to try and emulate this behavior. However, this hand is very expensive and fragile because of its tendons driving its palm articulations.

To rectify this issue, DLA Hand emulates the two articulations in the human palm as seen in Figure 4. These points are placed in the same locations that humans have them in their hands and are independently actuated by strong motors placed just below the replaceable skin of the palm. This direct-drive nature makes them accurate, strong, and simple to produce. The initial motor located near the thumb replicates the natural CMC fold of the thumb. This fold enables the skin in the palm area near the thumb to provide support for objects upon contact. It facilitates the thumb's movement toward the other fingers, enhancing its ability to approach and oppose them effectively. This feature is crucial for achieving significant pinch grasps. Second, we emulate the fold across the entire palm near the MCP joints of the hand. This emulates the human hand, where its MCP joints not only articulate the fingers but also part of the palm and allow the fingers to conform to objects better.

### C. Dexterous Finger Kinematics

The human finger, characterized by its compact size, strength, and numerous degrees of freedom, presents a considerable challenge to replicate in robot hands. Traditional attempts to emulate it often involve reducing the number of degrees of freedom (DOF) to simplify construction and actuation, as seen in robot hands like Psyonic, Inmoov, or Tesla Optimus [12, 14, 15]. However, this approach significantly restricts the range of possible grasps. Other hands, such as the Shadow Hand, maintain a substantial number of DOF, but their production is exceedingly complex and comes with a high cost and a 4.5kg weight [13]. On the other hand, hands like LEAP Hand and Allegro preserve most of the DOF found in a human hand but are much larger [10, 16].

In DLA Hand, we introduce a simple, yet effective finger kinematic design to create a small, highly actuated, strong robot hand that is very human-like. This simple design contains all

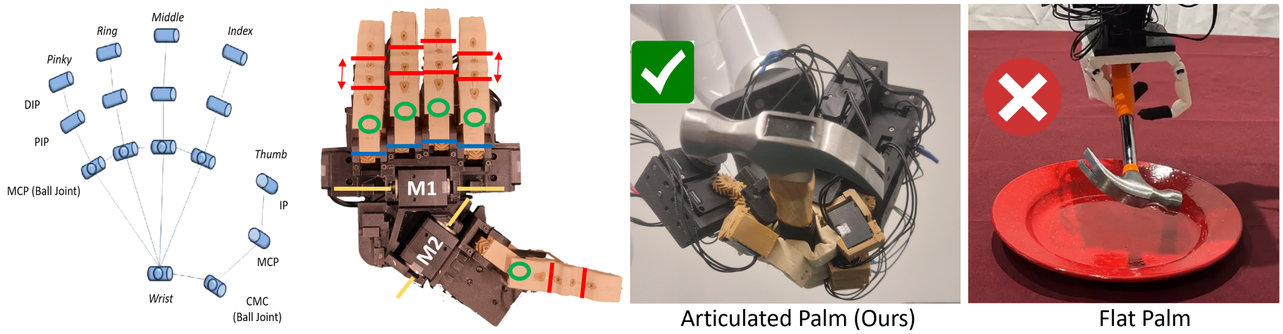


Fig. 4: **Kinematic Tree:** From Left to right. 1) The kinematic tree of DLA Hand is similar to a human hand. 2) The palm skin is removed to reveal structure with yellow lines for the palm articulations. The blue lines represent the MCP forward, the green circles represent the MCP side. The PIP and DIP are articulated together and are represented in red. Total: 22 joints powered by 17 motors. 3) This human-like palm kinematics allows it to grasp a hammer better than a hand with a flat palm.

of the 4 DOF of a human hand by using three motors while remaining easy to produce. The key part of this design is to store powerful motors densely in the palm while transferring as much power as possible to the fingers. This makes our robot hand useful for the demands of a large variety of different tasks that humans complete in their everyday lives.

*1) PIP and DIP*

Within the human hand, the PIP and DIP joints are inherently linked, allowing them to adapt and conform around objects. Our goal is to replicate this behavior in robot hands. While the instinctive approach involves placing motors directly in the fingers at these joints, this results in a bulky and weighty robot finger. Upon closer examination, this approach does not align with the natural functioning of the human hand. In reality, the human hand relies on muscles in the wrist to transfer power to the fingertips through tendons.

To mimic human tendons in a robot hand, we position the motor lower in the palm and have it transmit power through a synthetic tendon (1mm diameter 100 lb. fishing line). This means that the motor can be large and powerful, but far away from the fingers themselves. Many tendon-based hands such as Shadow hand require many tendons because of the spring-back requirements of the joints. We can use only one tendon per finger which is very easy to route. This is because the soft TPU rubber material acts as a flexure joint when pulled and acts as a built-in spring and returns to the open position once the tension on the tendon is released. This gives the hand very strong curling strength with the motor and a good return to open. One downside is that this makes the PIP and DIP joints coupled together in actuation, but this is natural for human hands as well. The coupling of these joints gives a natural conforming nature around objects, which makes DLA Hand very effective at grasping.

## II. Fabrication and Software Details

### A. Assembly Information

DLA Hand can easily be built by a novice roboticist in a few hours and only requires simple hand tools and a 3D printer to assemble. It weighs about 1.5kg and can be mounted on most commodity robot arms.

### B. 3D printing

How can the fabrication and assembly of a sophisticated robot hand be so simple? Despite the complexity and multi-material nature of these parts, accomplishing the task becomes straightforward with a dual nozzle 3D printer equipped with precisely calibrated settings. Remarkably, we observe that these settings are transferable to two entirely distinct 3D printers, enabling easy replication of the parts by anyone.

The intricacy of the 3D-printed components results in significant portions of the hand being incorporated into a single printable piece, simplifying the assembly process. For instance, the finger is printed as one multi-material piece and is attached to the palm using under 10 screws. The whole palm is three frame pieces that are easily connected using a few motors. With this, the whole hand can be assembled with under 100 screws and 5 easy-to-pull tendons in a couple of hours.

### C. Controlling Soft Fingers

The compliance of soft material makes it impossible to know the full state of it by using sensors such as encoders. In our system, we have two soft flexure joints in between the bones of the fingers that are actuated by one tendon on one pulley. The rigid internal structure of the fingers prevents the soft fingers from flexing too much in undesirable directions and makes the characteristics of our fingers more deterministic when not under extreme load. There are two parts to this control system: calibration and retensioning. In calibration, we attach an AR tag to the fingertip and track its location relative to the base joint. We find that this behavior is mostly linear so we learn a simple second-order model for each of PIP and DIP that maps motor angle to finger joint positions. This only needs to be calculated once. However, since the material and tendon could change over time we also must adjust to it. To do this, we use the current control mode for the motor to find the fully-tensioned and untensioned positions of the finger automatically. We save this as an offset term to use at test time.

## III. DLA Hand Applications

An important way to assess the capabilities is to assess our hand's performance directly at its end goal: How well can it complete tasks we expect robot hands to perform? First, DLA Hand is tested on grasping against a variety of other hands.

Second, DLA Hand is teleoperated by an expert operator using a Manus Meta glove DLA Hand and a xArm. We choose a variety of different tasks that outline different grasps that humans can perform. Finally, we collected 75 demos through teleoperation on two different tasks. We train autonomous policies and see how DLA Hand performs during this whole learning process which requires resiliency and accuracy.

### *A. Teleoperation Results*

Because the kinematic structure is so similar between the human and DLA Hand, it is easy for the operator to teleoperate it. To achieve this, we use a motion capture glove from Manus Meta to operate DLA Hand. The joint outputs directly from the motion capture glove from Manus Meta are used to operate the robot hand. While an energy function such as from Dexpilot [17] or Robotic Telekinesis [18] can be used, we find that this is not required due to the similarity of kinematics between the human and robot hand. The Ufactory xArm 850 robot arm is controlled by a SteamVR-based outside-in tracking system mounted on the wrist of the human operator.

To test the effectiveness of the system, human teleoperates the hand for 10 different tasks. These tasks are inspired by Vazhapilli et. al. [19], Mannam et. al. [11], [20] and [17]. These tasks are designed to test many different types of grasps, both prehensile and non-prehensile as well as power, pinch, precision, and many others.

Thanks to its strong articulated palm, DLA Hand can complete teleoperation very well. For instance, the drill and hammer are very firmly grasped inside the palm and MCP joints of the palm and cannot be easily removed.

The finger is very strong but also flexible. One can observe that the fingers are lifting very heavy weights and objects. The finger is also curling very tight to grasp small-diameter objects. However, when the finger is in contact with the table, it smoothly bends away from the table and does not break or snap. This is thanks to its robotic skin and inner-bone structure as outlined in I-A.

### *B. Learning from Human Demonstration Results*

In robot learning, researchers often want to collect human demonstrations to train autonomous policies. Learning from demonstration puts difficult requirements on robot hardware. DLA Hand must collect hundreds of demonstrations consistently without overheating, losing accuracy, or breaking. DLA Hand must be resistant to bumps and scrapes while researchers quickly teleoperate the hand using strong robot arms. DLA Hand must be able to perform even with non-smooth and jittery behavior cloning policies.

To test this we collect 75 demonstrations per task through the teleoperation of DLA Hand and the xArm. These tasks are lifting a heavy hammer and picking up a red cup. Thankfully, in the data collection process, we do not observe any degradation of the behavior. We verified this by playing back the first demonstration we collected after collecting 74 more. We find that DLA Hand consistently performed the same actions over and over again without tiring or degrading.

| Task | Teleoperation | Behavior Cloning |
|---|---|---|
| Red Cup | 0.92 | 0.8 |
| Hammer Pickup | 0.89 | 0.6 |

TABLE I: We collect 75 demos of DLA Hand completing two different tasks. We then train policies, pre-trained on internet videos, and fine-tuned on our robot hand demos, and report our results as a percentage of success.

Fig. 5: **Simulation Test:** DLA Hand can be imported into most simulators and can be faithfully recreated for sim2real purposes. We will release videos and the example task of in-hand reorientation to encourage the community to continue to build different tasks onto this robot hand.

Once the policies were trained, they were rolled out on the robot. In Table I we see that DLA Hand continually performs and can provide good performance on these rollouts. Please see the supplemental for further information on the training procedures, the architecture of the models, and results.

### *C. Simulation Modelling and Reinforcement Learning*

In robot learning research, one often would like to use simulation to debug ideas or transfer policies to the real world learned from simulation. To this end, we create a URDF and MJF that can be successfully imported into MuJoco or Isaac Gym. One difficulty is that it is difficult to simulate hybrid soft-hard material of the fingers in these simulators. However, the soft material in the hand has a shore hardness of 85a which is similar to a leather belt, the rubber soles of your shoes, or tire treads. Combined with the PLA makes it behave similar to a normal rigid hand with grip tape. Therefore, while Isaac Gym only has limited support for soft materials, the finger joints can be successfully modelled as rigid body rotational joints similar to many other robot hands. We highly recommend using Isaac Gym due to the fast GPU training abilities even with tendons at the current time of writing.

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