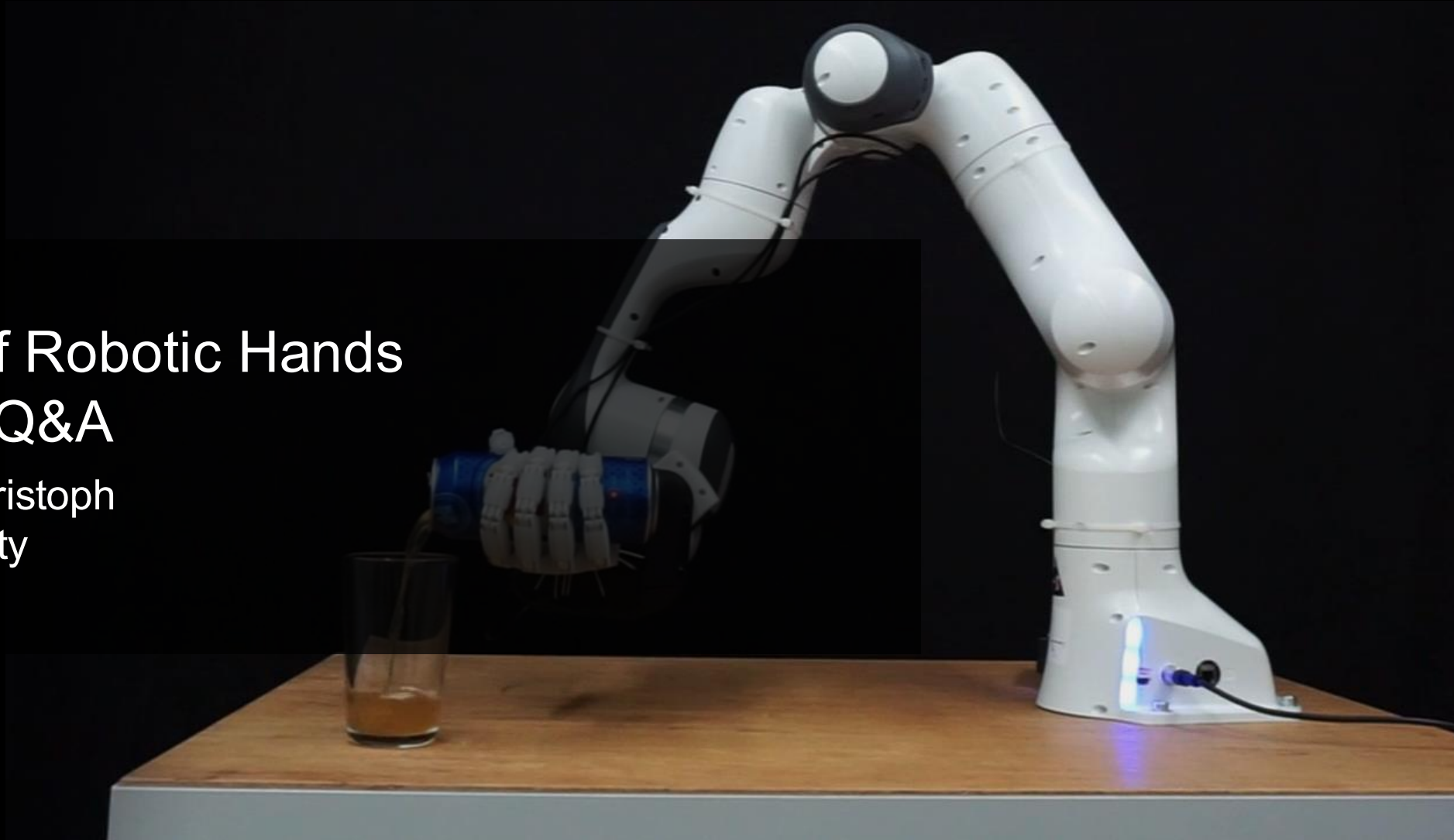




Design of Robotic Hands Focus & Q&A

Clemens Christoph
Orca Dexterity



External Design Constraints



Task

- Flight
- Locomotion
- Manipulation
- Medical

Scale

- μm (Micro robots)
- mm
- cm
- dm
- m (Elephant-like)

Environment

- Air
 - Low density
 - Gusts of wind
- On ground
 - Power density
 - Rough terrain
- Water
 - Watertightness
 - Density of water
- On or inside a living being
 - Small size
 - Compatibility

Dexterous manipulation task at dm-scale in air or on ground



Swift coordination



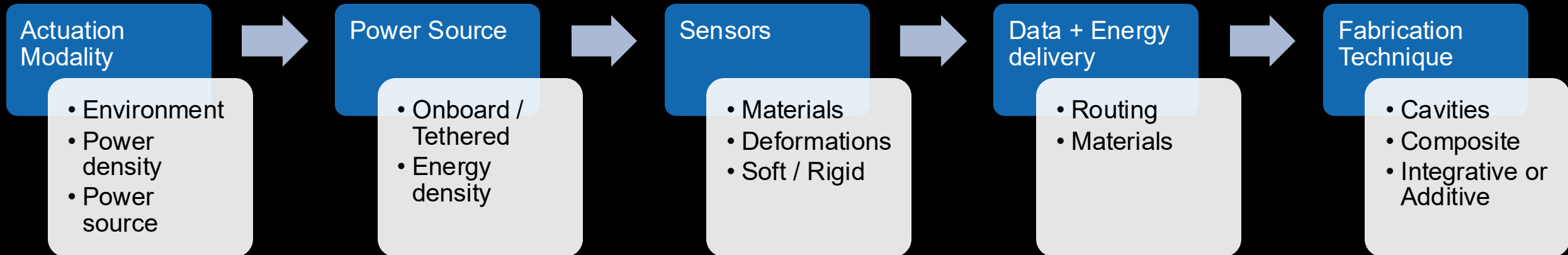
Multi-tasking



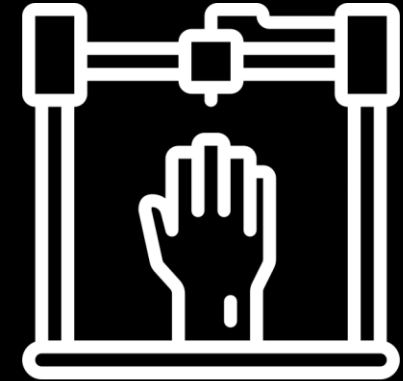
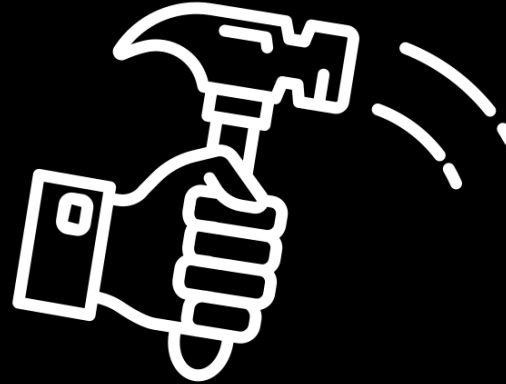
Fast chopping



Internal Design Constraints



Example Design Constraints for a Robotic Gripper



Anthropomorphic

- Proportions
- Trajectories
- Proprioception

Robust

- Durable
- Strong
- Reliable

Low-Cost Fabrication

- Reduced number of parts
- 3D Printable
- Simple injection-molding
- Off-the shelf components

Image sources from left to right:

https://ceti.one/wp-content/uploads/2018/09/human-hand_960.png

<https://thenounproject.com/icon/construction-3997459/>

<https://thenounproject.com/icon/3d-hand-print-3511765/>

Example: Actuation Modality for a Robotic Gripper



At joint

- Inflating bellows introduce bending motion
- Highly integrated
- Intrinsic compliance
- Bulky



Away from joint

- Move joint with tendons
- Modularity
- Shown to be stronger
- More anthropomorphic

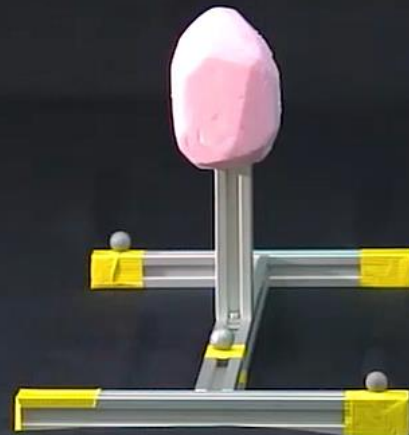
1. Images source (from left to right):
2. https://cdn0.nwcdn.com/wp-content/blogsdir/1/files/2017/10/SoftRobotics_Picking_Tomato.jpg
3. Tavakoli, M., Batista, R., & Sgrigna, L. (2016). The UC soft hand: Light weight adaptive bionic hand with a compact twisted string actuation system. *Actuators*, 5(1). <https://doi.org/10.3390/ACT5010001>

Simple Linkage Designs



1. <https://www.bostondynamics.com/products/spot/arm>
2. <https://www.businesswire.com/news/home/20200305005216/en/Dexai-Robotics-Announces-Oversubscribed-Funding-Round-to-Launch-Alfred-a-Robotic-Sous-chef>
3. <https://everydayrobots.com/technology>

Two-fingered Soft Gripper in Air



Appius, Aurel X., et al. "Raptor: Rapid aerial pickup and transport of objects by robots." *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2022.

Bauer, Erik, Barnabas Gavin Cangan, and Robert K. Katzschmann. "Autonomous Vision-based Rapid Aerial Grasping." *arXiv preprint arXiv:2211.13093* (2022).



1x

Commercial Gripper Choices: Robust or Dexterous



Robust (and simple)

- Simple design
- Limited capabilities

Dexterous

- Highly biomimetic
- Fragile

Image source (from left to right):

- Hand-E Adaptive Gripper: <https://www.universal-robots.com/media/1808165/product-picture.jpg>
- Franka Emika Hand: <https://wiredworkers.io/product/franka-emika-hand/>

Image source (from left to right):

- Shadow Dexterous Hand: <https://www.shadowrobot.com/dexterous-hand-series/>
- Xu, Z., & Todorov, E. (2016). Design of a highly biomimetic anthropomorphic robotic hand towards artificial limb regeneration. *Proceedings - IEEE International Conference on Robotics and Automation*, 2016-June, 3485–3492. <https://doi.org/10.1109/ICRA.2016.7487528>

The challenge for an anthropomorphic hand



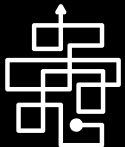
The Problem



Conventional robotic grippers **lack versatility**



Humanoid robotic hands are **expensive** and complex



Humanoid robotic hands are **complicated** and require programming expertise

The Desired Solution



Versatile & Dexterous

One universal robotic hand for a large range of use-cases with different grasp types and re-orientation motions



Cost-Efficient

Simplified joint design optimized for easy and cost-effective fabrication



Easy-to-use

Reduced programming effort by using gesture-based control

Motors in Joints



Allegro Hand



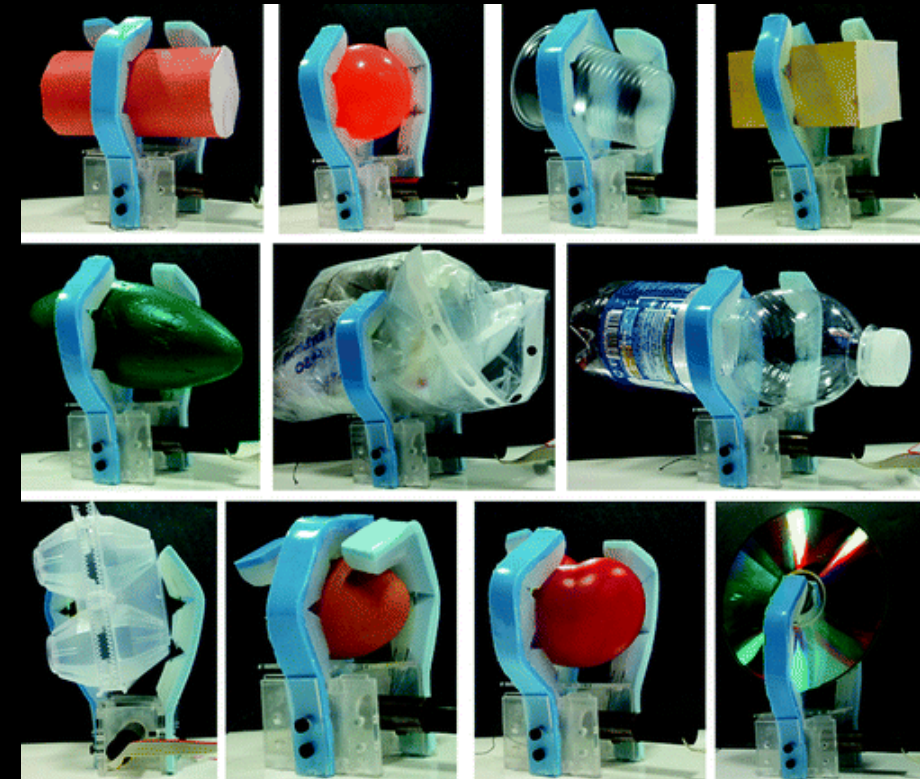
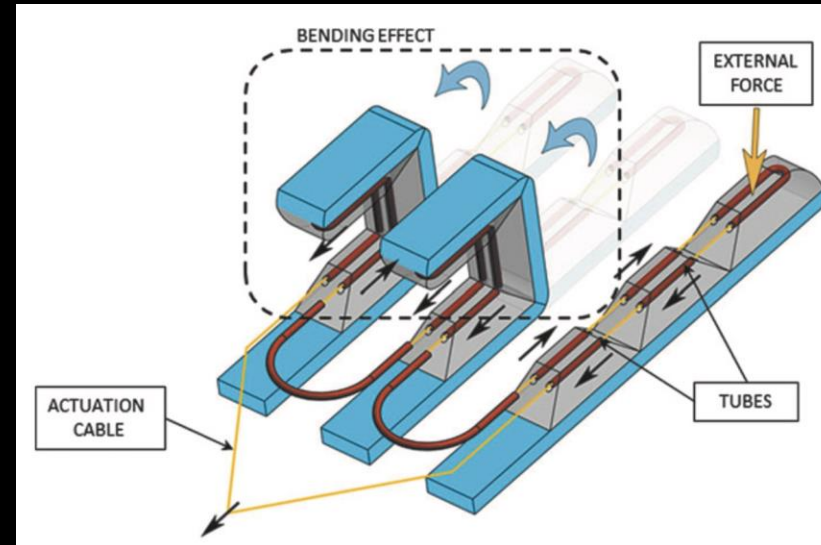
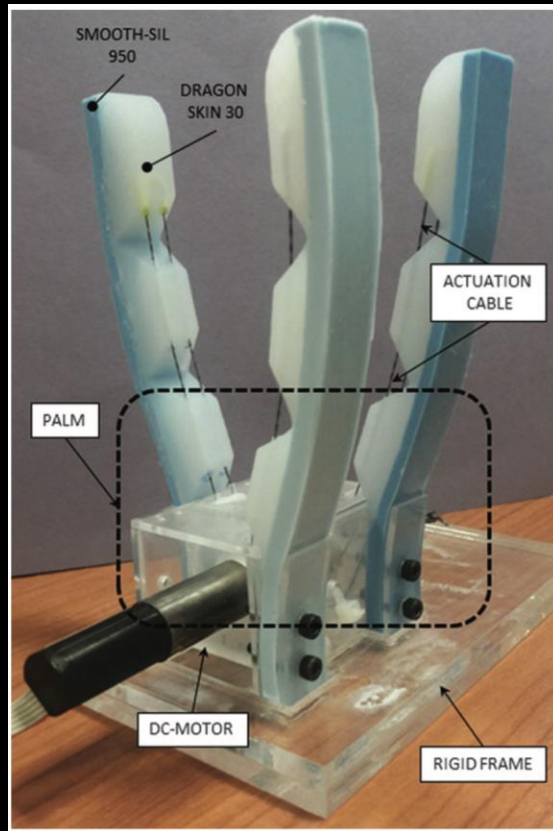
<https://www.wonikrobotics.com/research-robot-hand>

Schunk SVH Hand



https://schunk.com/us/en/gripping-systems/special-gripper/svh/c/PGR_3161

Tendon Driven – Grasping

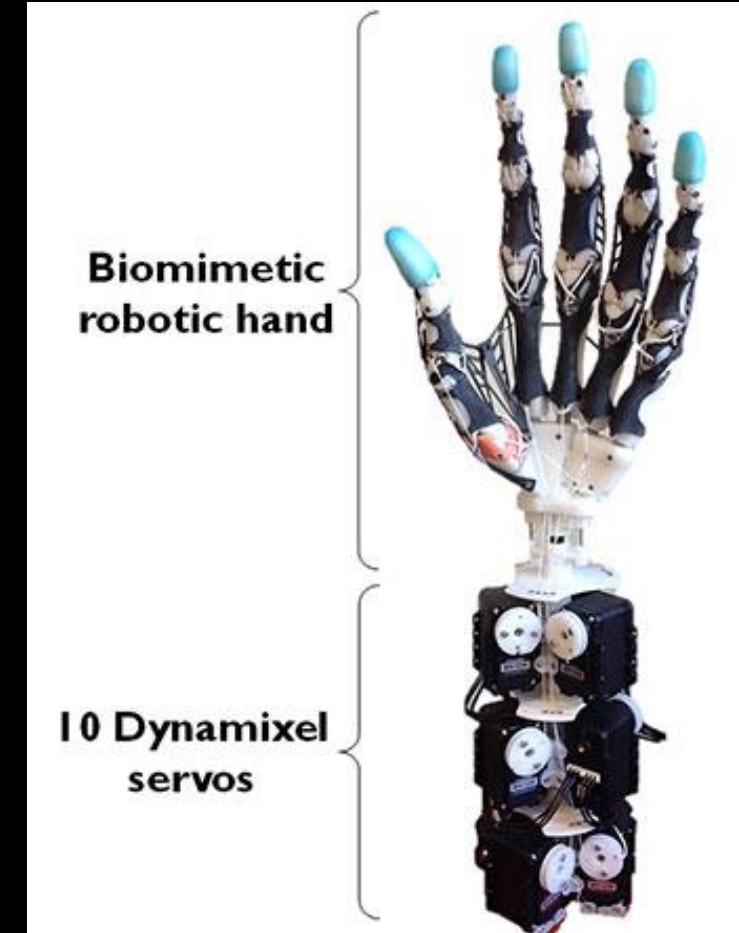


M. Manti, T. Hassan, G. Passetti, N. D'Elia, C. Laschi, and M. Cianchetti, "A Bioinspired Soft Robotic Gripper for Adaptable and Effective Grasping," *Soft Robotics*, vol. 2, no. 3, pp. 107–116, Sep. 2015, doi: [10.1089/soro.2015.0009](https://doi.org/10.1089/soro.2015.0009).

Tendon Driven Actuation – Design Principles



- Tendon
 - Extensible or in-extensible
- Routing
 - Channels guiding the tendon
- Power source
 - Electric motor
 - Battery
 - Tethered

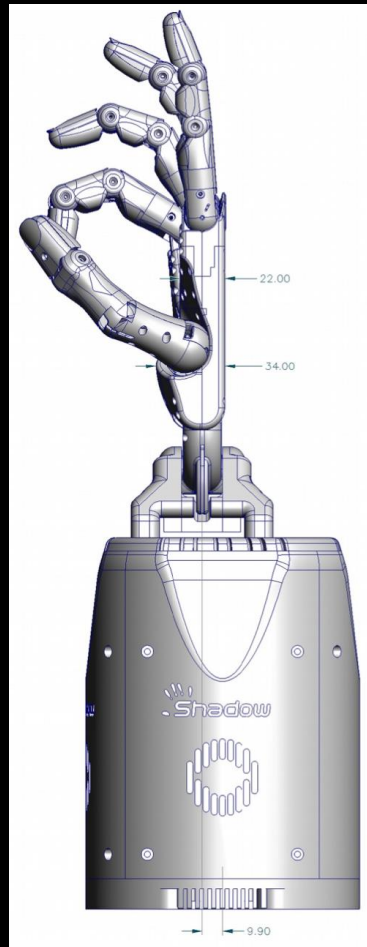


Zhe Xu and E. Todorov, "Design of a highly biomimetic anthropomorphic robotic hand towards artificial limb regeneration," 2016 IEEE International Conference on Robotics and Automation (ICRA), Stockholm, Sweden, 2016, pp. 3485-3492, doi: 10.1109/ICRA.2016.7487528

Pin Joint Type



Weiner, P., Starke, J., Hundhausen, F., Beil, J., & Asfour, T. (2018). The KIT Prosthetic Hand: Design and Control. *IEEE International Conference on Intelligent Robots and Systems*, 3328–3334. <https://doi.org/10.1109/IROS.2018.8593851>



Shadow Dexterous Hand :
<https://www.shadowrobot.com/dexterous-hand-series/>

Pin

- Classical approach
- Breaks on overstress
- Difficult manufacturing

Flexure Joint Type



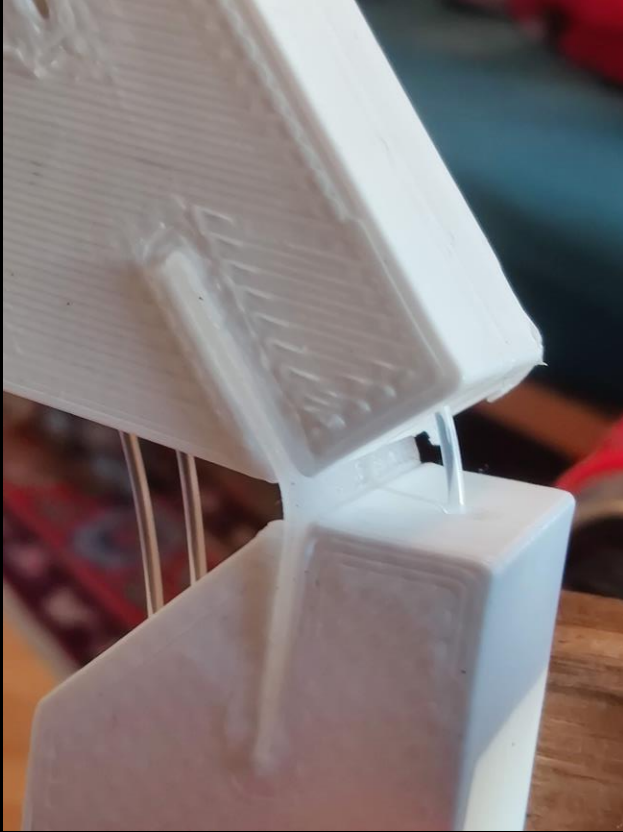
Flexure

- Simple manufacturing
- Low Friction
- Prone to wear
- Low cost if injection molded

Images source (from left to right):

- Tavakoli, M., Batista, R., & Sgrigna, L. (2016). The UC soft hand: Light weight adaptive bionic hand with a compact twisted string actuation system. *Actuators*, 5(1). <https://doi.org/10.3390/ACT5010001>
- Yale OpenHand Model Q, <https://www.eng.yale.edu/grablab/openhand/images/hand%20-%20q.png>

Examples of Flexure-based Joint Designs for Fingers

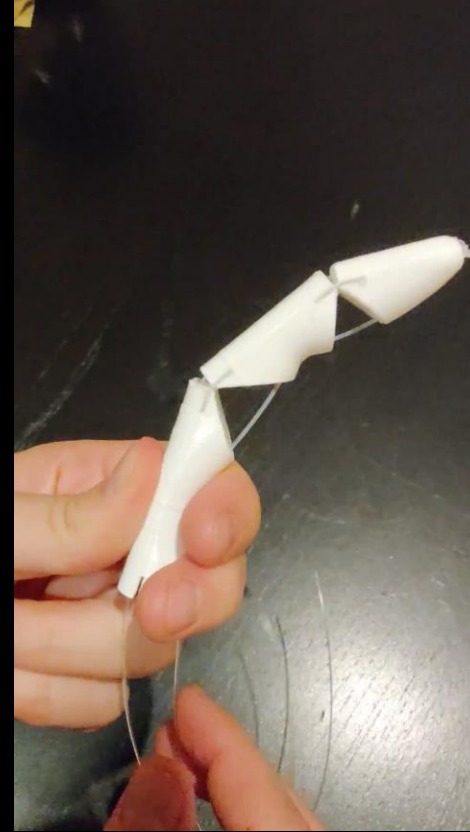


Flexure joint using
polypropylene sheets

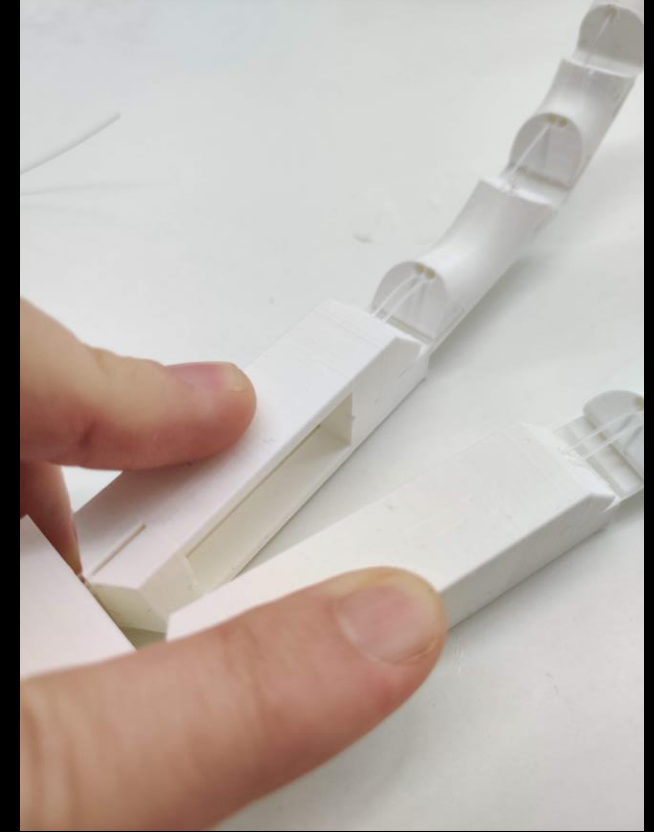
Lauener et al. 2022



Individual finger design

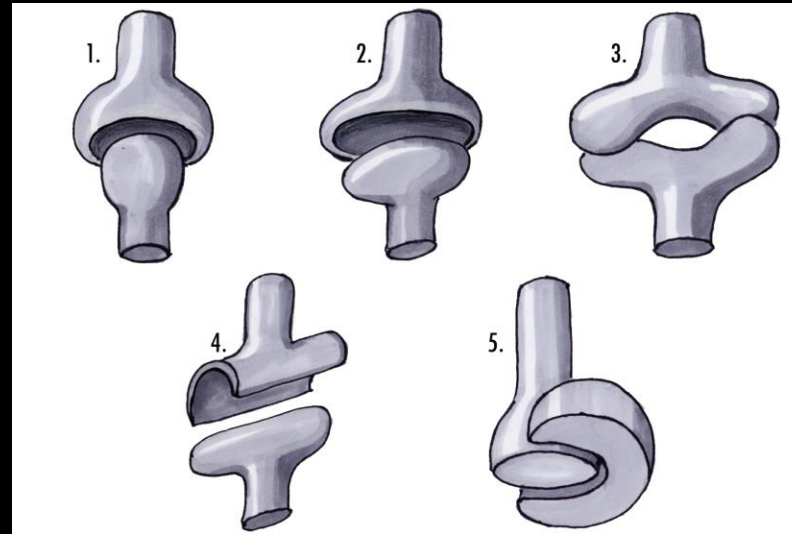


Refined geometries



Two finger gripper with added
adduction/abduction

Joint Type: Synovial



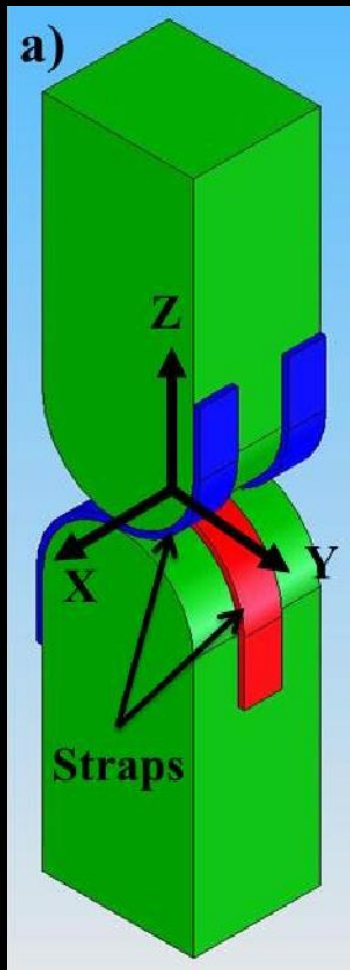
https://en.wikipedia.org/wiki/Ball-and-socket_joint#/media/File:Gelenke_Zeichnung01.jpg

Synovial

- Difficult to build
- Biomimetic
- Dislocate instead of breaking
- Potentially high cost

Xu, Z., & Todorov, E. (2016). Design of a highly biomimetic anthropomorphic robotic hand towards artificial limb regeneration. *Proceedings - IEEE International Conference on Robotics and Automation, 2016-June*, 3485–3492. <https://doi.org/10.1109/ICRA.2016.7487528>

Joint Type: Rolling Contact



Slocum, A.H. (2013). *Rolling contact orthopaedic joint design*.



Kim, Y.-J., Yoon, J., & Sim, Y.-W. (2019). Fluid Lubricated Dexterous Finger Mechanism for Human-Like Impact Absorbing Capability. *IEEE Robotics and Automation Letters*, 4(4), 3971–3978. <https://doi.org/10.1109/LRA.2019.2929988>

Rolling Contact

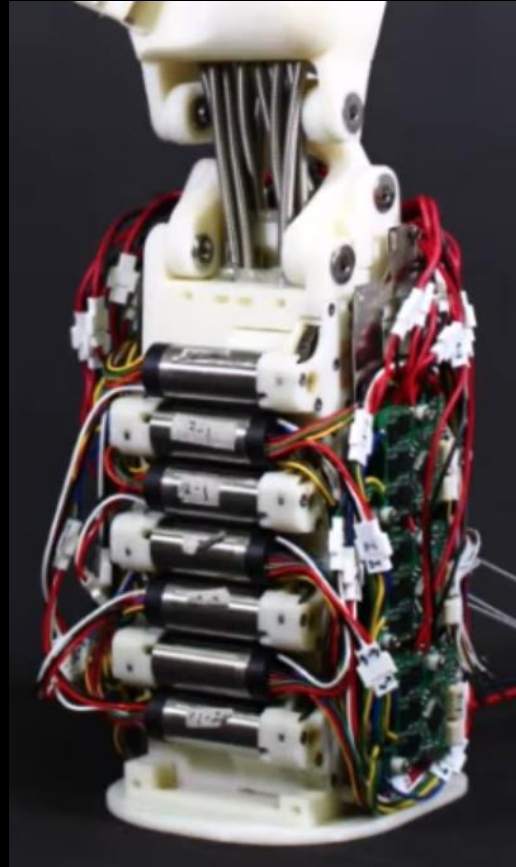
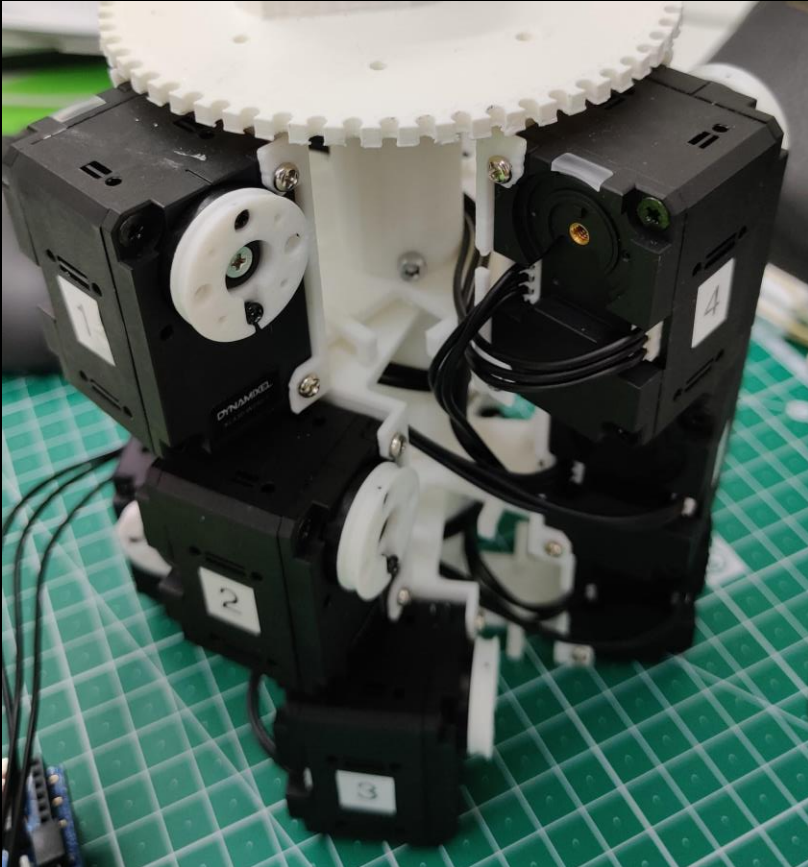
- Low friction
- Dislocates instead of breaking

Contact Rolling Joint: Existing design



FLLEX Hand Ver. 2 : Robustness and Payload Test, <https://www.youtube.com/watch?v=cZuzXdMyJsA>

Electromagnetic Motor-based Actuation



Servo Motor

- Controlling easier
- Inexpensive
- Efficient
- Bulky for actuating many DOF

1. SRL's test bench
2. FLEX Hand Ver. 2 : Robustness and Payload Test,
<https://www.youtube.com/watch?v=cZuzXdMyJsA>

Fluidic Actuation Types



Stefan Weirich, Development of a Biomimetic, Soft Actuator System for a Tendon-driven Hand, 2021 (at SRL)



Artificial Muscles Robotic Arm, Real Copy of Human Arm, https://www.youtube.com/watch?v=gd9d_BAXWvg

Pneumatic

- Compliance by compressible air
- Equipment intensive

Hydraulic

- Stronger than pneumatic
- Difficult plumbing

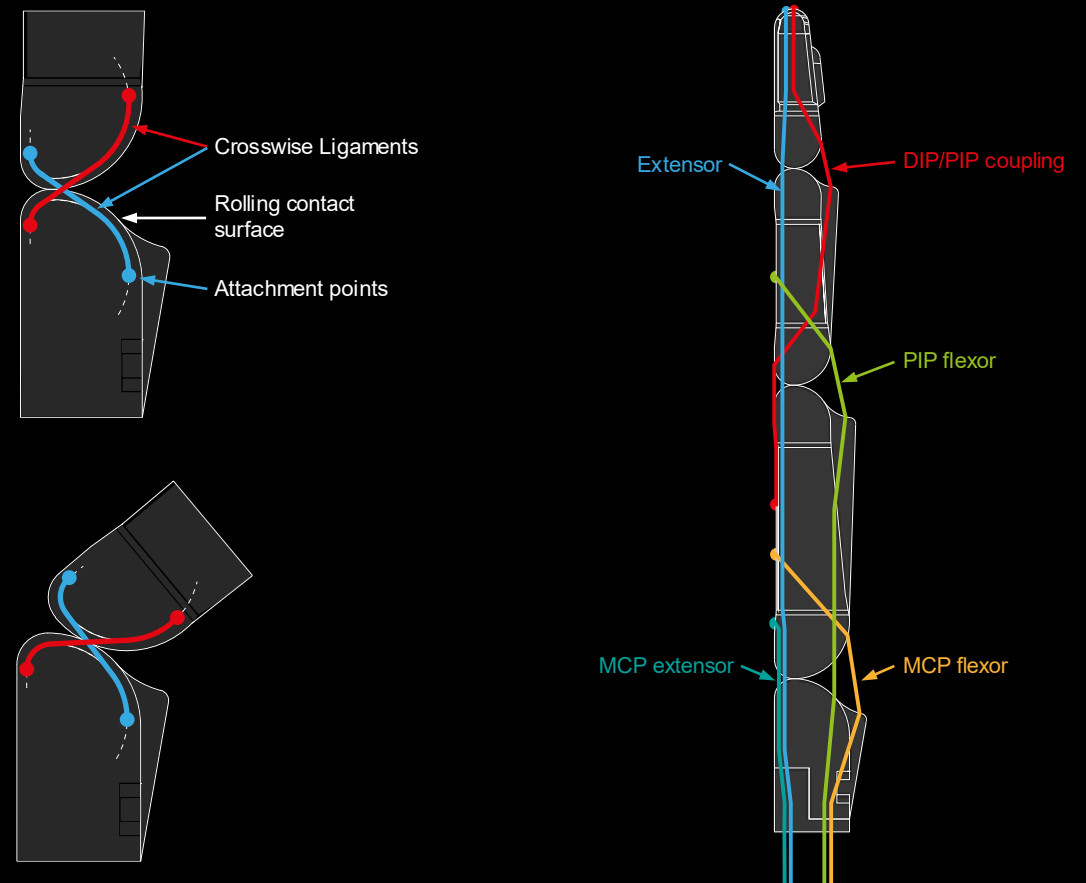
Finger Design



Dexterity

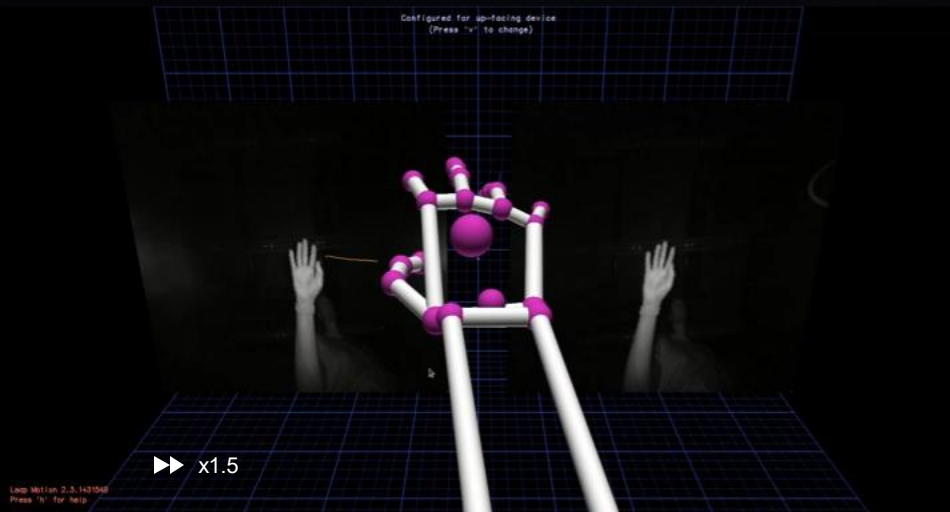
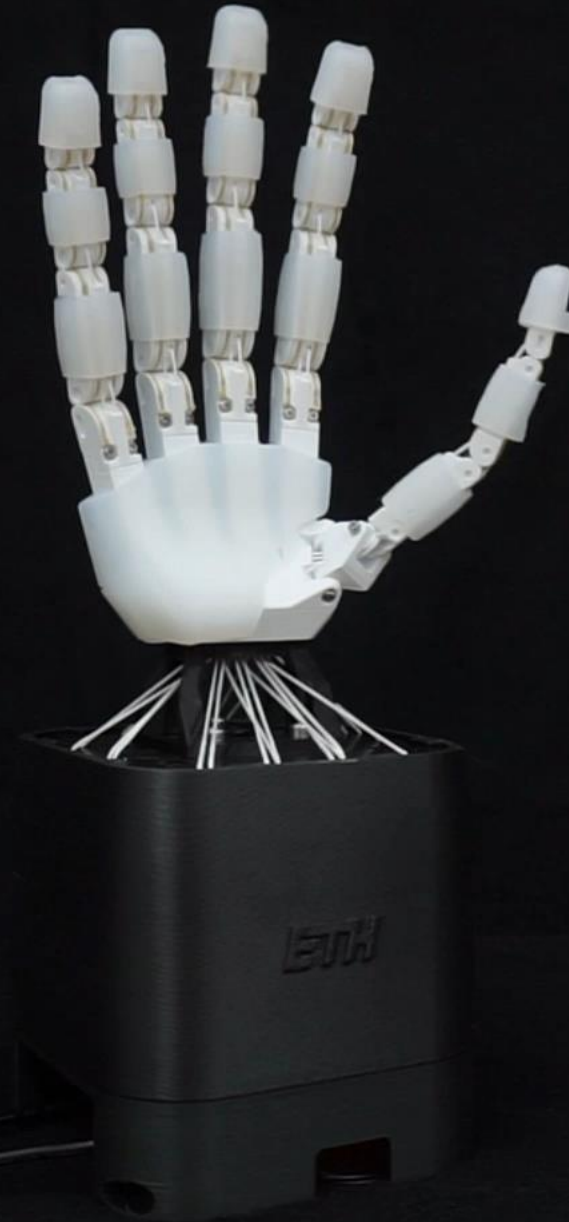


Ligaments & Tendons



Actuation, Sensing and Control

- Dexterous 16-20 DoF
- High Payload 10 kg
- Lightweight 1 kg
- Compliance
- Integrated Sensing



Potential Applications of an Anthropomorphic Hand



Detailed Comparison of Anthropomorphic Hands



Product	ShadowRobot (UK) [1]	Schunk SVH (Germany) [2]	Clone Inc. (Poland) [3]	QB SoftHand (Italy) [4]	Allegro Hand (Korea) [5]	Robotiq 3-finger Gripper (Canada) [6]	faive robotics [7]
Cost-Efficient	72.000 – 190.000 €	56,000 €	?	7.500 – 9.000 €	?	15.000 €	20.000 €
Versatility /Dexterity (DoF, actuators)	20 Electric motors	9 DC motors	27 hydraulic McKibben actuators	2 Electric motors	16 DC motors	3 Electric motors	21 DoF 17 DC Motors
Compliance	No	No	Not yet demonstrated	Yes	No	No	Yes
Payload	4 kg	?	7 kg	2 kg	5 kg	10 kg	10 kg
Weight	4.3 kg	1.3 kg	?	0.77 kg	1.09 kg	2.3 kg	1 kg
Limitations	Highly dexterous but very expensive, High weight Low Usability Entirely rigid	Dexterous but very expensive, Only produced on demand (4 Months lead time) System complexity	Develops entire torso system, Limited mobility due to hydraulics Aims to be commercially available in 2023	No independent finger control, No complex motions or in-hand manipulation	Bulky dimensions, Unreliable, No compliance	Limited grasping motions and functionality	

Tendon Driven – Key Takeaways



Advantages:

- High force transmission
- Electromagnetic motors are efficient
- Volume of force generation and action do not need to be the same
- Mimics biological musculoskeletal systems

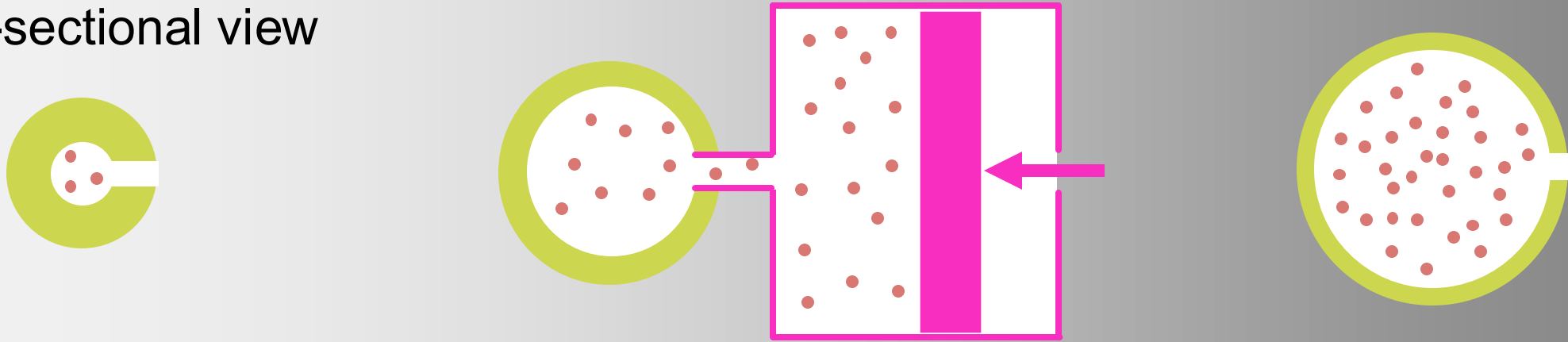
Disadvantages:

- Friction at joints
- Routing difficult for complex systems
- Rigid attachment points in soft structure
- Rigid motor needed

Working principle of a fluidic-powered soft actuator: constraints and pressurization



Cross-sectional view

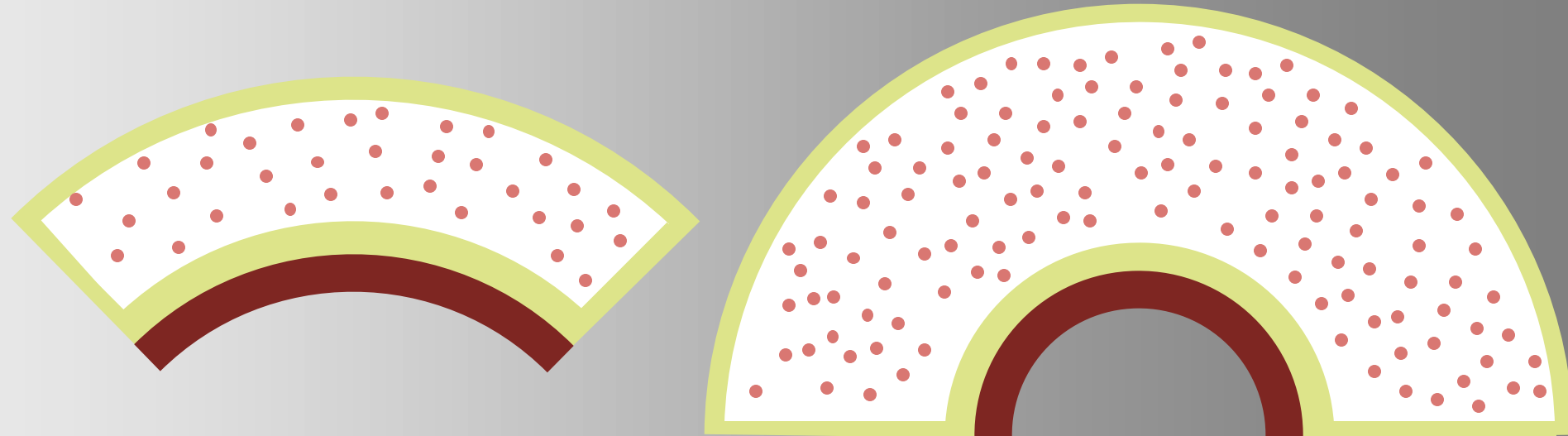


Side view

Silicone Elastomer

Cavity

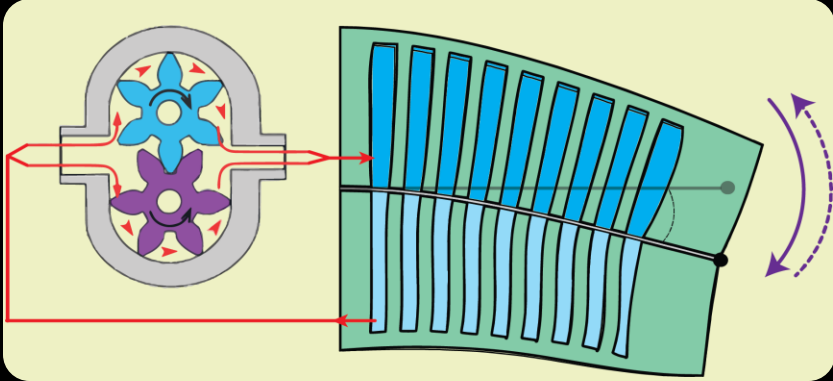
Inextensible constraint



Soft actuators can be powered by displacement pumps, pneumatic cylinders, or valve arrays

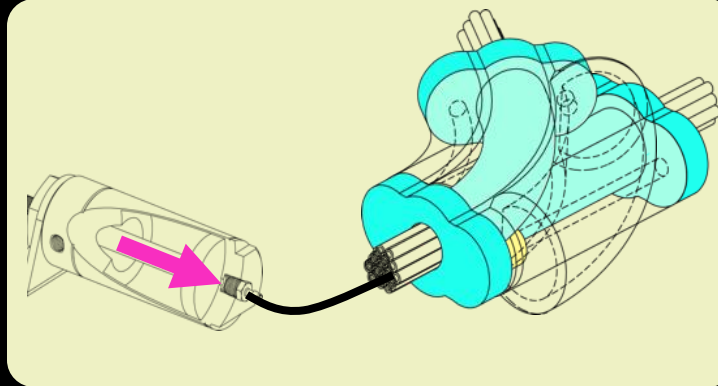


Displacement pump



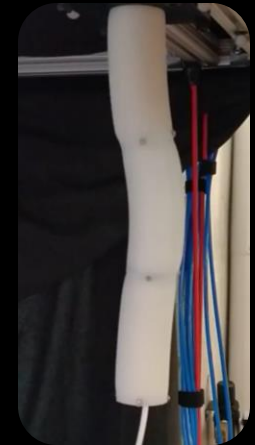
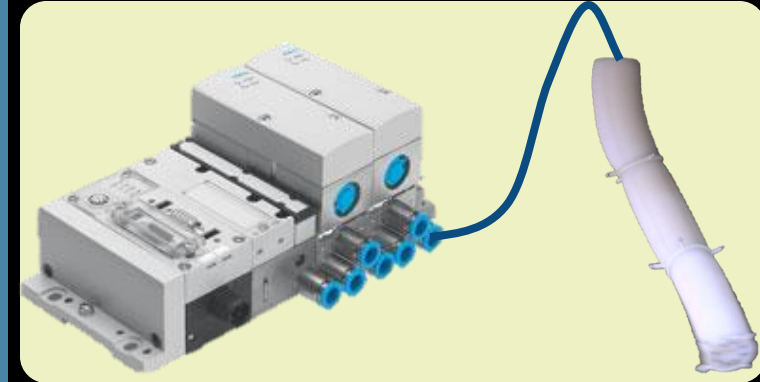
Katzschmann et al., ISER (2014)
Katzschmann et al., IROS (2016)

Pneumatic cylinder



Marchese, Katzschmann, Rus, IROS (2015)

Valve Array

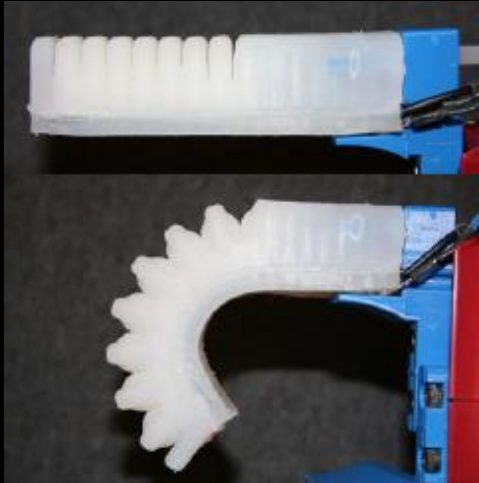


Katzschmann*, Della Santina*, Toshimitsu,
Bicchi, Rus, RoboSoft (2019)

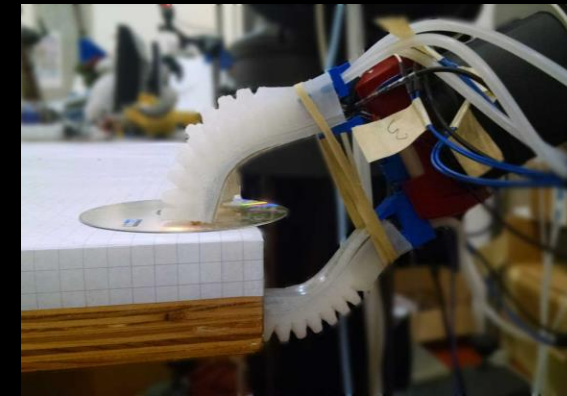
From making contact to manipulation: Multi-finger hand with inlaid strain + force sensors



Bending through inflation



Sliding off table



Use of environment



Small envelope



Large envelope

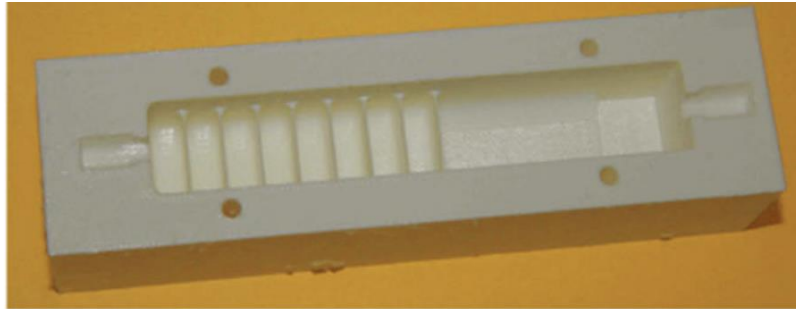


Pinch

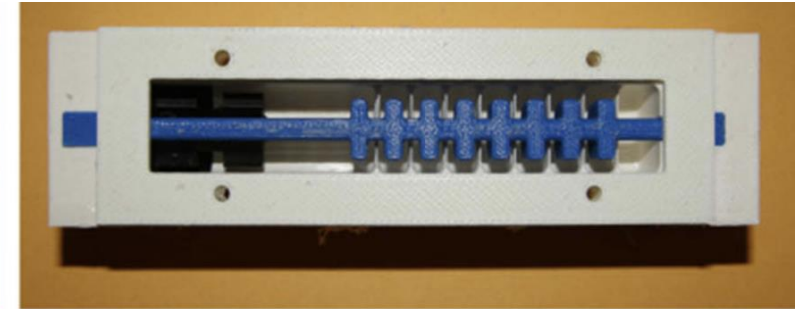
Bend and force sensor in finger



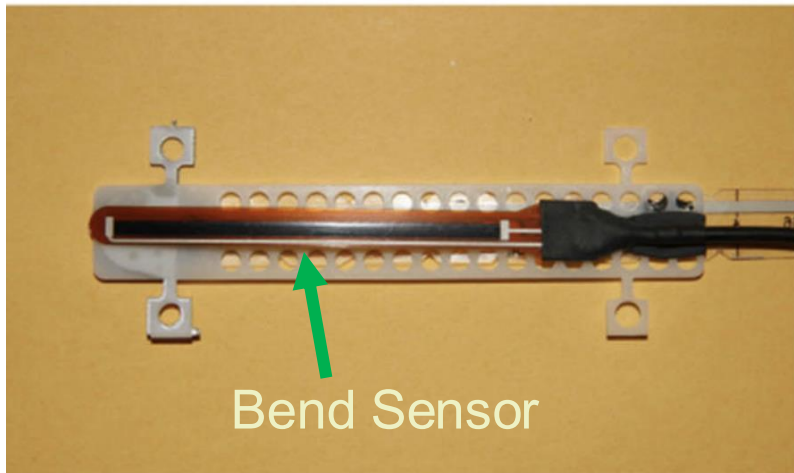
(a) *Wax core model*



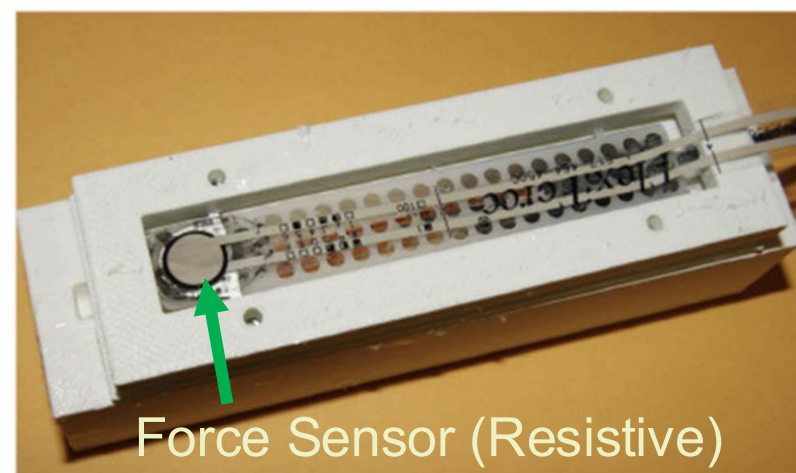
(b) *Base finger mold*



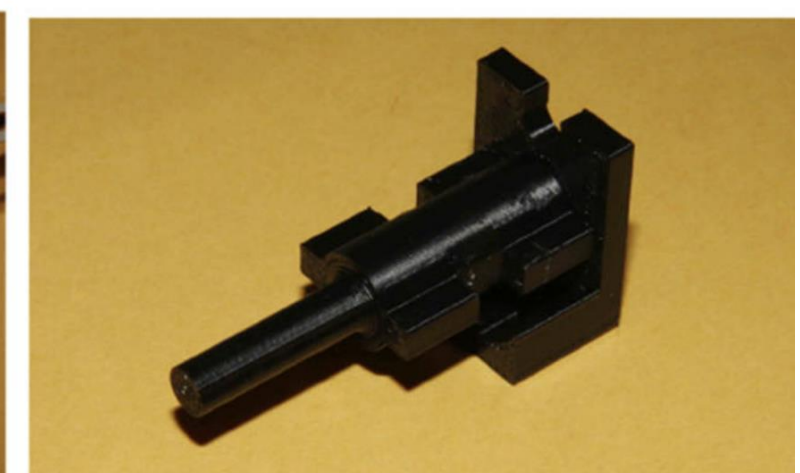
(c) *Mold assembly for finger base*



(d) *Constraint layer*



(e) *Top mold for constraint and sensor*



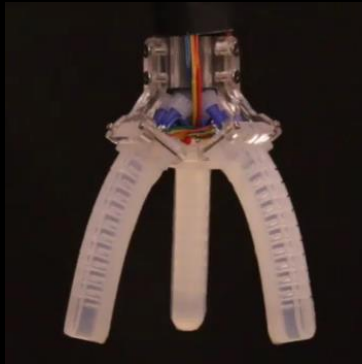
(f) *Insert part*

Guide the gripper to make contact before lifting



Actuation

Base only



Base + Tip



Summary

Pin (+ Tendon)



Weiner et al. 2018

Rolling Contact (+Tendon)



Faive Robotics

Synovial (+Tendon)



Xu et al. 2016

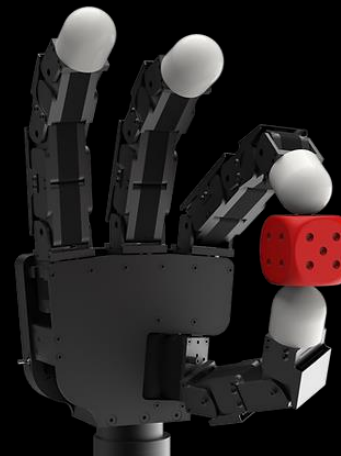


Flexure (+Tendon)



Yale OpenHand Model Q

Motor in Joint



Wonik Robotics Allegro hand

Soft Fluidic



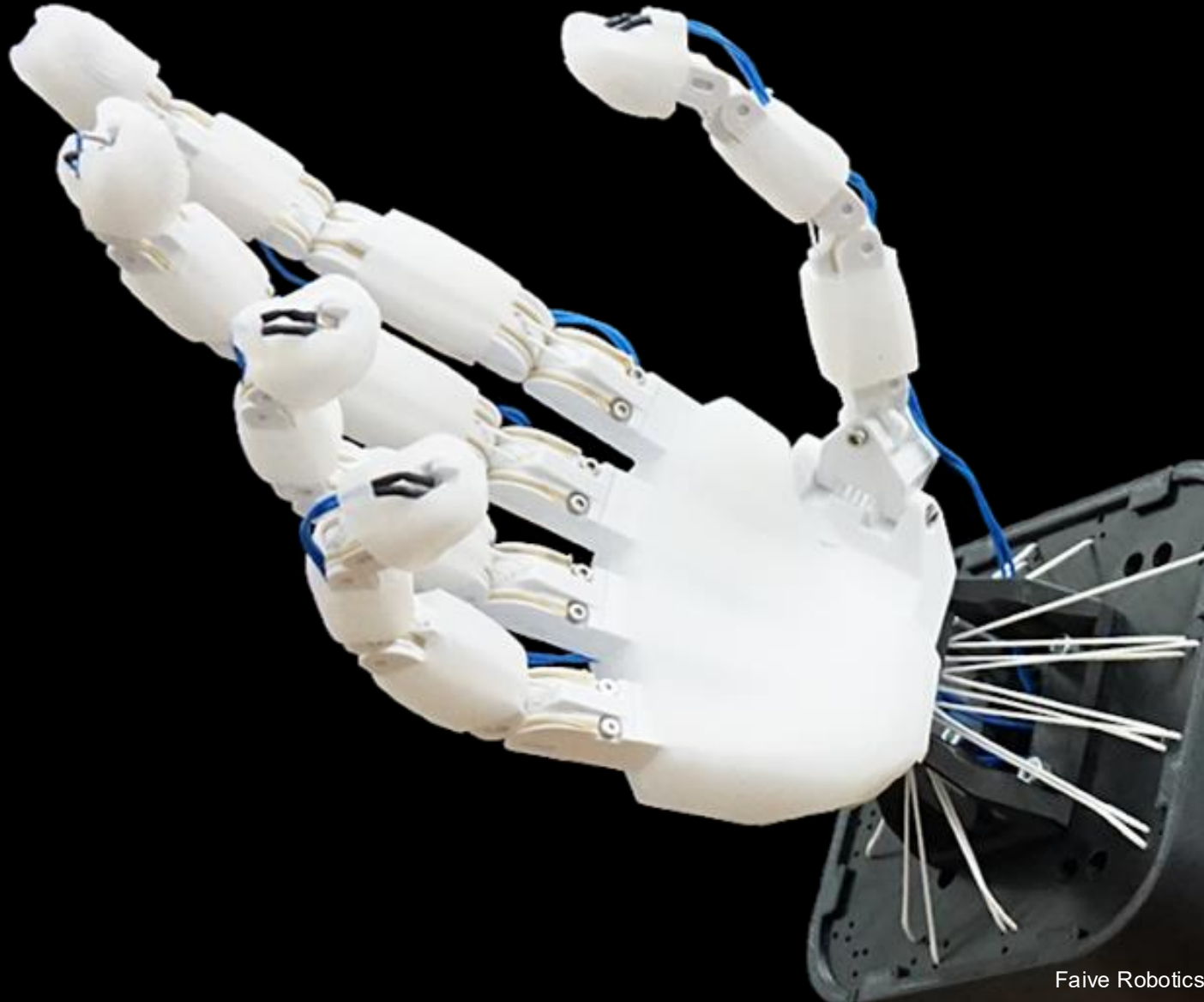
Truby et al. 2019



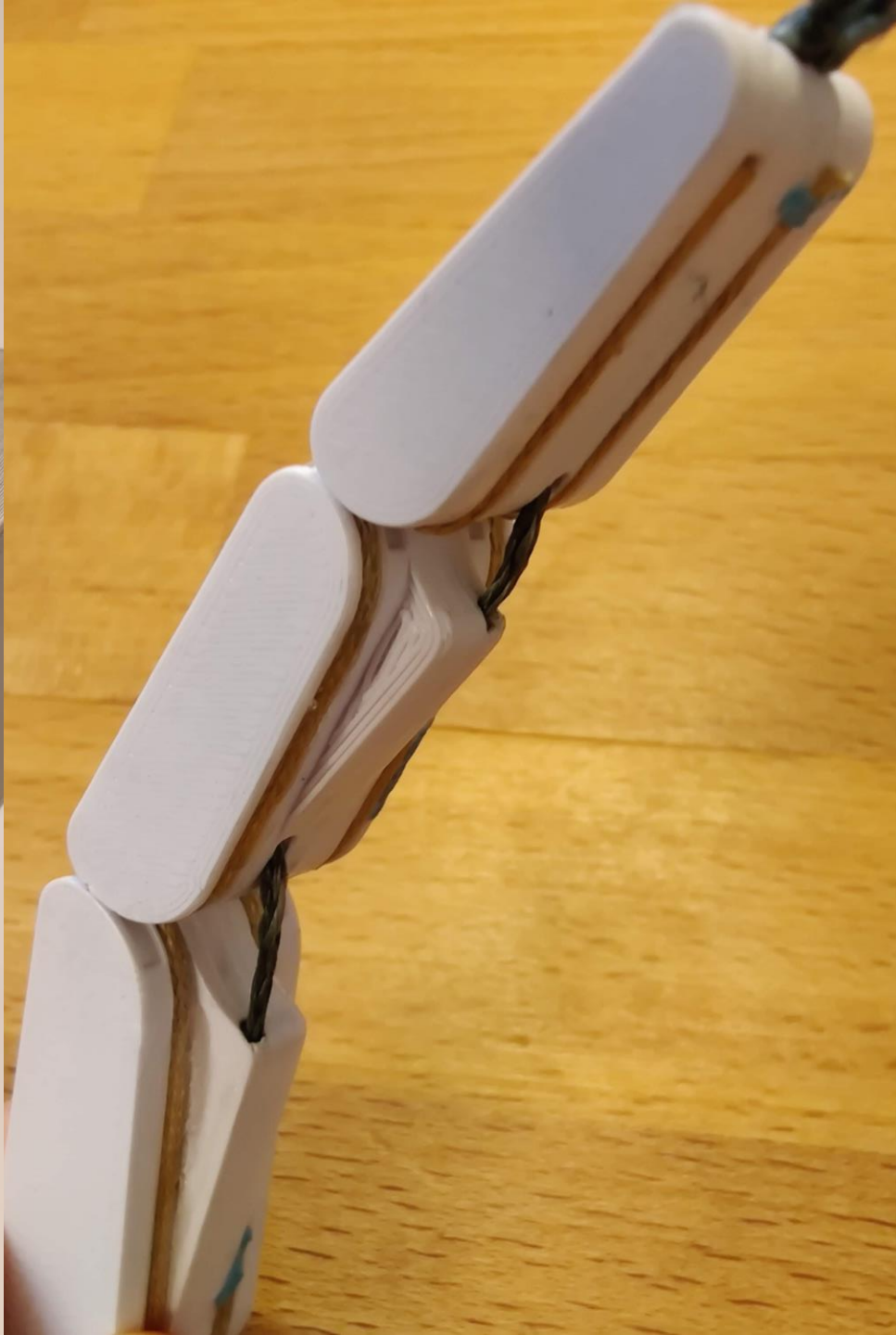
Fabrication Techniques to build an Articulated System with Soft Skin Focus & Q&A

Prof. Dr. Robert Katzschmann
Soft Robotics Lab
ETH Zurich

How to make a hand?



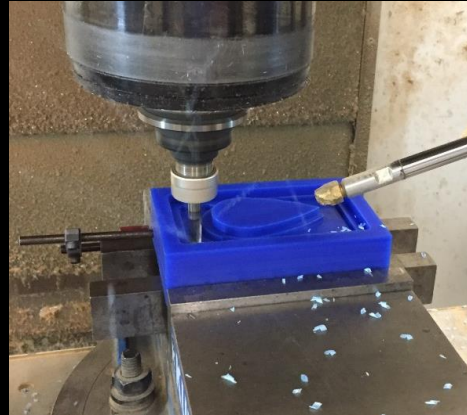
Iterate...



Summary of Fabrication Techniques for Robotic Hands



Machining



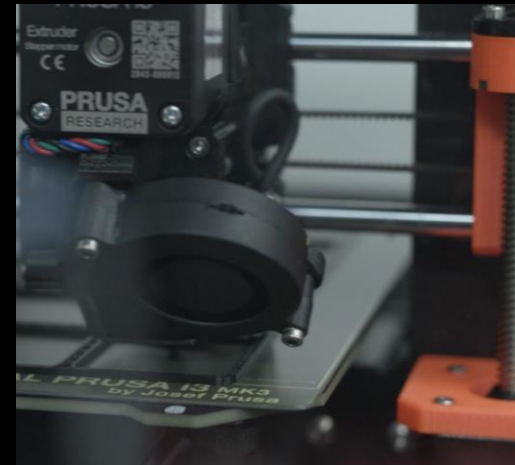
Joining



Casting / Molding



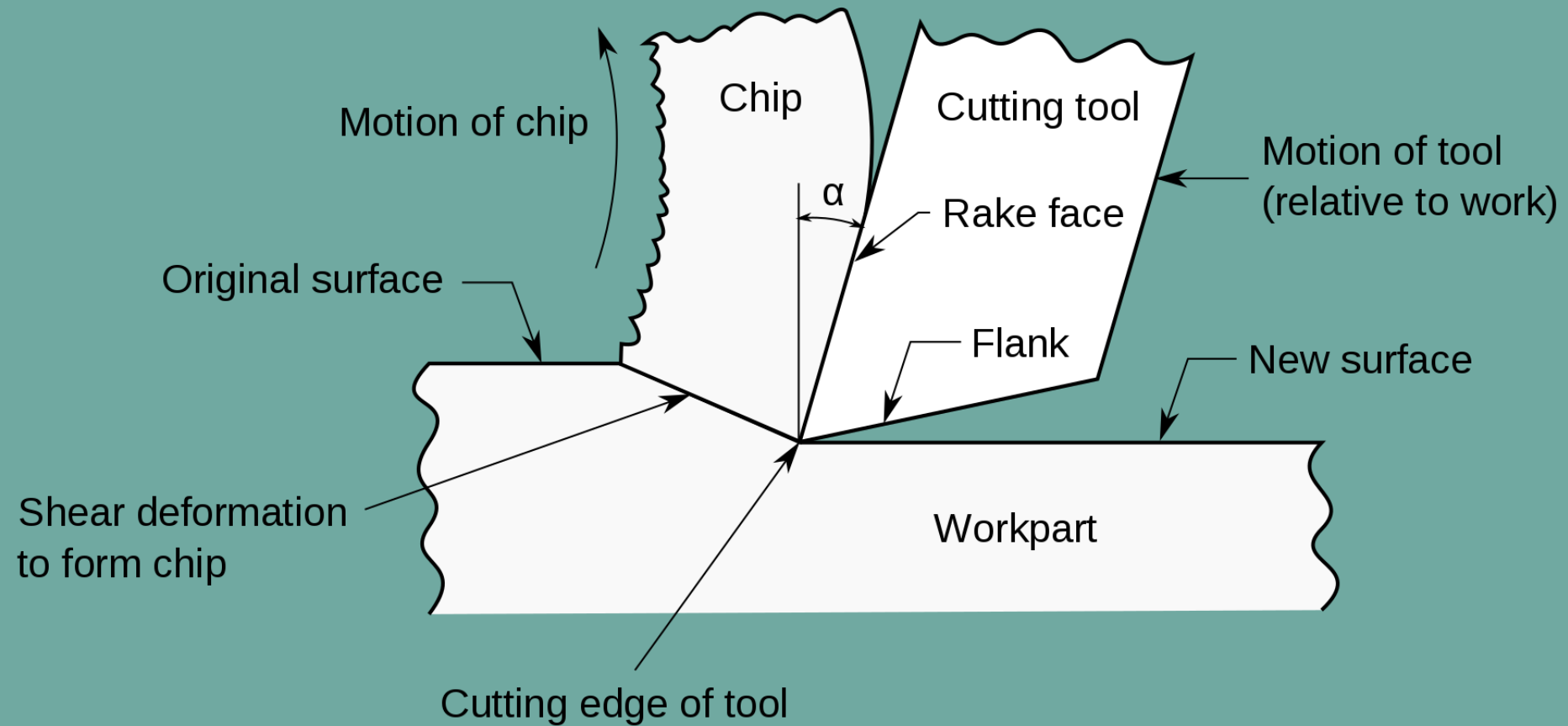
Additive Manufacturing





Machining

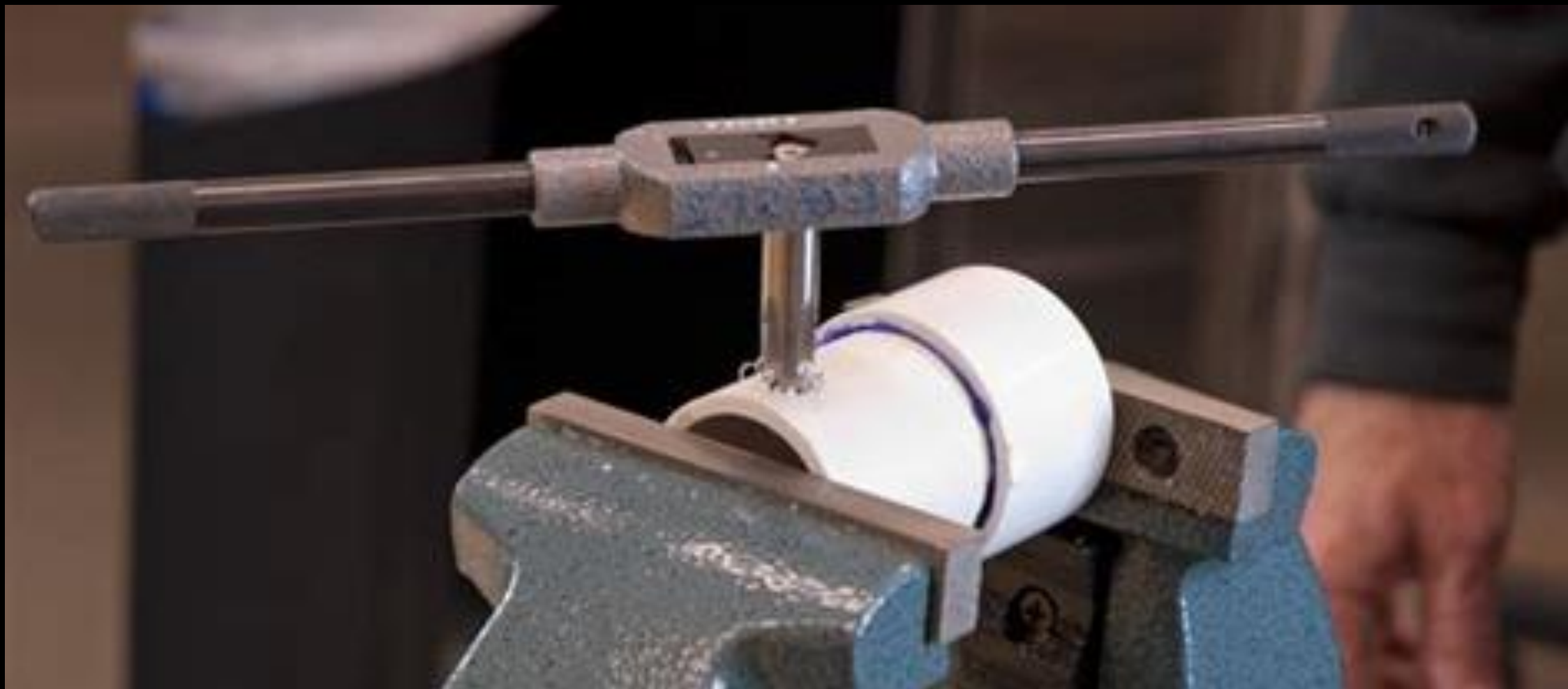
A material is cut to a desired final shape and size by a controlled material-removal process



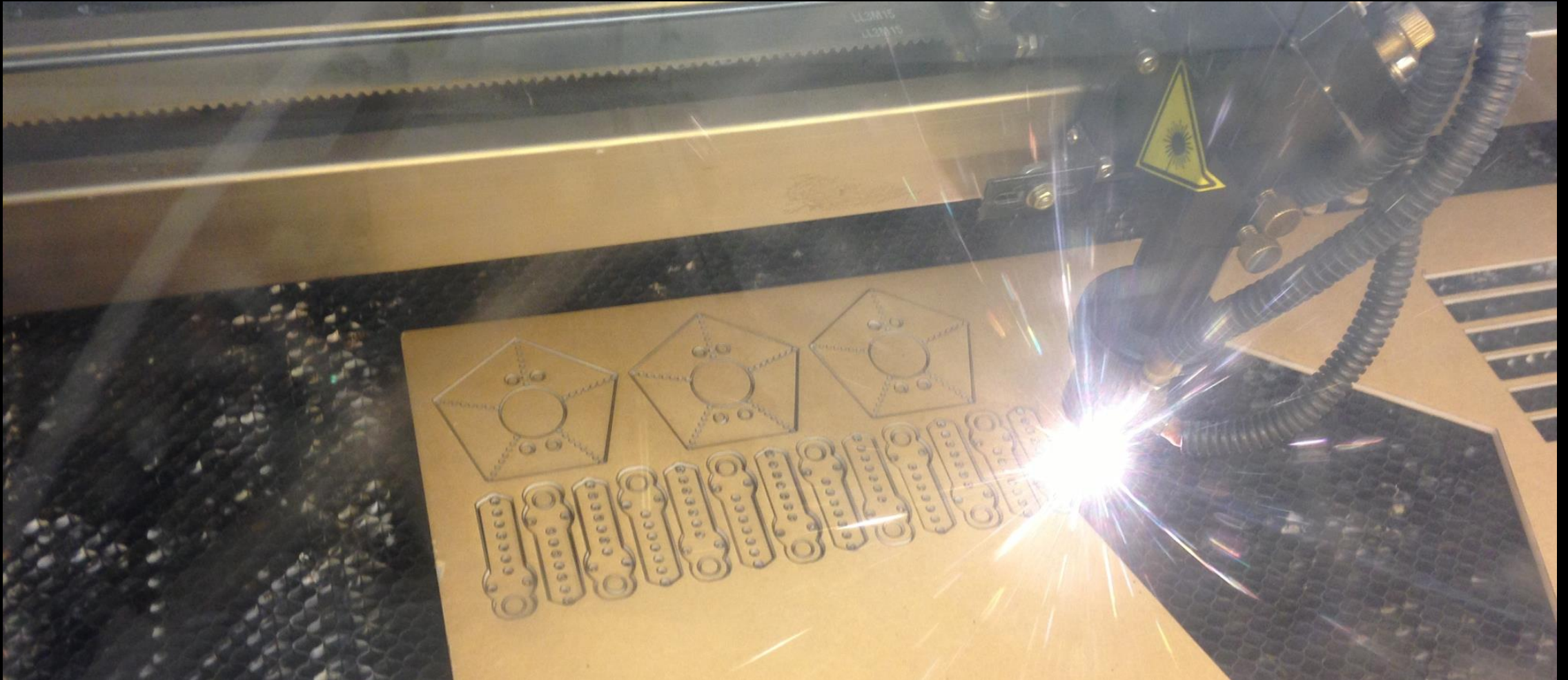
Drilling



Tapping



Laser Cutting



Water Jet Cutting



Milling



Turning

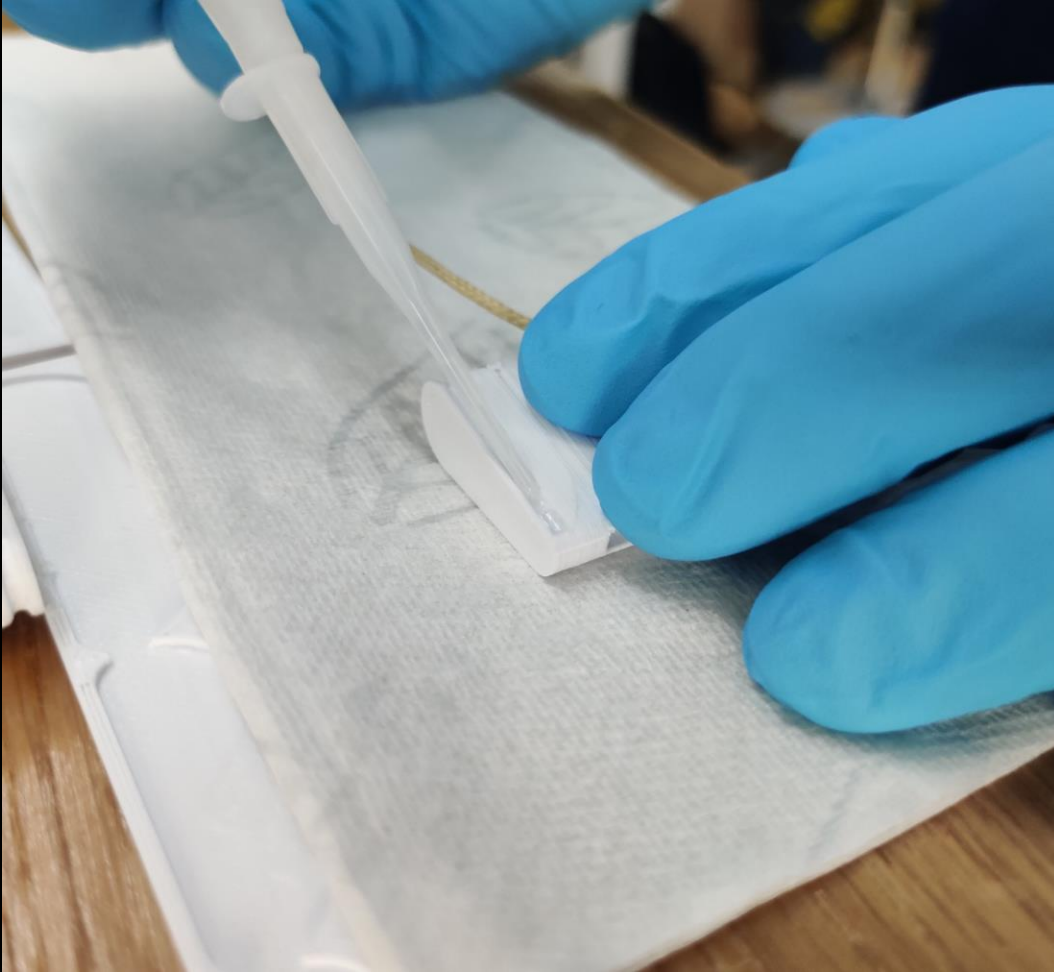


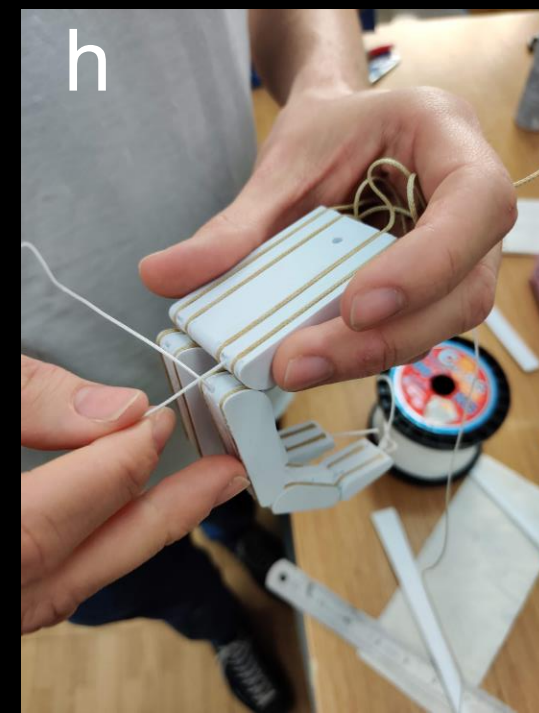
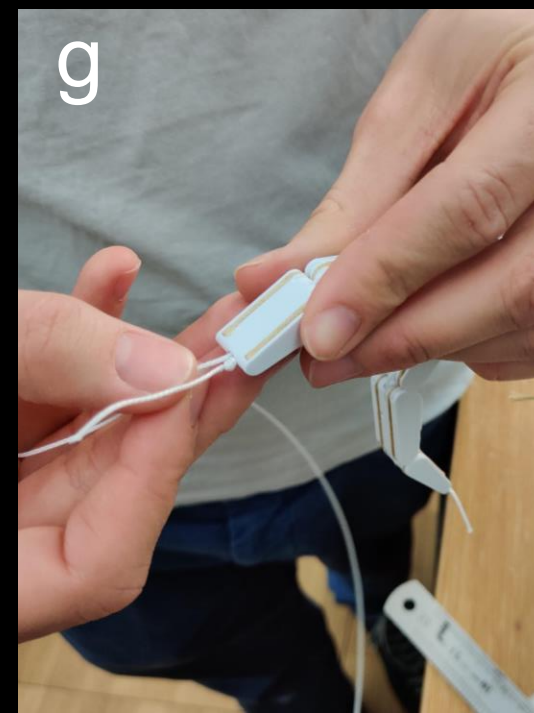
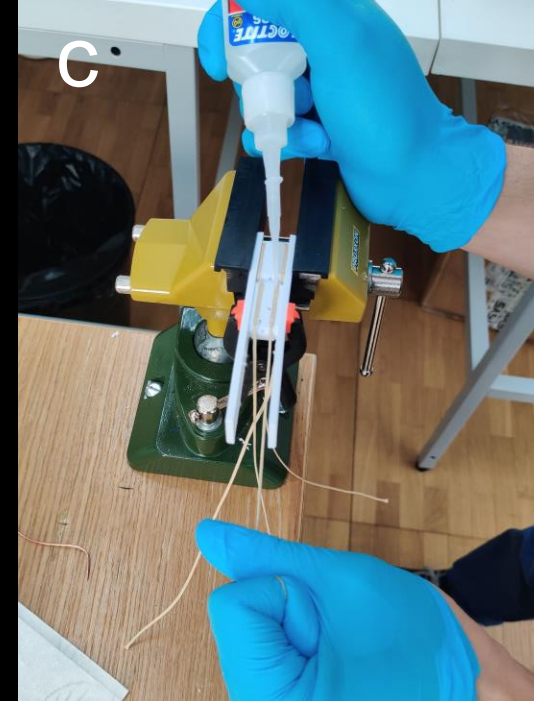
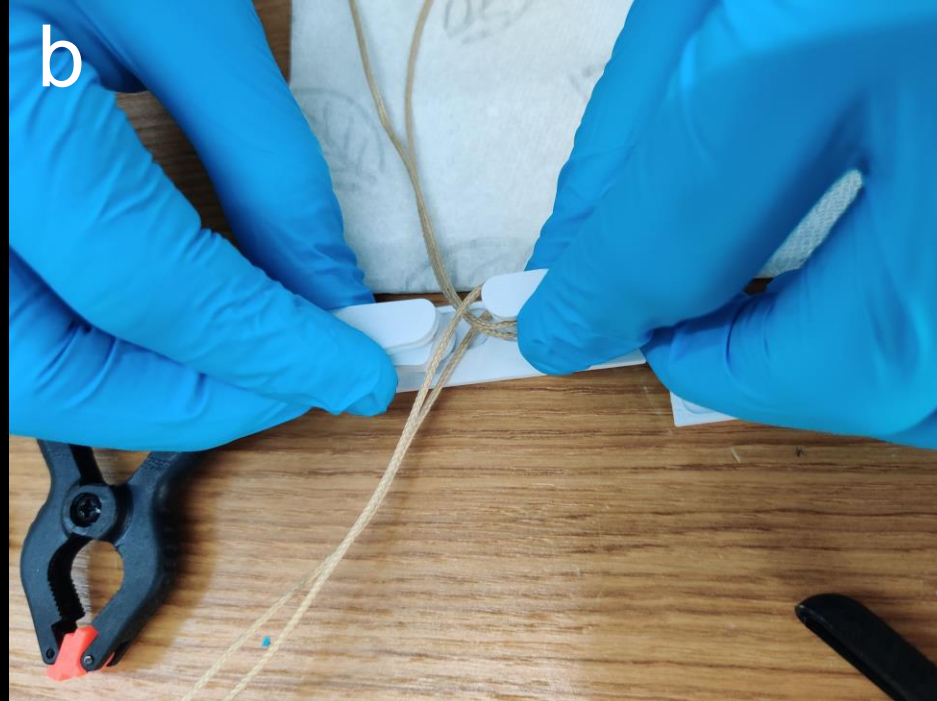


Joining

Two or more materials can be permanently or temporarily joined or assembled together with or without the application of external element to form a single unit

Adhesive Bonding

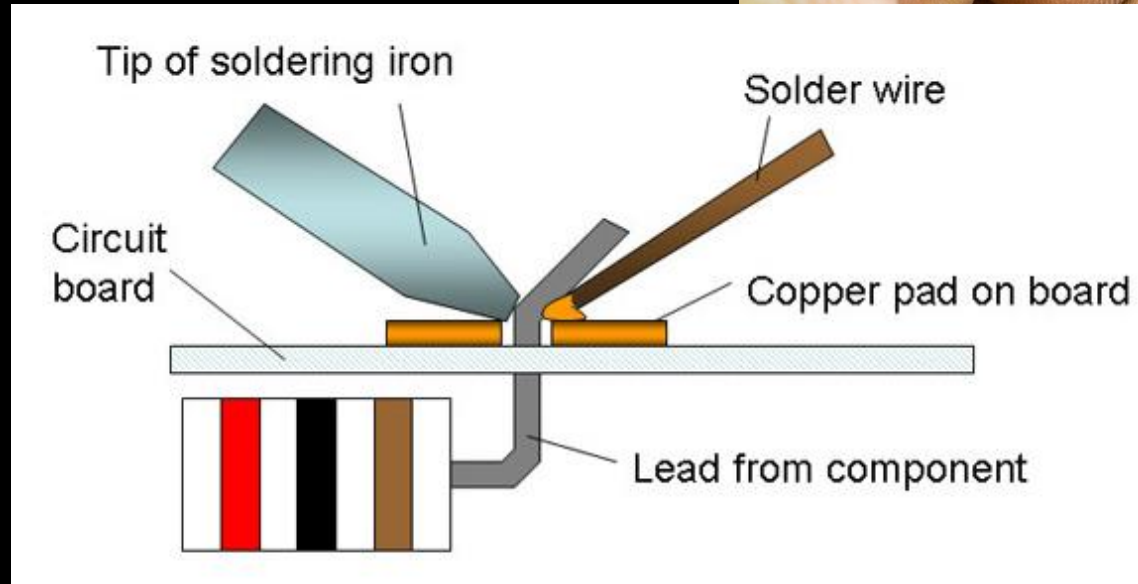




Fastening



Soldering

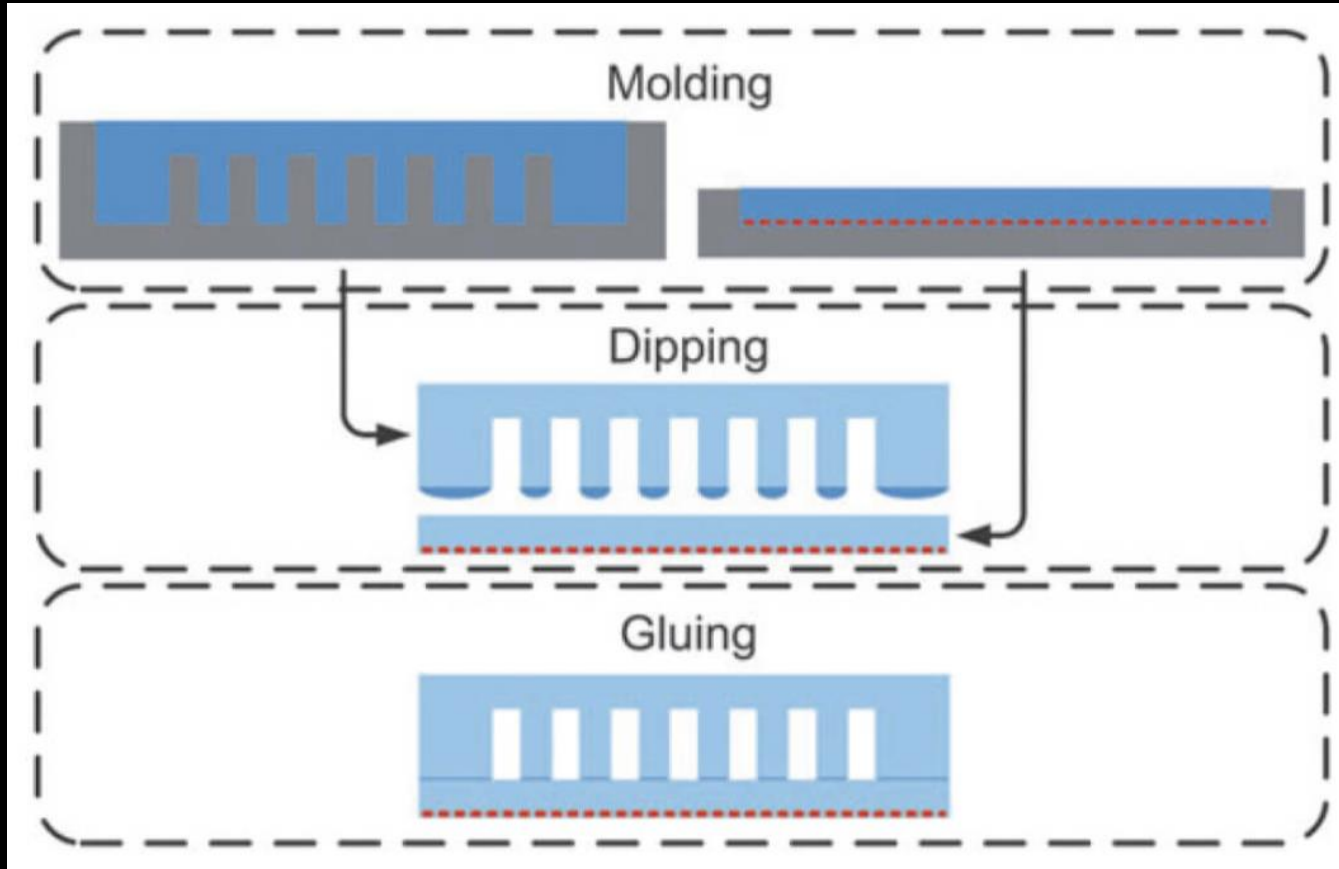




Casting and Molding Techniques

Fabricating or replicating structures using (elastomeric) stamps, molds, and masks

Layer-by-layer Molding of Silicone Elastomer (Soft Lithography)



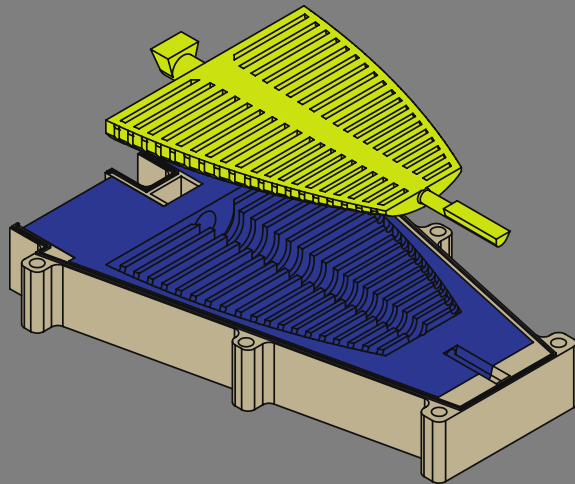
Each layer is casted and cured in separate molds.

Cured layers are removed and joined using a thin layer of uncured elastomer as glue.

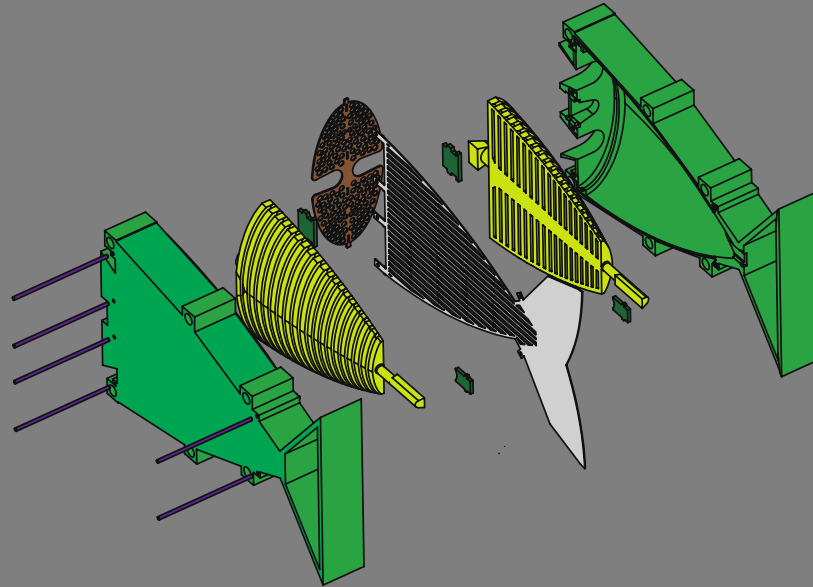
Lost-wax casting to produce interior cavities in molded elastomer materials



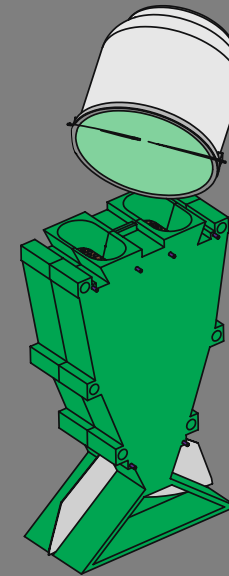
Wax Core Creation



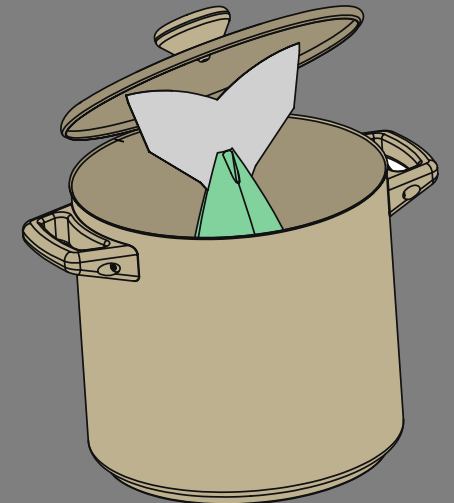
Assembly



Molding



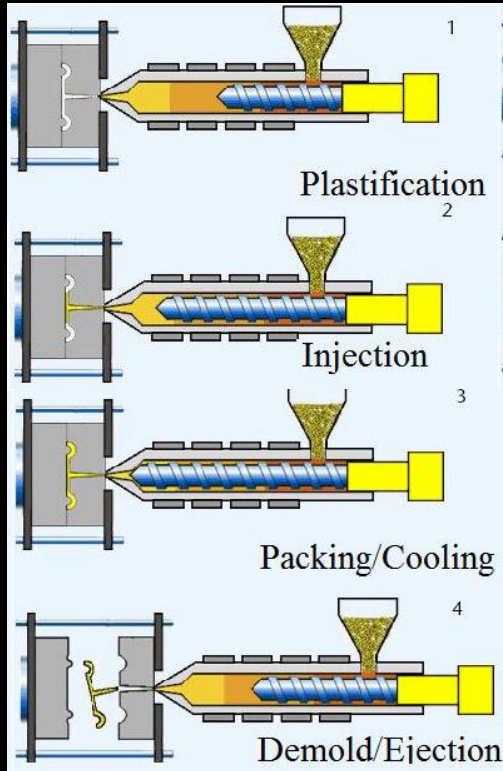
Melting



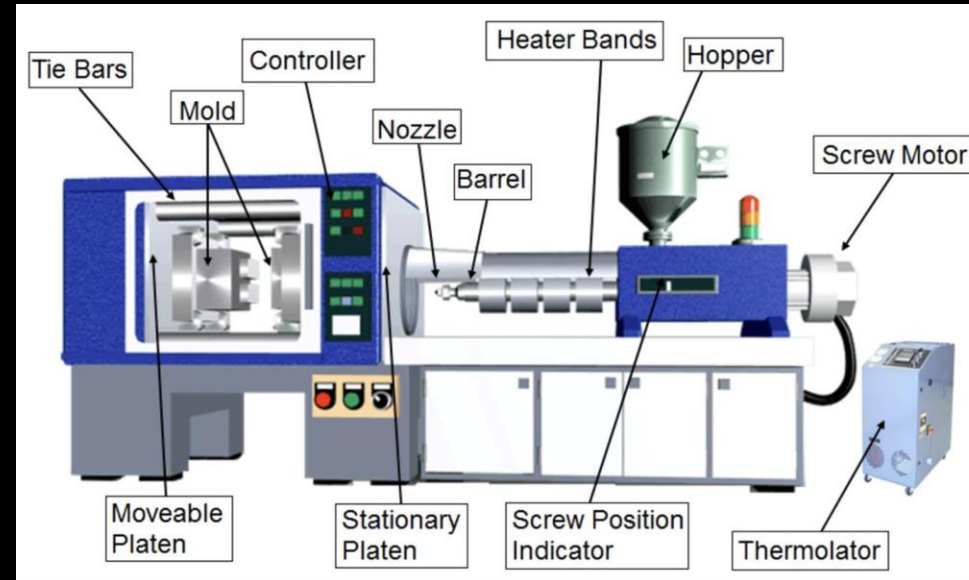


Injection molding of molten materials

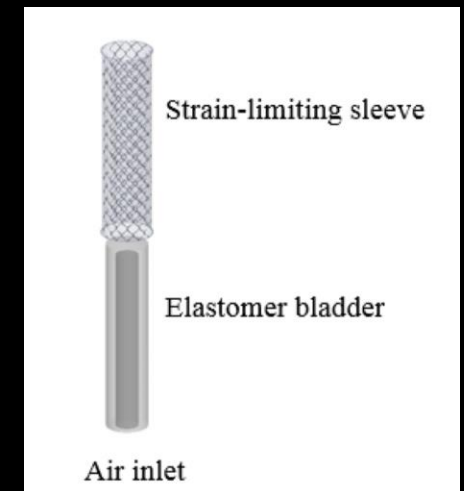
A manufacturing process for producing parts by injecting molten material (thermoplasts) into a mold



Injection molding process



The structure and components of injection molding machine



Example: Pneumatic actuator fabricated using injection molding

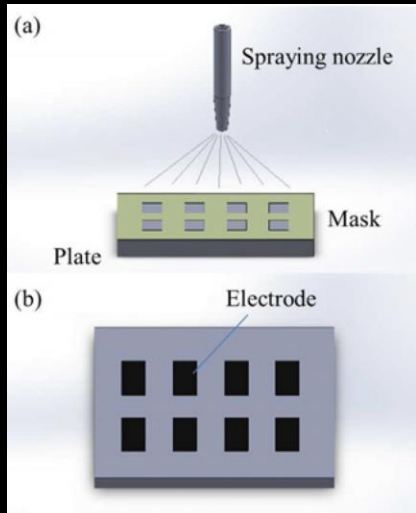
Li, Wanying. "Fabrication of soft robotic actuators by using injection molding technology." (2017).

Cho, Kyu-Jin, et al. "Review of manufacturing processes for soft biomimetic robots." *International Journal of Precision Engineering and Manufacturing* 10.3 (2009): 171-181.

Coating of Electrostatic Actuators

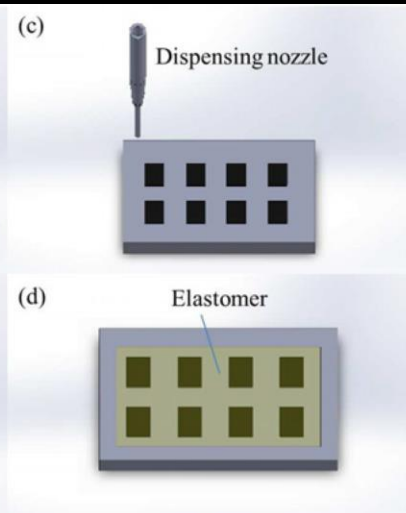


Spraying

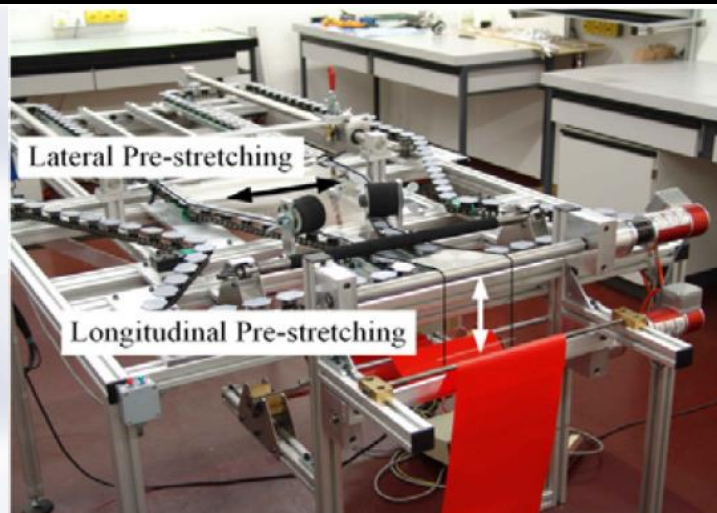


[Nguyen et al. 2014]

Molding



Premanufactured tapes

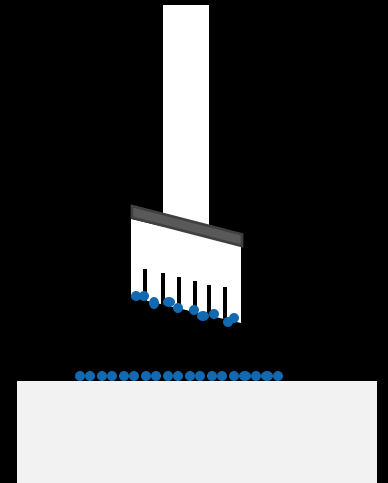


[Kovacs et al. 2007]

Blade Coating



Brushing



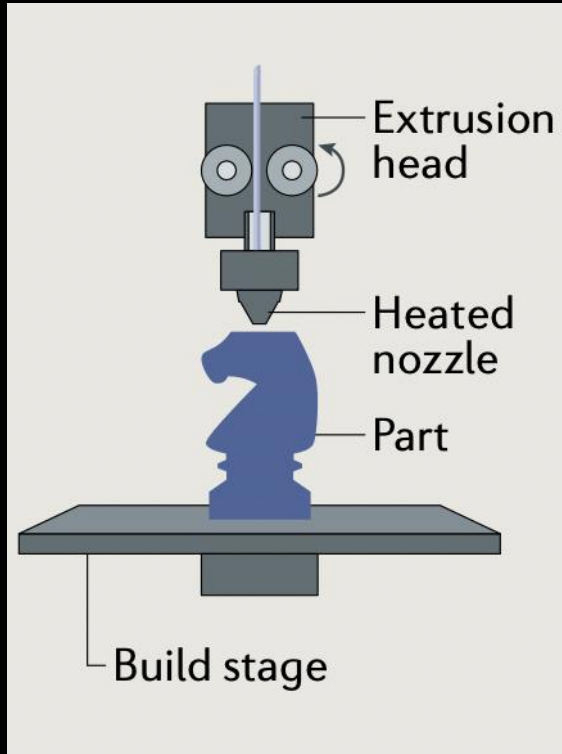


3D Printing Technologies

A subset of additive manufacturing that creates 3D objects from design files through the digitally controlled deposition of material layers



Fused Deposition Modeling (FDM)



The working principle: A solid thermoplastic filament is extruded through a heated nozzle to melt, deposit, and fuse the material.

The head moves in 2D to deposit one horizontal plane at a time; the build stage or the print head is then moved vertically by a small amount to begin a new layer.

The reliance on melting and cooling processes limits the use of FDM to thermoplastic polymers.

The most successful FDM material for soft robotics is the Ninjabflex family of thermoplastic polyurethanes, which can withstand strains above $\gamma_{ult} > 500\%$ with a Young's modulus $E \approx 10$ MPa.

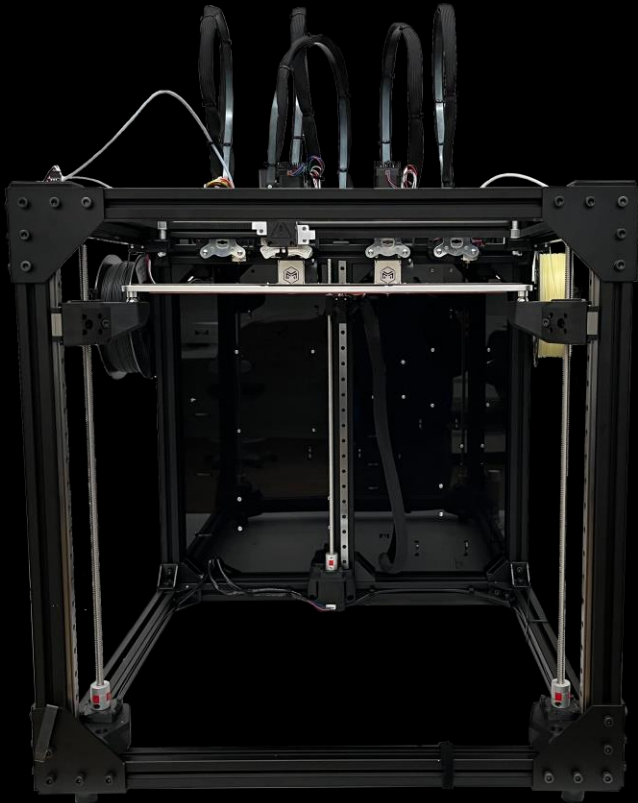
Approximate deposition rate: $10^5 \text{ mm}^3 \text{ h}^{-1}$

Approximate resolution: $100 \text{ }\mu\text{m}$

Wallin, T. J., J. Pikul, and R. F. Shepherd. "3D printing of soft robotic systems." *Nature Reviews Materials* 3.6 (2018): 84-100.

FDM Example:

Hydra MK1 – developed at the Soft Robotics Lab

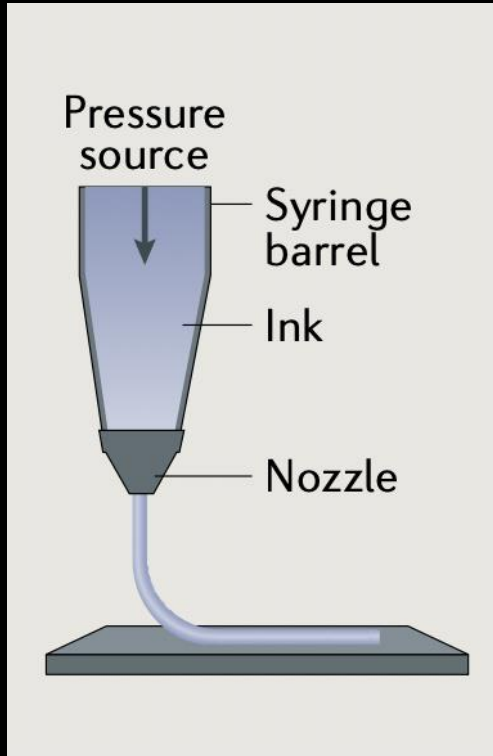


- The Hydra MK1 is an open-source project that aims to bring multi-material printing of exotic materials to research facilities and individuals worldwide.
- It features a tool swapper that can switch between up to four tools. In the standard configuration, it uses two filament printing heads, and two pellet extruders.
- Detailed documentation:

<https://hydramk1.readthedocs.io/en/latest/>



Direct Ink Writing (DIW)



The working principle: A viscoelastic ink flows through a nozzle. Upon deposition, the ink solidifies into a solid object.

A pressure source forces a liquid ink of a polymeric precursor above the yield stress, allowing it to be selectively deposited through a nozzle.

Once extruded, a sudden stress reduction, phase change, solvent evaporation, polymerization (either continuous or initiated in response to external stimuli) or combination thereof restrains the deposited material into a specific shape.

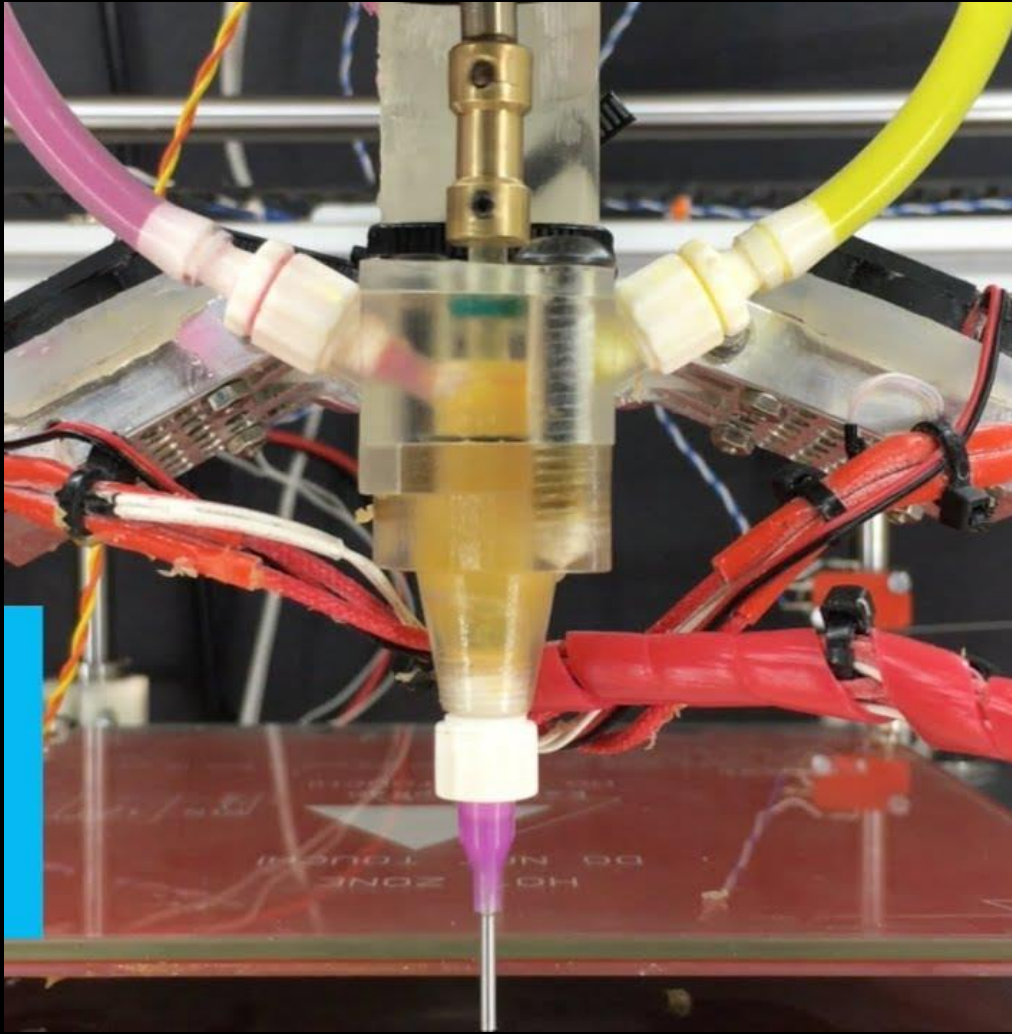
The solidification process competes with the gravitational fluid flow, 'wetting-out' and self-levelling tendencies of the ink and must be properly balanced to ensure shape retention and interlayer adherence.

Approximate deposition rate: $10^5 \text{ mm}^3 \text{ h}^{-1}$

Approximate resolution: 1-100 μm

Wallin, T. J., J. Pikul, and R. F. Shepherd. "3D printing of soft robotic systems." *Nature Reviews Materials* 3.6 (2018): 84-100.

Direct Ink Writing with Two Part Silicone Elastomer

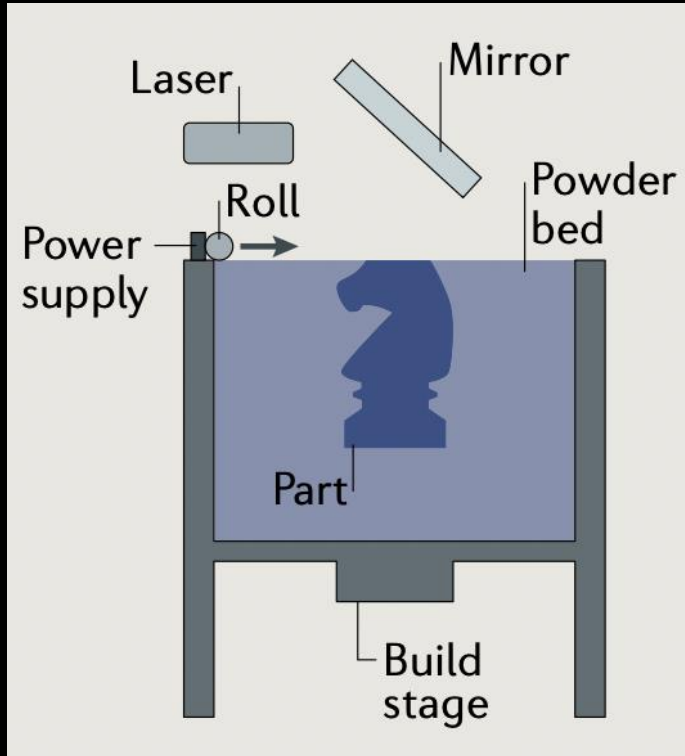


Two soft uncured components are mixed with a drill head and then extruded through a nozzle to deposit the material.

Yirmibesoglu et al. "Direct 3D printing of silicone elastomer soft robots and their performance comparison with molded counterparts." 2018 IEEE International Conference on Soft Robotics (RoboSoft). IEEE, 2018.



Selective Laser Sintering (SLS)



The working principle: A bed of solid, thermoplastic powder is selectively heated by a scanning laser. This irradiation causes localized melting and fusion of the material. Powder is then cast to recoat the bed, and the process is repeated. This technique is also called 'selective laser melting' when thermoplastic polymers are printed.

SLS requires a thermoplastic material in the form of a powder with narrow size distribution and homogeneous morphology to promote a uniform, dense powder bed.

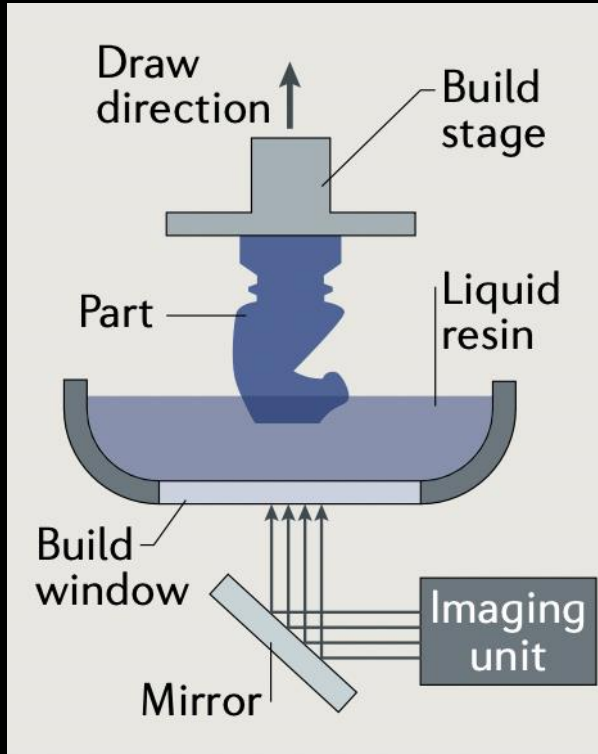
Moreover, the temperature fields must maintain an appropriately sized melt pool in order to fully melt and fuse the material without distorting previously printed geometries.

Approximate deposition rate: $10^6 \text{ mm}^3 \text{ h}^{-1}$

Approximate resolution: $100 \text{ }\mu\text{m}$

Wallin, T. J., J. Pikul, and R. F. Shepherd. "3D printing of soft robotic systems." *Nature Reviews Materials* 3.6 (2018): 84-100.

Stereolithography (SLA)



The working principle: A bath of liquid photopolymer is selectively exposed to light (through either a scanning laser or a projected photo pattern). The liquid resin polymerizes into a solid layer in response to photoirradiation. The object is then translated, liquid recoats the interface and the next layer is similarly exposed.

Synthesis in a dense medium provides buoyant forces capable of supporting soft, compliant structures, which is particularly useful for the printing of thin, overhanging structures.

The free-radical polymerization of acrylates and the cationic polymerization of epoxies provide the basis of many SLA resins.

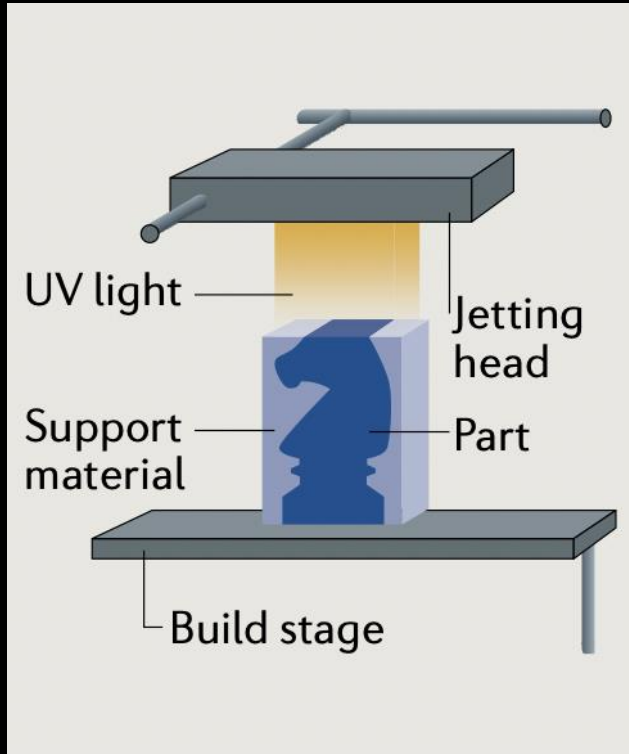
Approximate deposition rate: $10^6 \text{ mm}^3 \text{ h}^{-1}$

Approximate resolution: $1 \text{ }\mu\text{m}$ (microsystem-based), $50 \text{ }\mu\text{m}$ (projection-based)

Wallin, T. J., J. Pikul, and R. F. Shepherd. "3D printing of soft robotic systems." *Nature Reviews Materials* 3.6 (2018): 84-100.



Inkjet Printing



The working principle: Small droplets of liquid ink are simultaneously ejected from print heads. These droplets then solidify on the surface, often in response to light or heat. Jetting and solidification are iteratively repeated until the entire object is built.

Multiple nozzle heads can jet millions of droplets of different inks within seconds and at the same time maintain a lateral resolution on the order of $50\text{ }\mu\text{m}$.

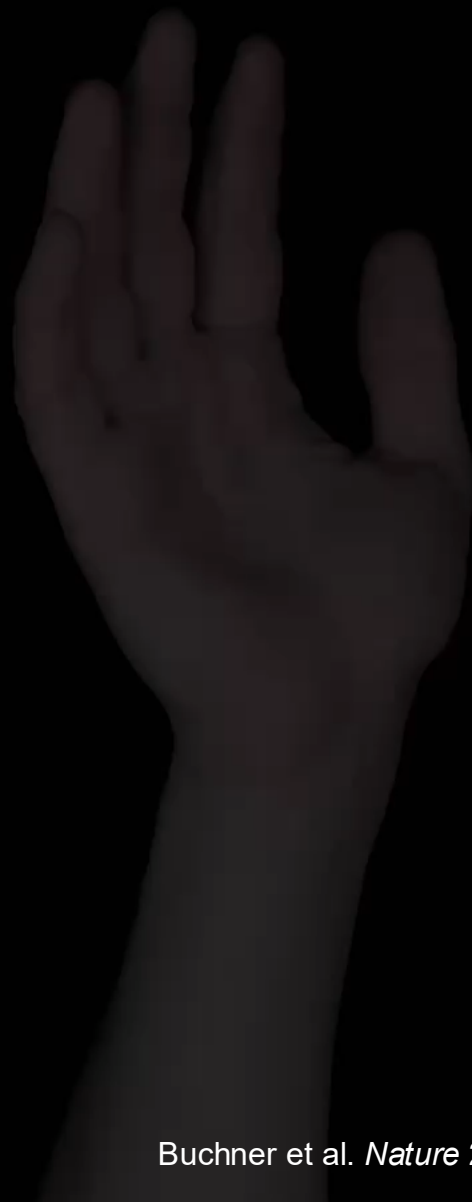
Mainly the flexible urethane-acrylate Tango series of materials ($E \approx 0.7\text{ MPa}$ and $\gamma_{\text{ult}} \approx 270\%$), commercially available from Stratasys, has been used for soft robotic devices.

Limitation: limited viscosity range of ink

Approximate deposition rate: $5 \times 10^5\text{ mm}^3\text{ h}^{-1}$

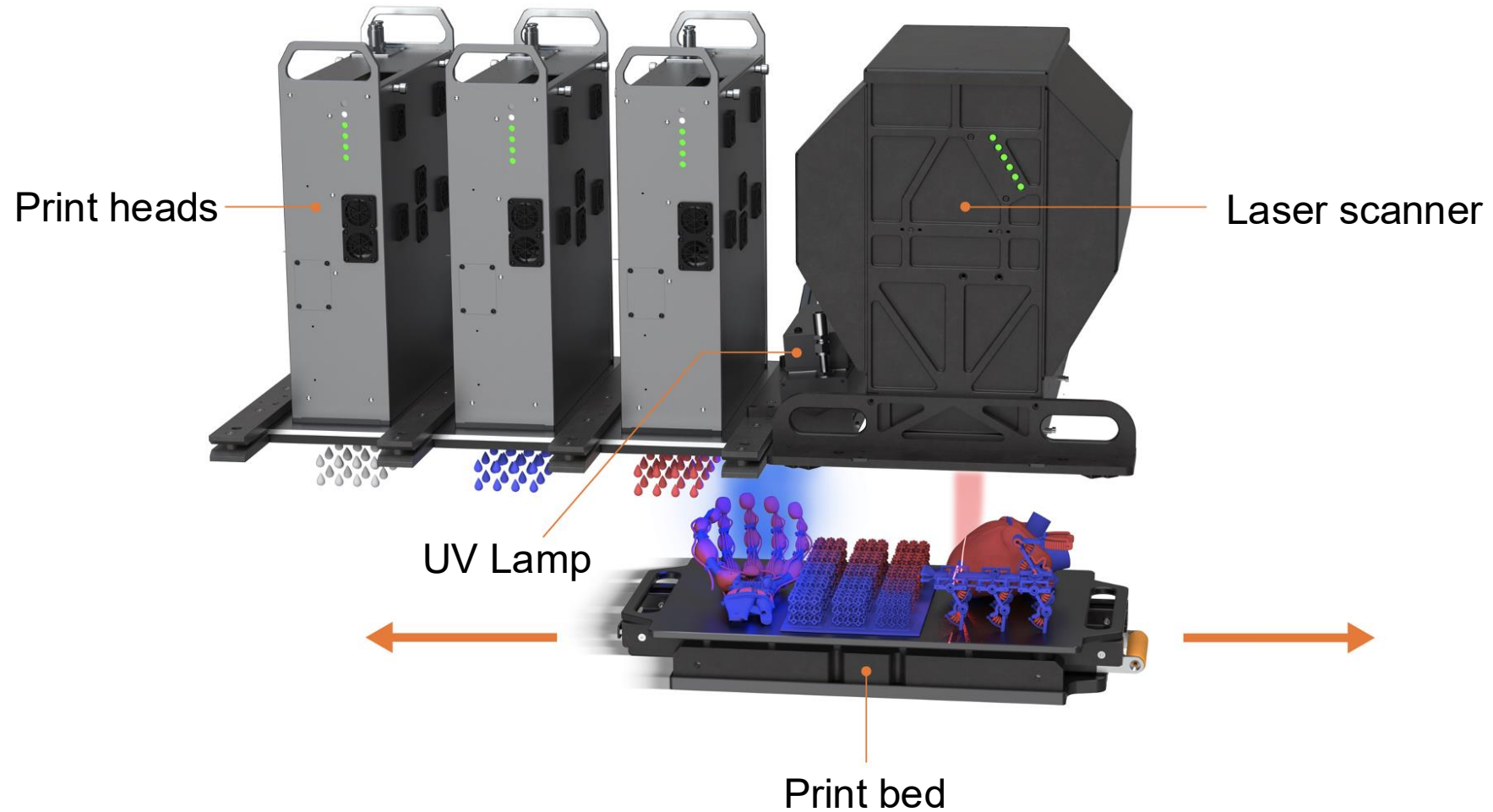
Approximate resolution: $50\text{ }\mu\text{m}$

Wallin, T. J., J. Pikul, and R. F. Shepherd. "3D printing of soft robotic systems." *Nature Reviews Materials* 3.6 (2018): 84-100.



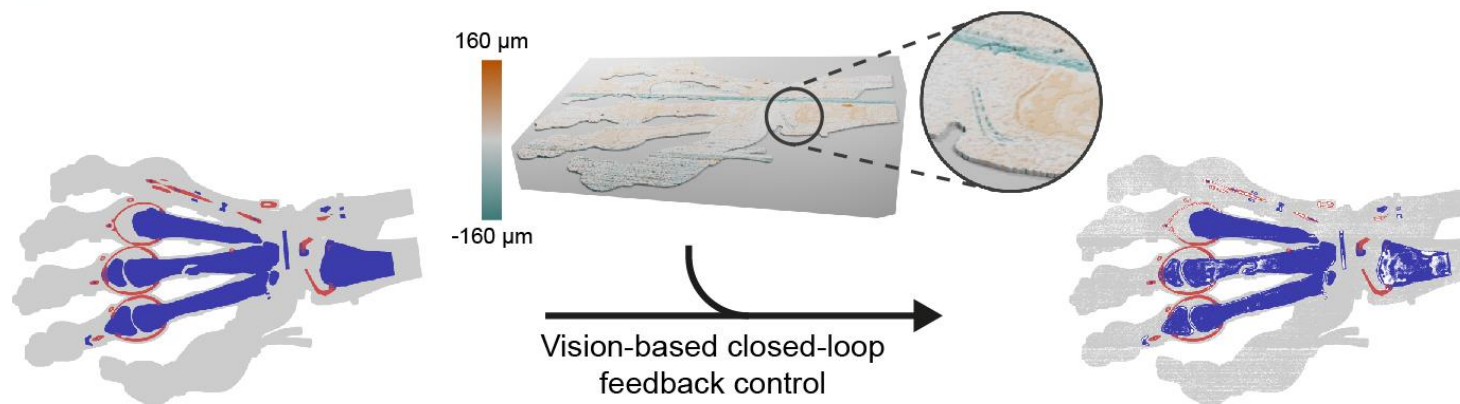
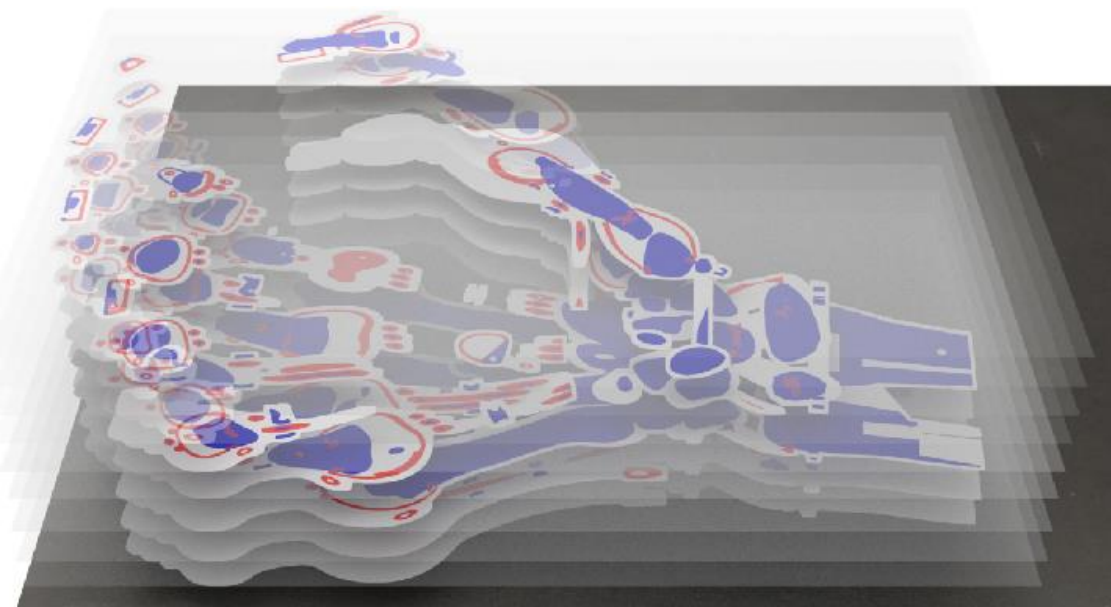
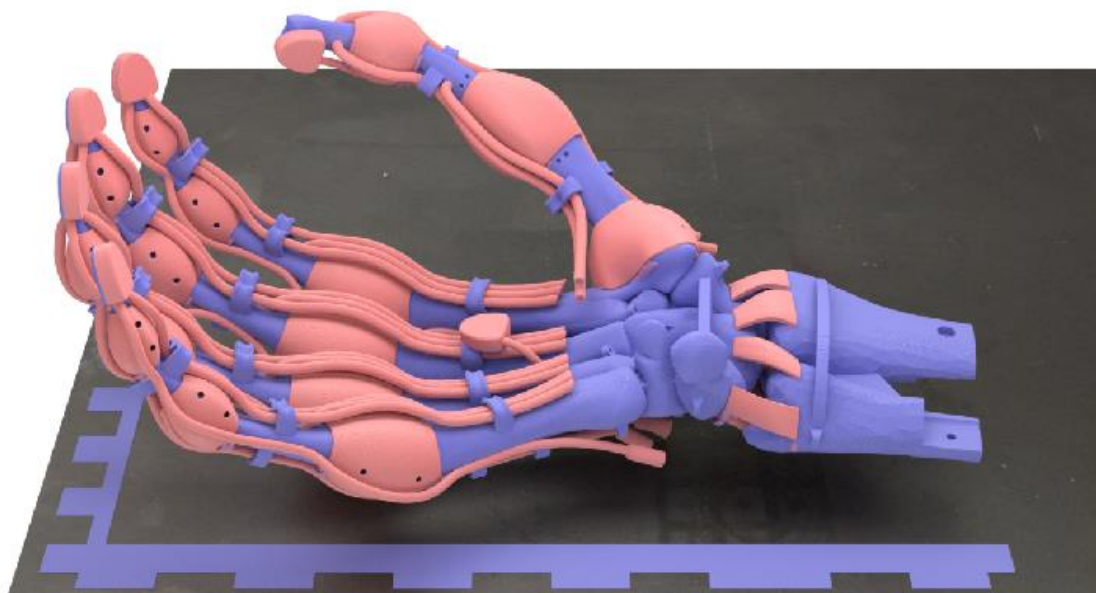
Buchner et al. *Nature* 2023

Vision Controlled Jetting: Contactless 3D Inkjet Deposition

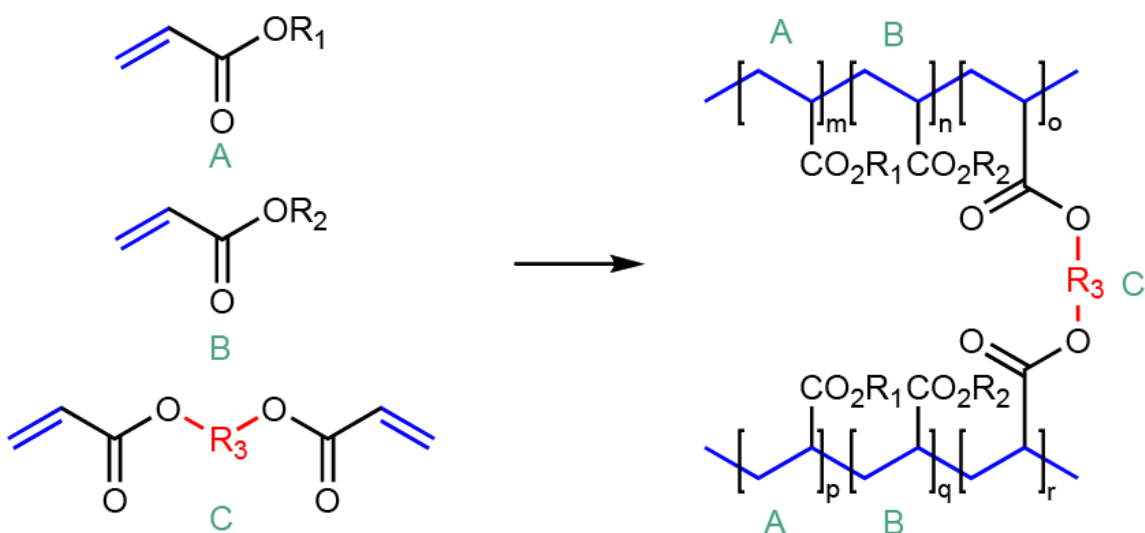


**PRINT
HEAD**

**UV
LIGHT**



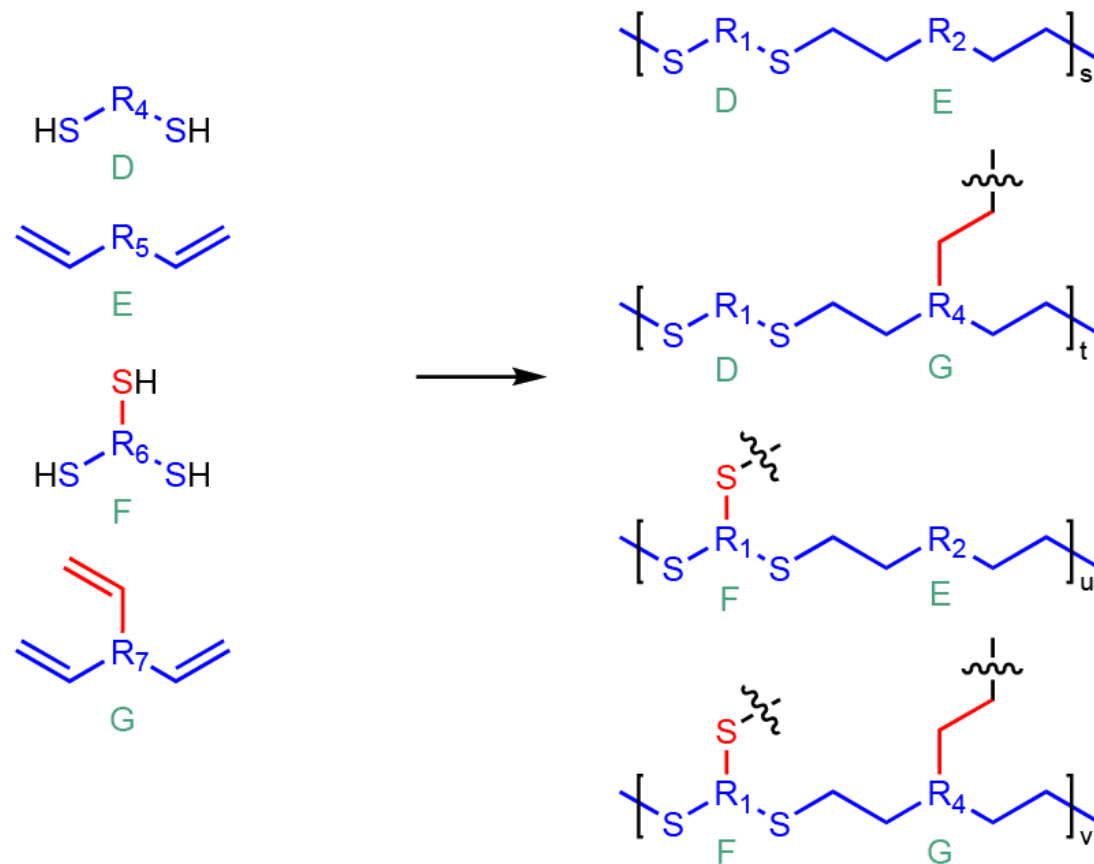
Acrylate



Chain Growth

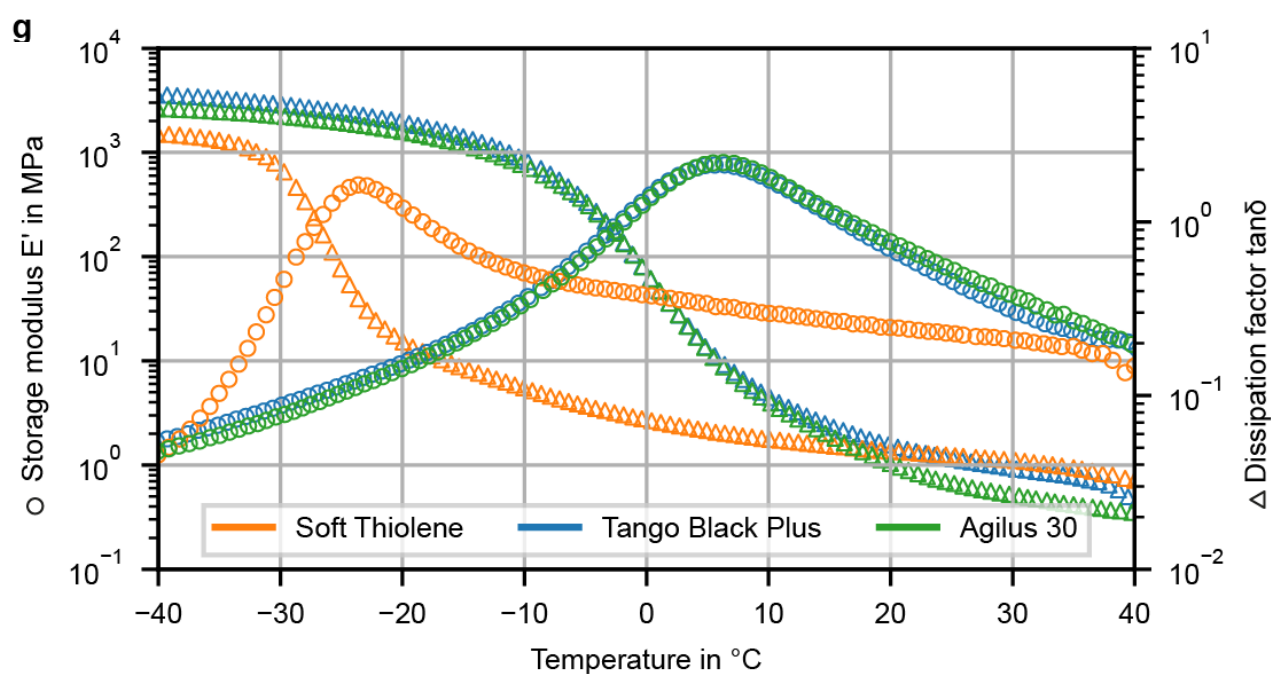
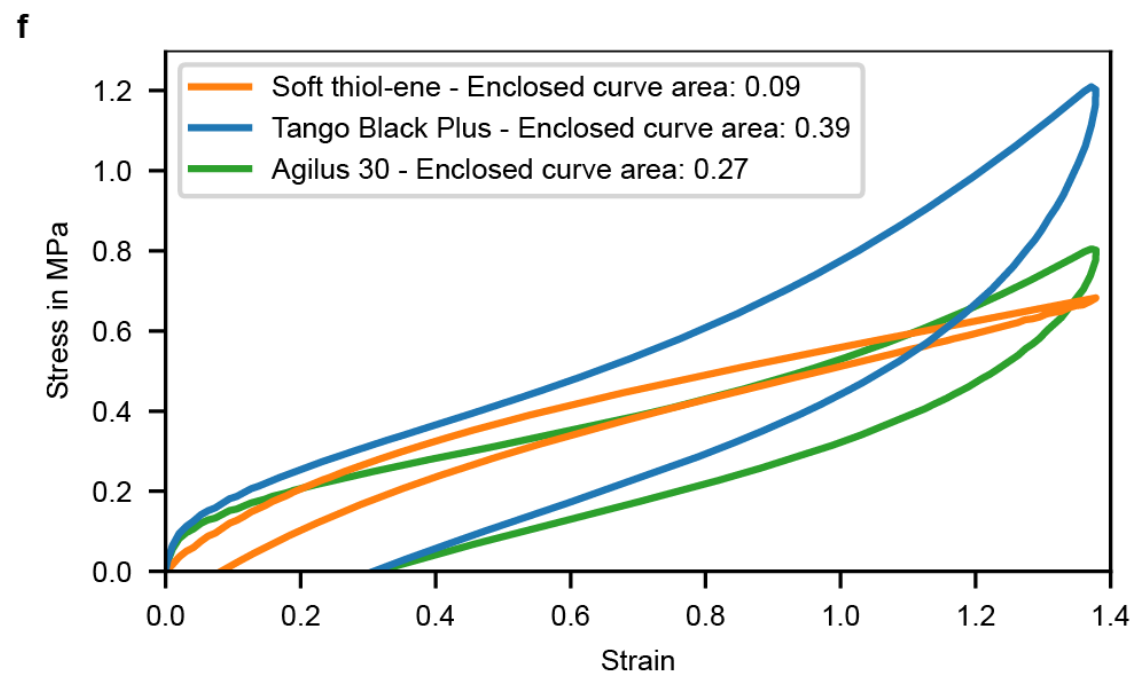
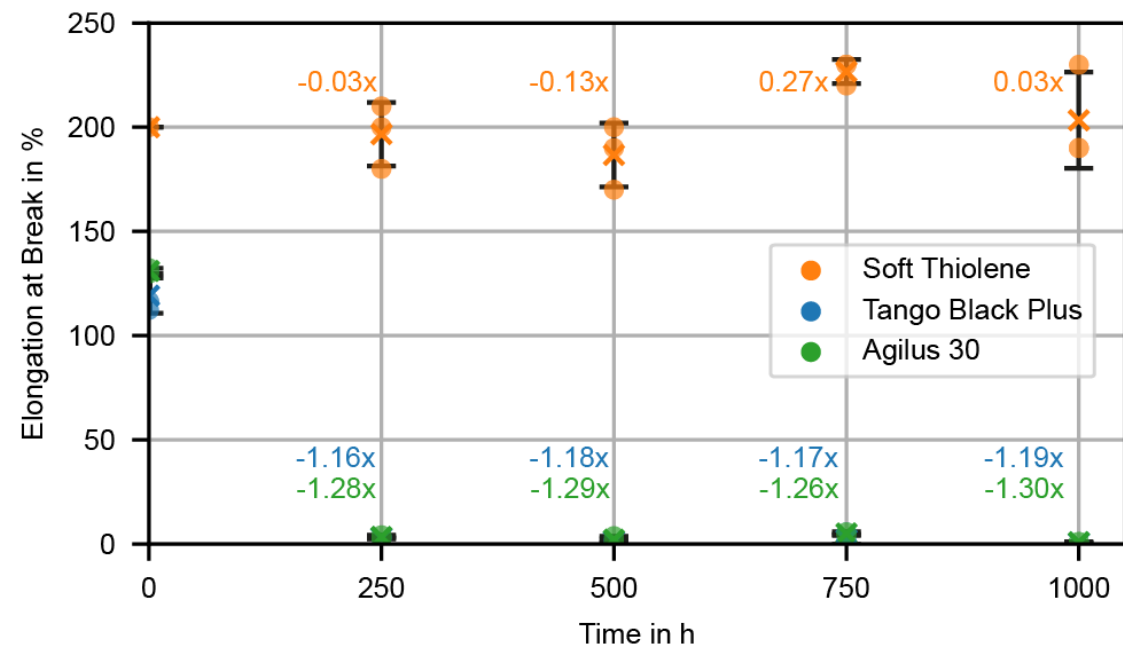
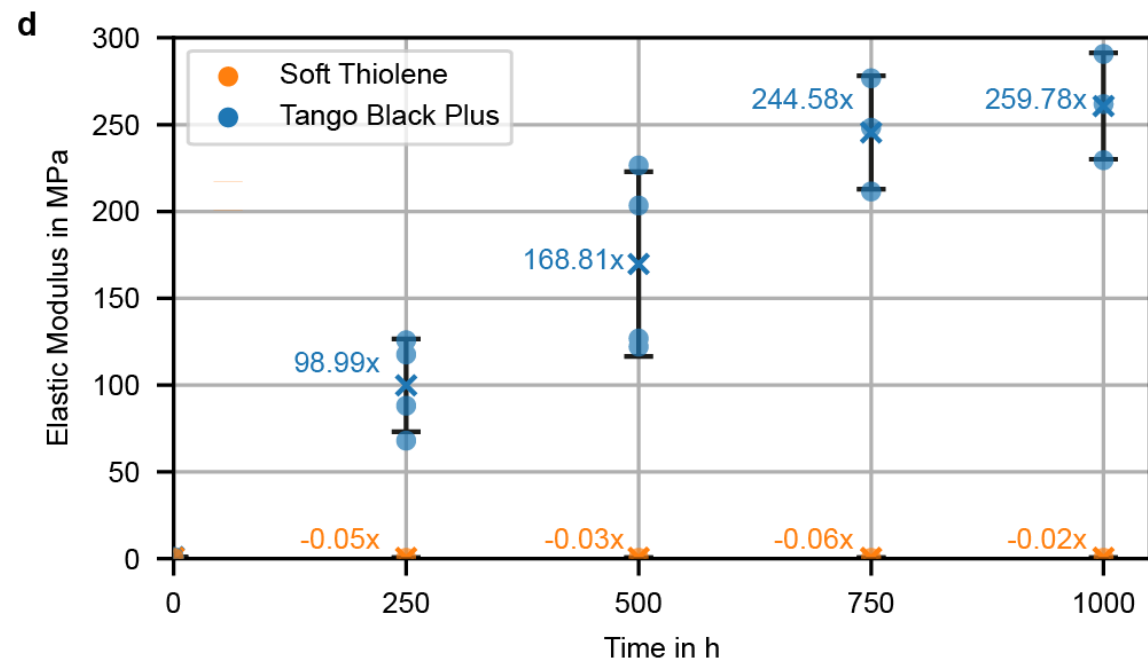
Random and irregular distribution of monomers

Step-growth polymer (Thio-lene, Epoxy, ...)



Step Growth

Regular backbone and crosslinking



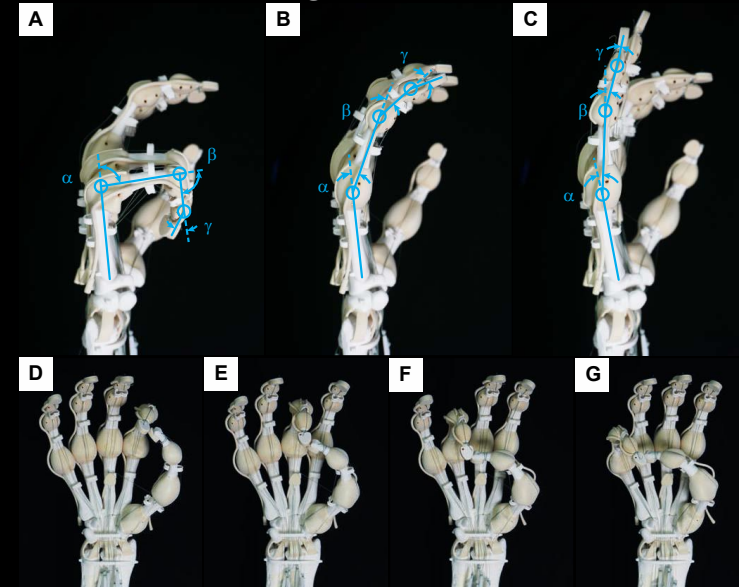




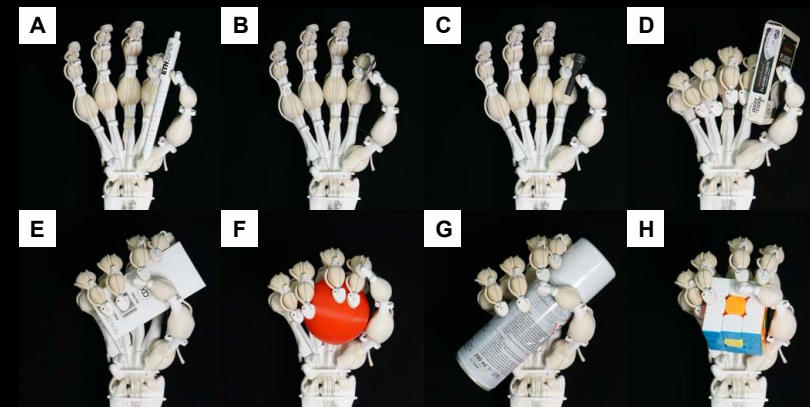
Integrating McKibben actuators



Range of Motion



Object Grasping





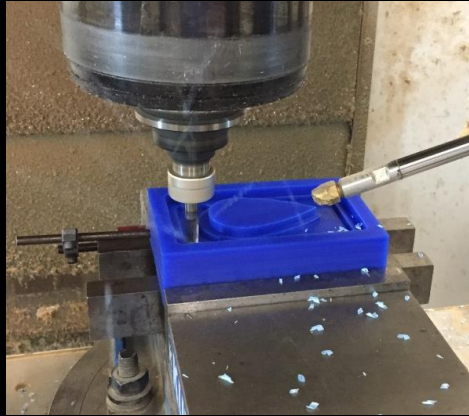
Summary

Machining, Joining, Casting, and 3D Printing

Fabrication Techniques for Robotic Hands



Summary



Machining

1. Drilling
2. Tapping
3. Laser cutting
4. Water jet cutting
5. Milling
6. Turning

...



Joining

1. Adhesive Bonding
2. Fastening
3. Soldering

...



Casting / Molding

1. Soft Stereolithography
2. Lost Wax Molding
3. Injection Molding

...



3D Printing / Additive Manufacturing

1. Fused deposition modeling (FDM)
Fused filament fabrication (FFF)
2. Direct Ink Writing (DIW)
3. Selective Laser Sintering (SLS)
4. Stereolithography (SLA)
5. 3D Inkjet printing

...

Open To Dos



1. Determine who in your team is responsible for the key to the workshop room
2. Start building your hands
3. Get access to the 3D printers
4. Please always scan for attendance.
5. Please set yourself up on Slack.
6. Please ask questions on Slack channels; do not use direct messages.
7. Please provide feedback to us about your experience in the course (in person or on Slack).