Bringing Dexterity to Robot Hands

Nancy Pollard

December 13, 2023

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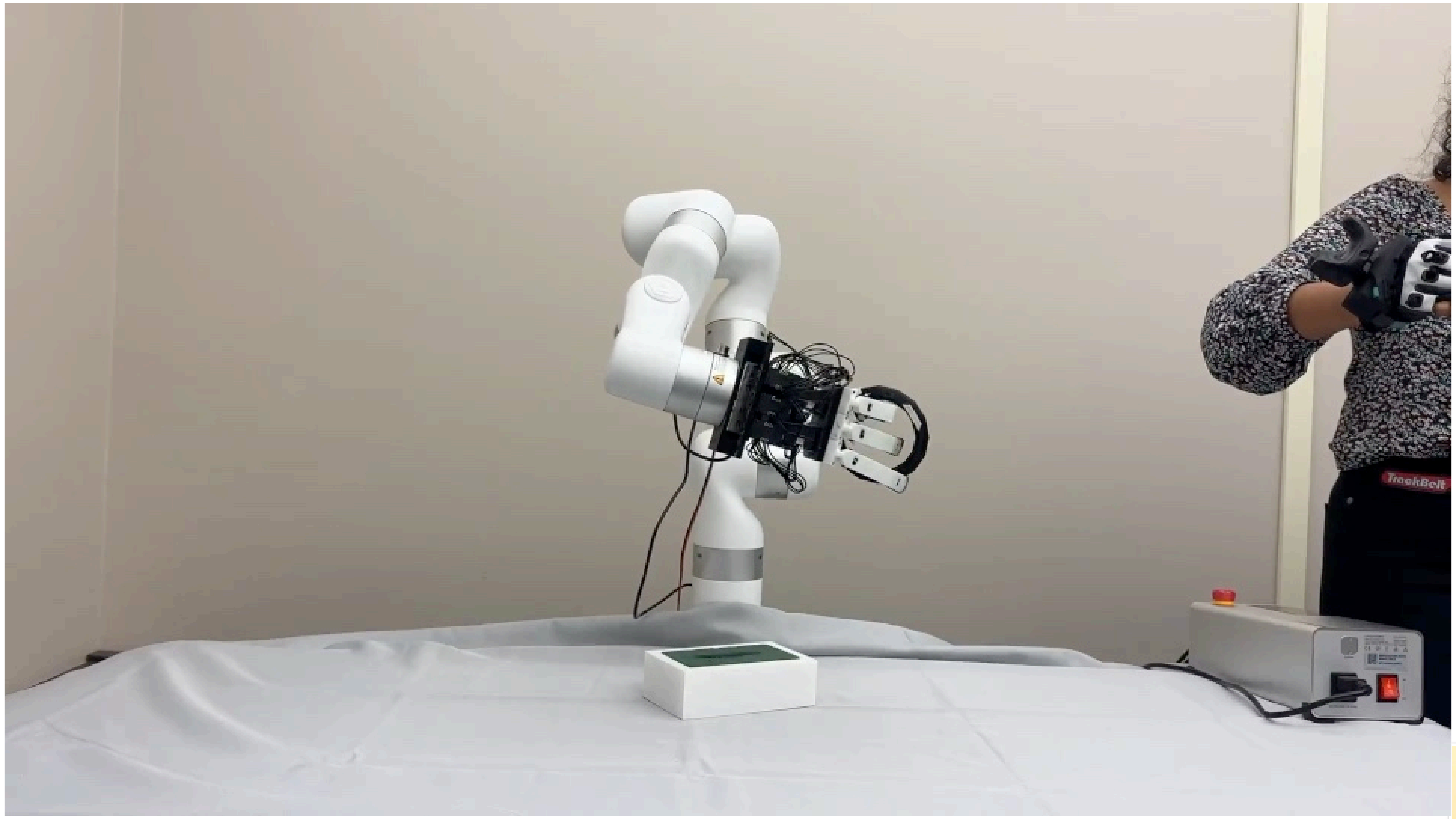
What is Dexterity?



Pragna Mannam, Kenneth Shaw, Dominik Bauer, Jean Oh, Deepak Pathak, and Nancy Pollard.
Designing Anthropomorphic Soft Hands through Interaction, Humanoids 2023

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What is Dexterity?

Bernstein's definition

Dexterity is the ability to find a motor solution for any external situation, that is, to adequately solve any emerging motor problem

– correctly (i.e., adequately and accurately)

– quickly (with respect to both decision making and achieving a correct result)

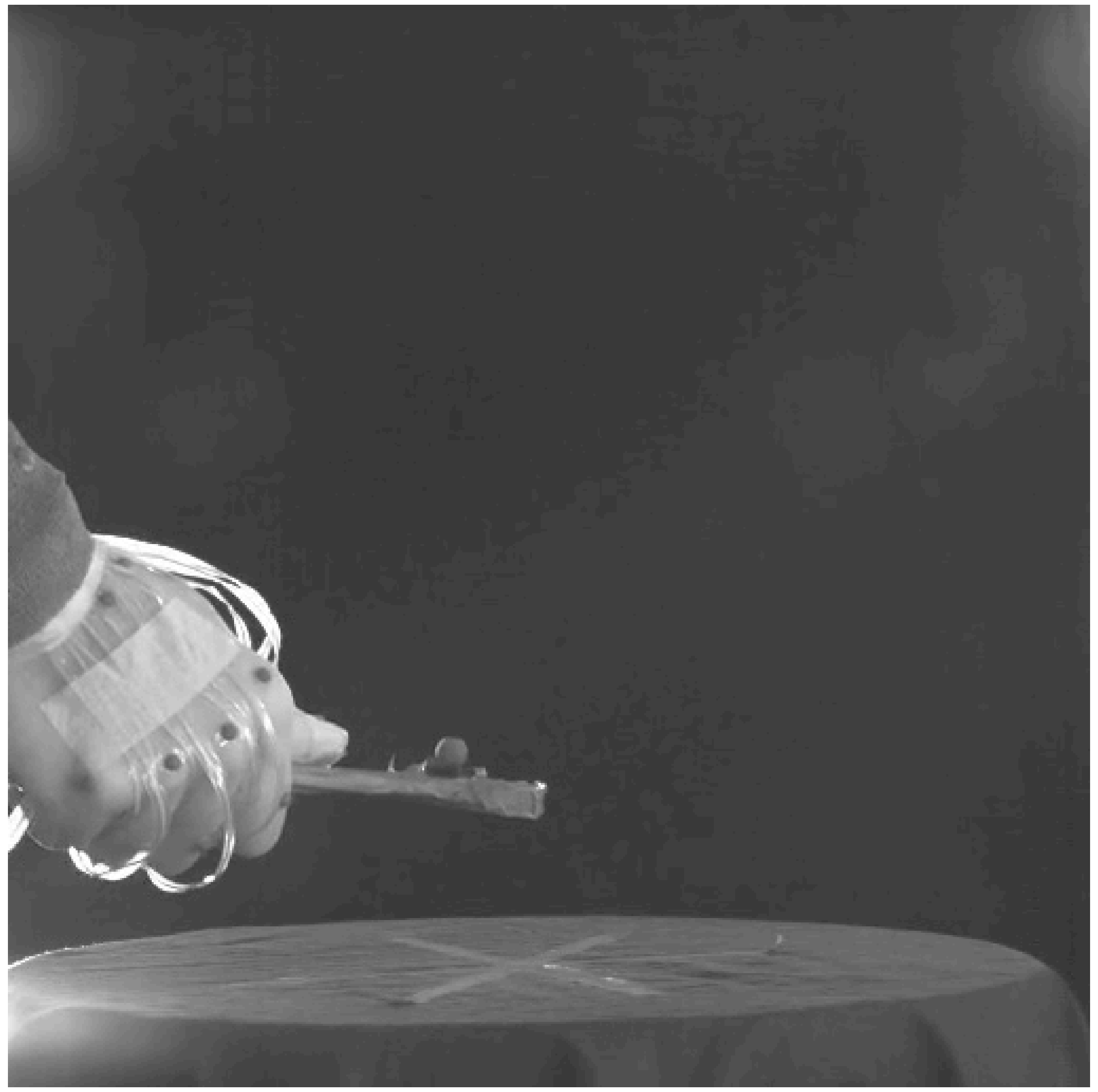
– rationally (i.e., expediently and economically), and

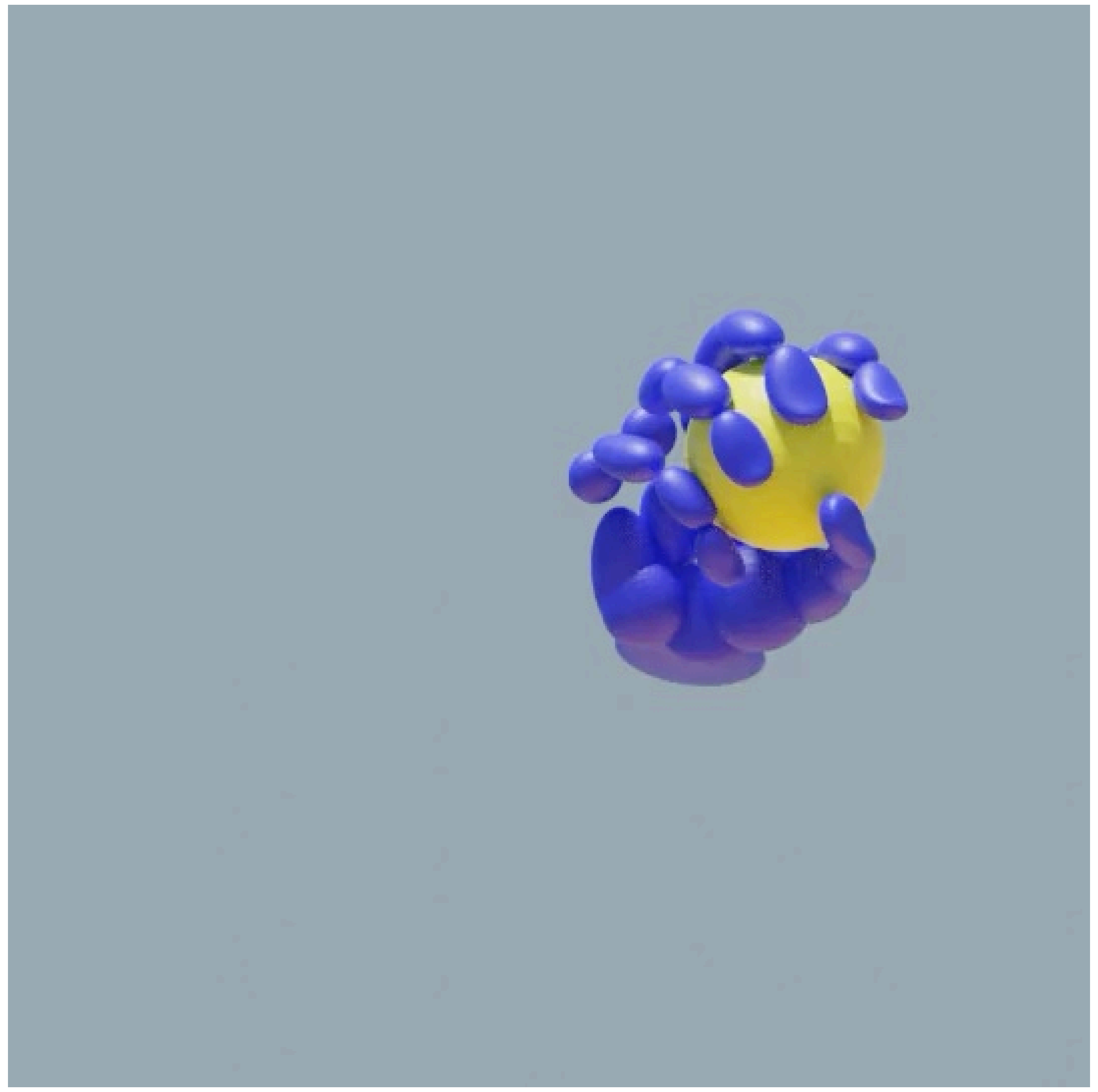
– resourcefully (i.e., quick-wittedly and initiatively)

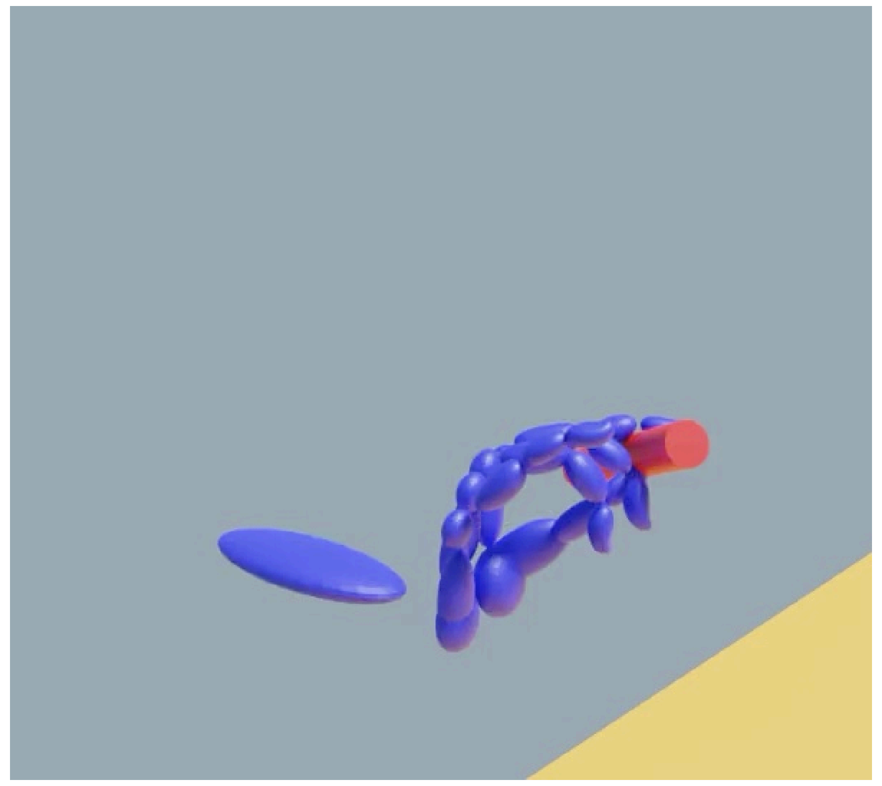
N. Bernstein, On Dexterity and Its Development, p. 228.

What is Dexterity?

Emerging Motor Problem







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What is Dexterity?

Some interesting things about these motions

- Contain many collisions,
- Appear tolerant of mistakes,
- Show ability to adapt to the unexpected, and are
- Ultimately successful!

What is Dexterity?

These motions..

- Contain many collisions,
- Appear tolerant of mistakes,
- Show ability to adapt to the unexpected, and are
- Ultimately successful!

How do we design for these capabilities?

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This talk

- Measuring Dexterity
- Contacts Everywhere
- Design for Dexterous Manipulation

Measuring Dexterity

Benchmarks for people

Benchmark	Target
Purdue Pegboard (1948)	Fine dexterity
Box and Blocks Test (1957)	Coarse dexterity
Jebsen Taylor Hand Function (1969)	Daily living
Kapandji Test (1986)	Thumb opposition
Sollerman Hand Function Test (1995)	Daily living, including bimanual
SHAP Test (2002)	Originally developed for prosthesis

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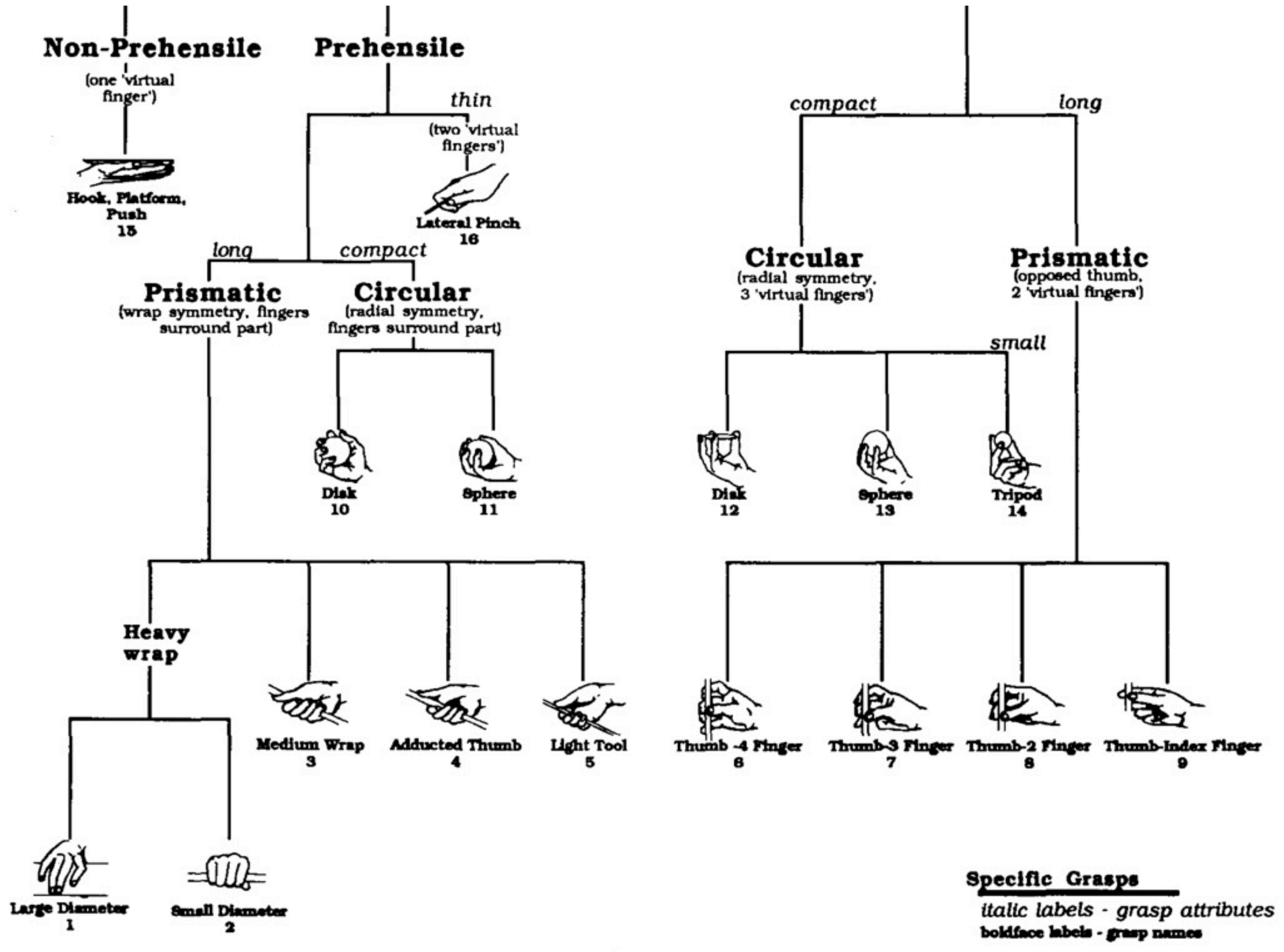
Measuring Dexterity

Benchmarks for robots

Benchmark	Target
NIST In-Hand Manipulation (2018)	Workspace of grasped object
NIST Assembly Taskboard (2020)	Insertions, meshing, threading
Modular Dexterity Test (2020)	Simple, reorient, fine, and tool manipulations
Bimanual Manipulation of Semi-Deformable Objects (2020)	Manipulate semi-deformable objects with tools
Box and Blocks (2020)	Coarse dexterity
In-Hand Benchmark (2020)	Workspace of a grasped object

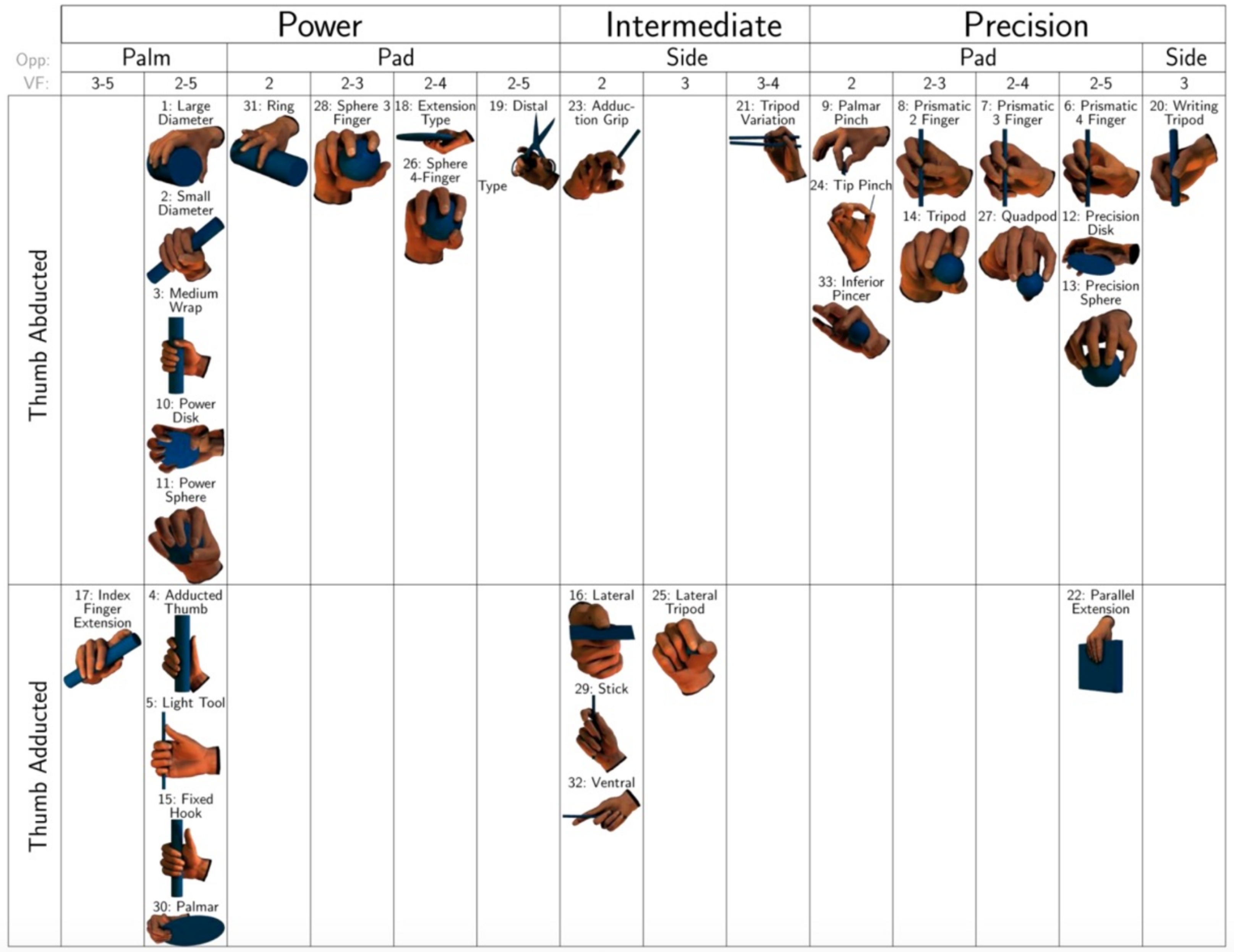
Measuring Dexterity

Grasp Taxonomies

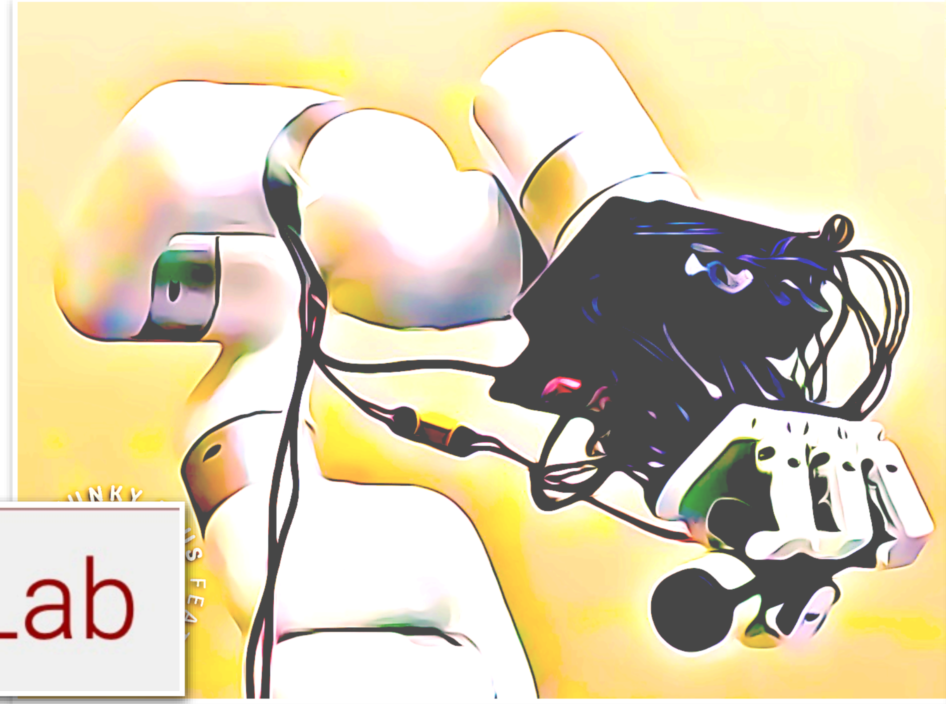


Cutkosky (1989)

Kamakura (1980)



Feix (2016)



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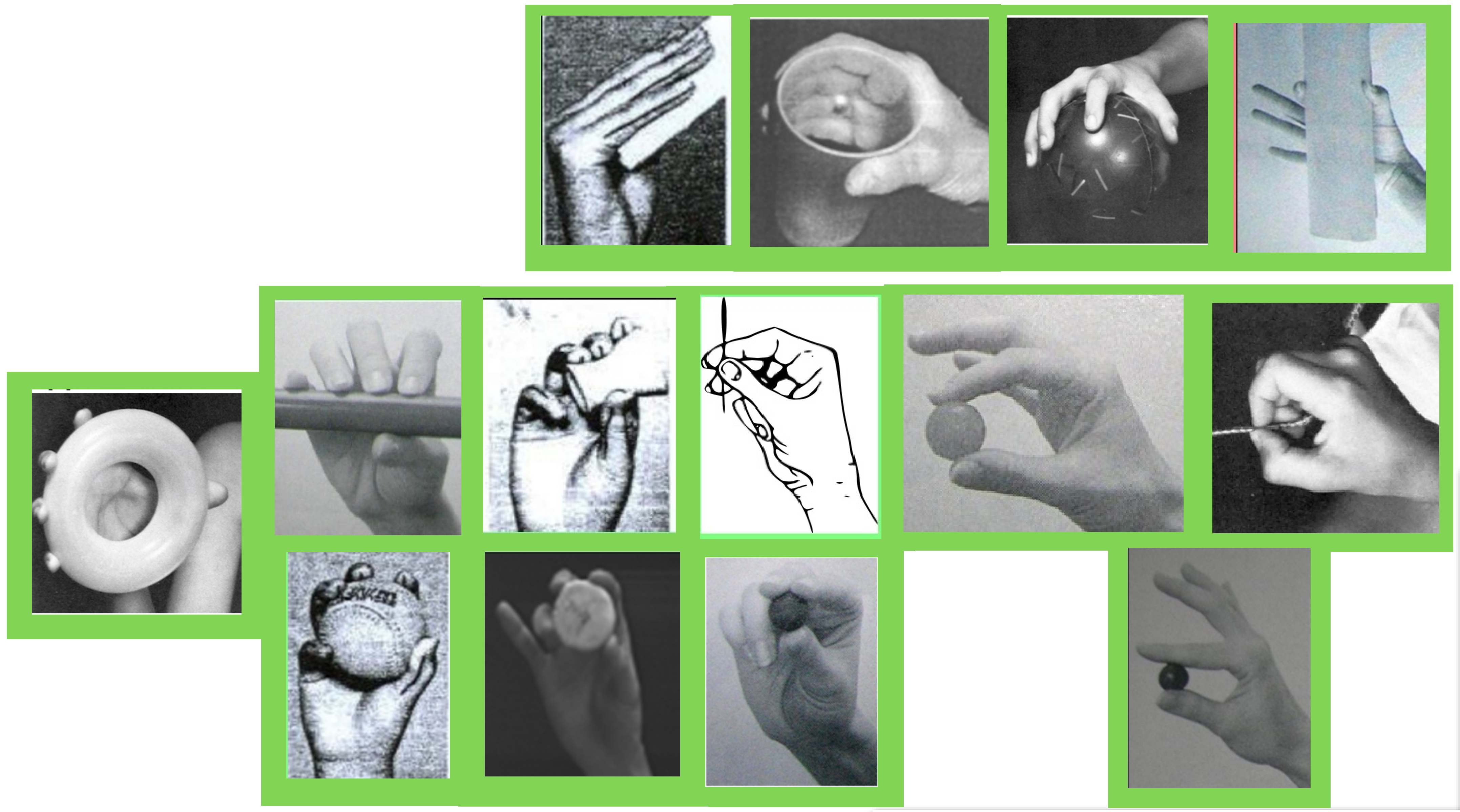
Measuring Dexterity

Power Palm

Lateral

Pad
Opposition



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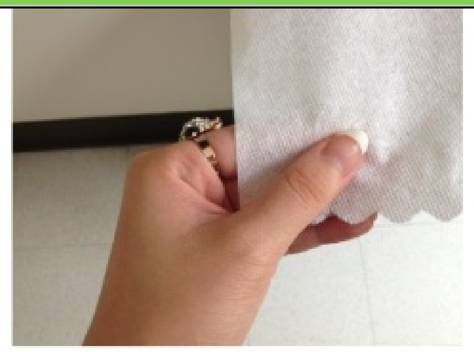
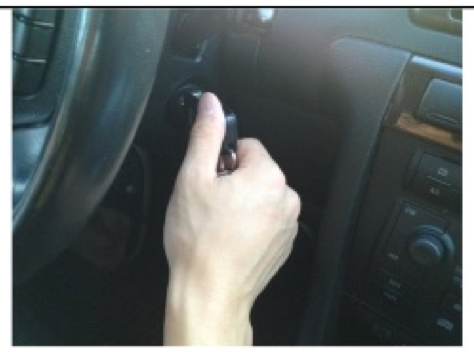
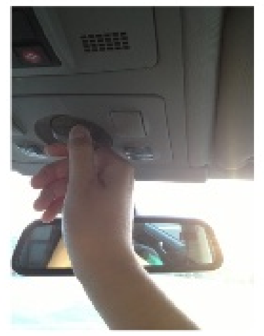
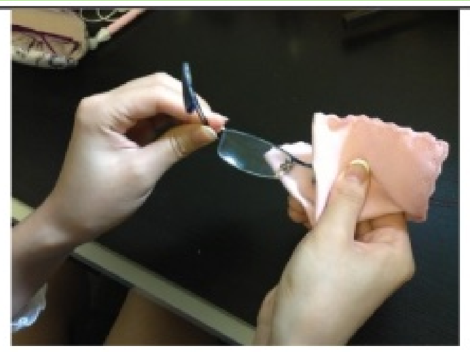
Measuring Dexterity

Expressing grasp function

Example		
Force Type	Pull	Pull
Motion Dir	-x (hand)	xz plane (hand)
Force Dir	-	-
Flow	Bound Motion/ Bound Force	Half Bound Motion/ Bound Force
Annotation	Put on gloves(along the arm)	Drag toilet paper
Example		
Force Type	Twist	Twist
Motion Dir	around y axis (hand)	around x axis (hand)
Force Dir	-	-
Flow	Bound Motion	Bound Motion
Annotation	Twist the key to start up the car	Twist the knob in car

Example		
Force Type	Hold	Rub/Stroke
Motion Dir	xy plane (hand)	xy plane (hand)
Force Dir	-	inwards (hand)
Flow	Free Motion/ Half Bound Force	Half Bound Motion/ Bound Force
Annotation	Give card to someone	Wipe classes
Example		
Force Type	Hold	Hold
Motion Dir	z (global)/ -z (global)/ around x axis (hand)	around x axis (hand)
Force Dir	-	-
Flow	Free Motion/ Bound Force	Half Bound Motion/ Bound Force
Annotation	Eat with scoop	Pour washing powder

179 grasps

20 different action verbs

Jia Liu, Fengxiaoyu Feng, Yuzi Nakamura, and Nancy S. Pollard, 2014. A Taxonomy of Everyday Grasps in Action, Humanoids 2014.

http://www.cs.cmu.edu/~jialiu1/database.html

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Measuring Dexterity

Pick up the object

Transition to functional (e.g., power) grasp

Use the object as a tool

Transition grasp again (e.g., to precision grasp)

Place object

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Measuring Dexterity

Pick up the object

Transition to functional (e.g., power) grasp

Use the object as a tool

Transition grasp again (e.g., to precision grasp)

Place object

Measuring Dexterity

Pick up the objec

Transition to fu ...) grasp

Use the objec

Transition grasp again (e.g., ... rasp)

Place object

Is there a general dexterity measure for grasp transitions?

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Measuring Dexterity

A CLASSIFICATION OF MANIPULATIVE HAND MOVEMENTS

J. M. Elliott
K. J. Connolly

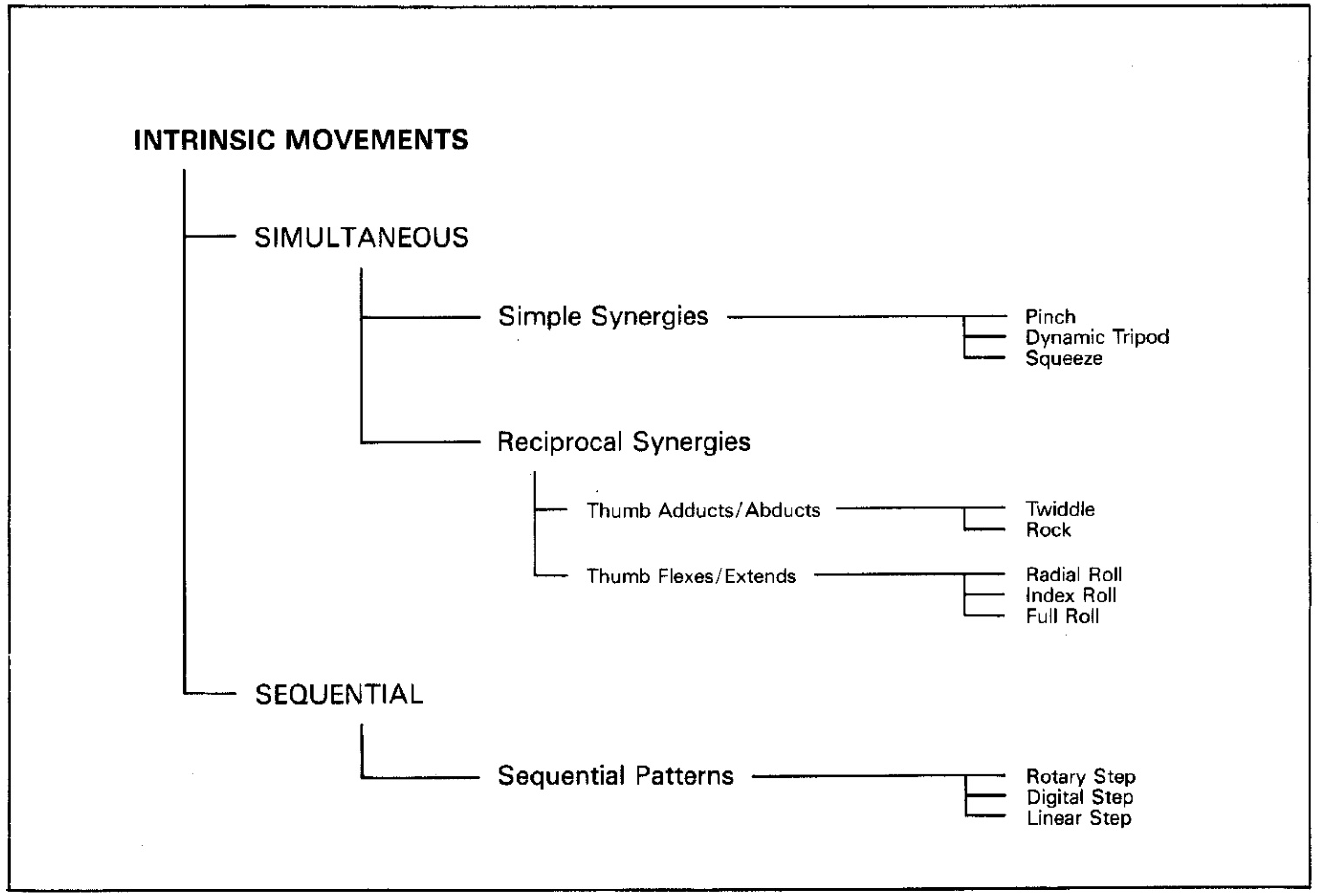


***Fig. 1.** Classification of intrinsic hand movements.*

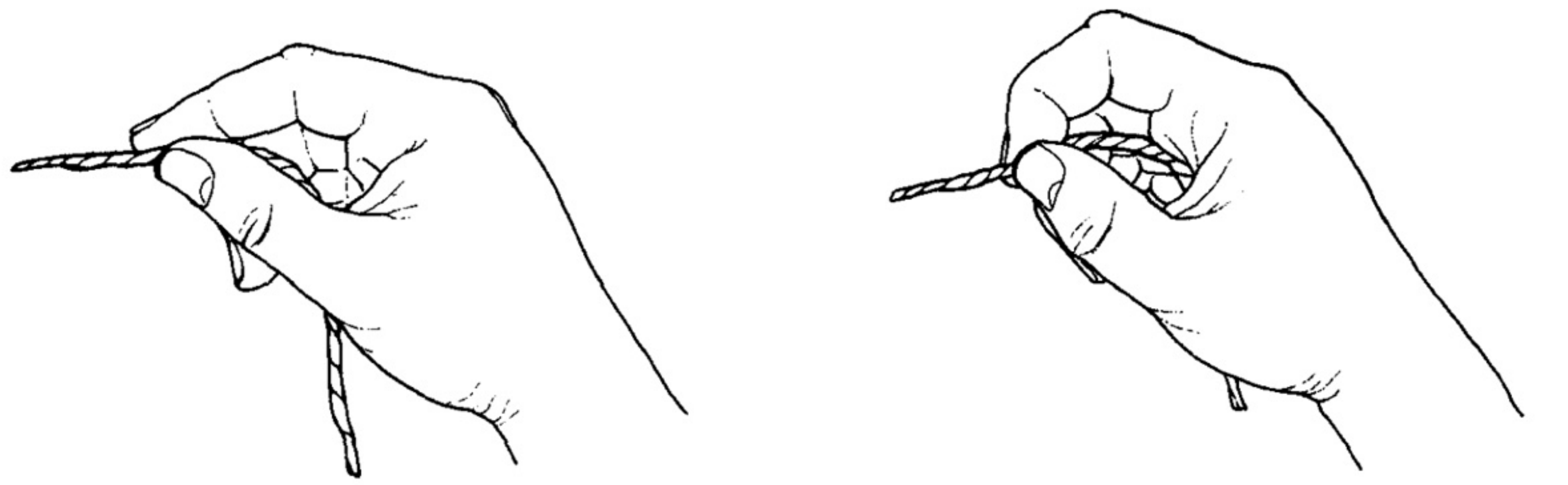


***Fig. 4.** Pinch:* (a) *thumb and index extended,* (b) *thumb and index flexed. These represent terminal positions for digits when executing this pattern of movement.*

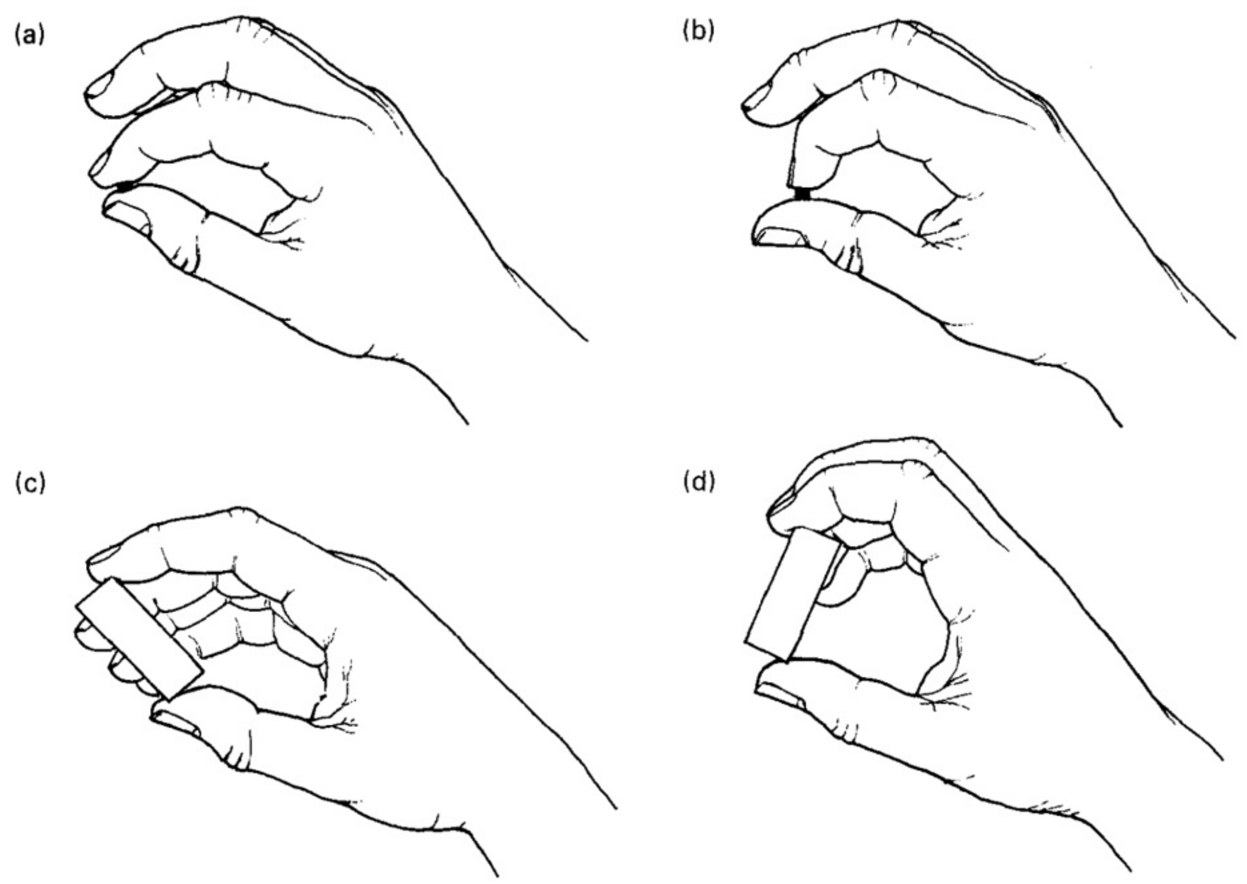
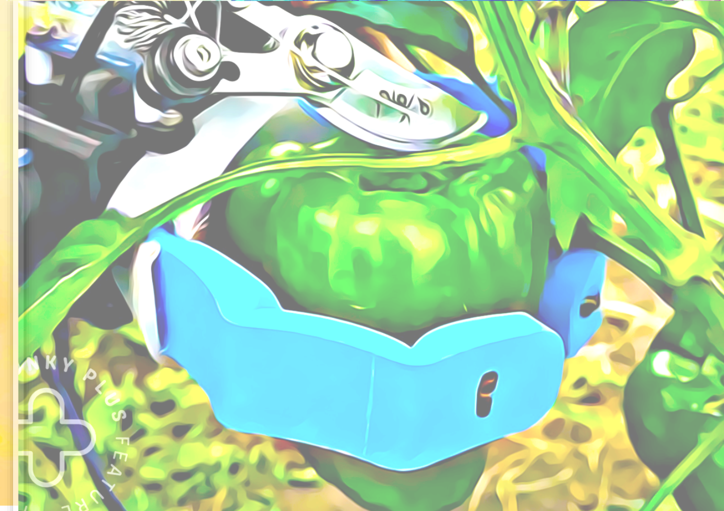


***Fig. 11.** Index Roll* (a,b), *showing slight reciprocal flexion of thumb and extension of index* (a), *and the reverse* (b). *Full roll* (c,d), *as for index roll, but with involvement of additional digits. The object rocks about the radio-ulnar axis as result of movement between positions illustrated.*

Elliott JM, Connolly KJ. A classification of manipulative hand movements. Developmental Medicine & Child Neurology. 1984



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Measuring Dexterity

Elliott and Connolly Primitives Capture Grasp Transitions

6. Prismatic 4-finger

6. Prismatic 4-finger

Rock

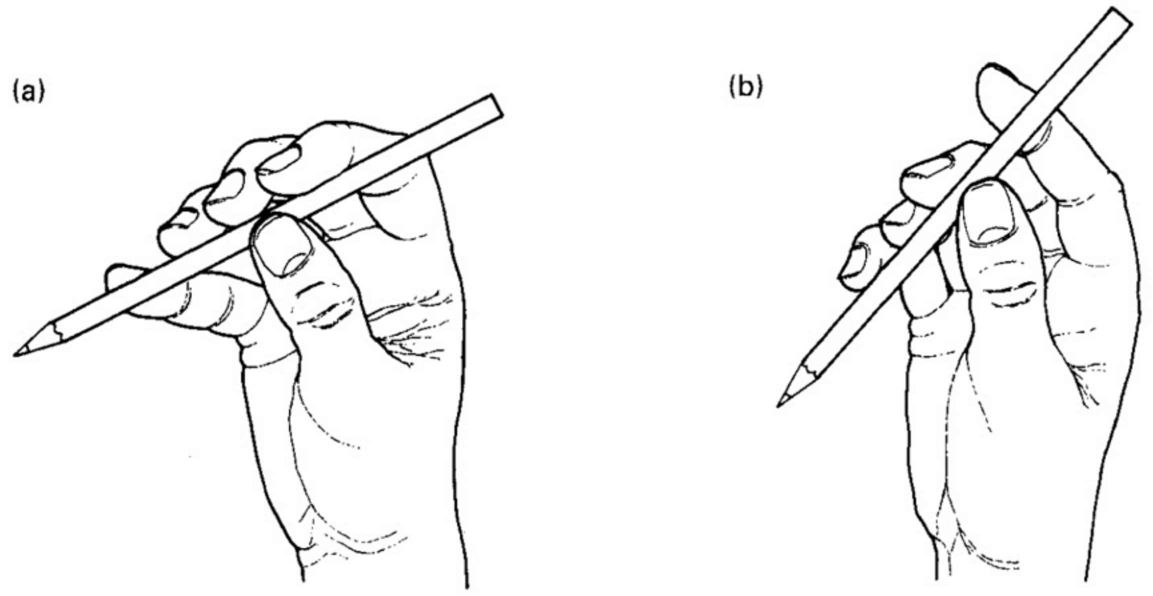
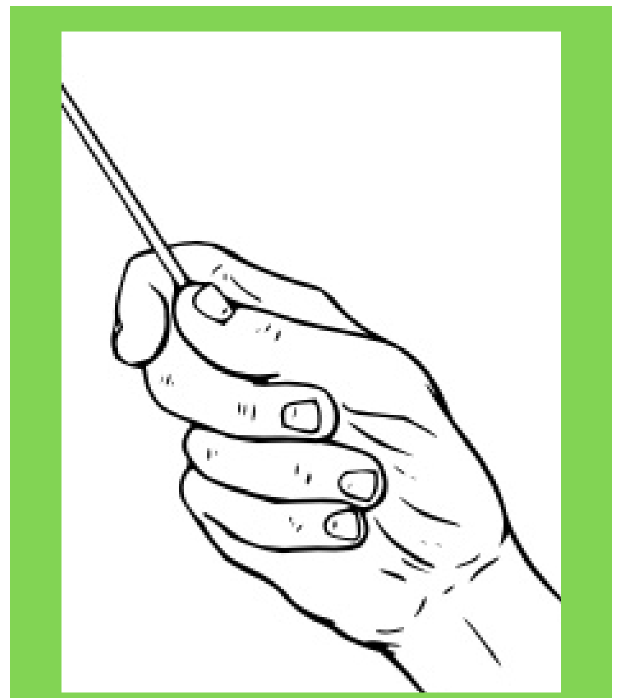
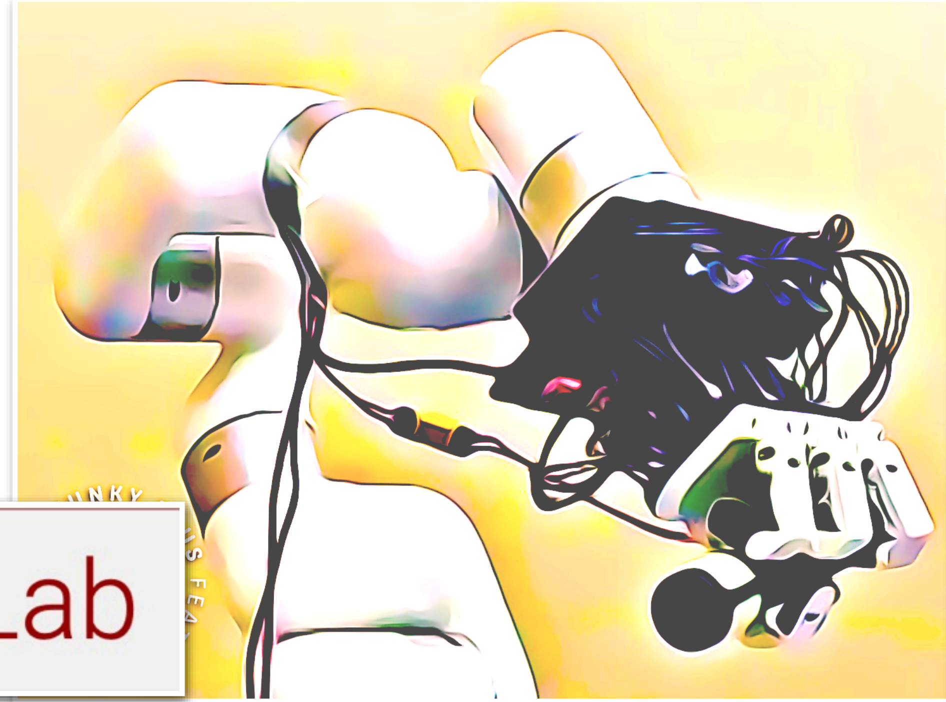


Fig. 9. Rock: illustrated with pencil held transversely, in radio-ulnar axis. Movements of thumb and digit 3 are much reduced compared with movements of other digits. (a) Ulnar digits relatively extended, (b) ulnar digits relatively flexed.



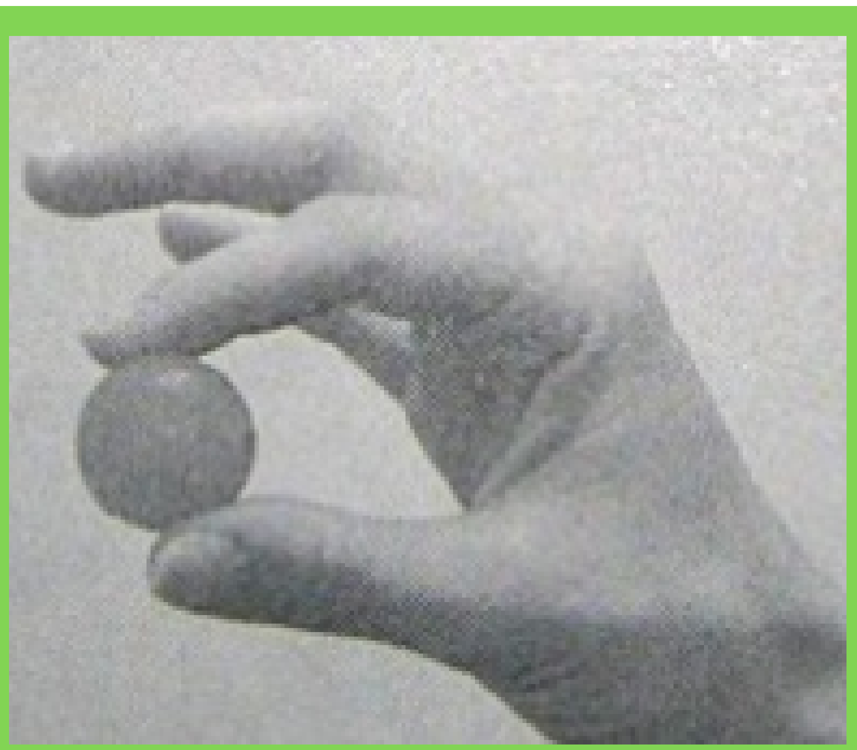
29. Stick

32. Ventral



Measuring Dexterity

Elliott and Connolly Primitives Capture Grasp Transitions



9. Palmar Pinch

Pinch

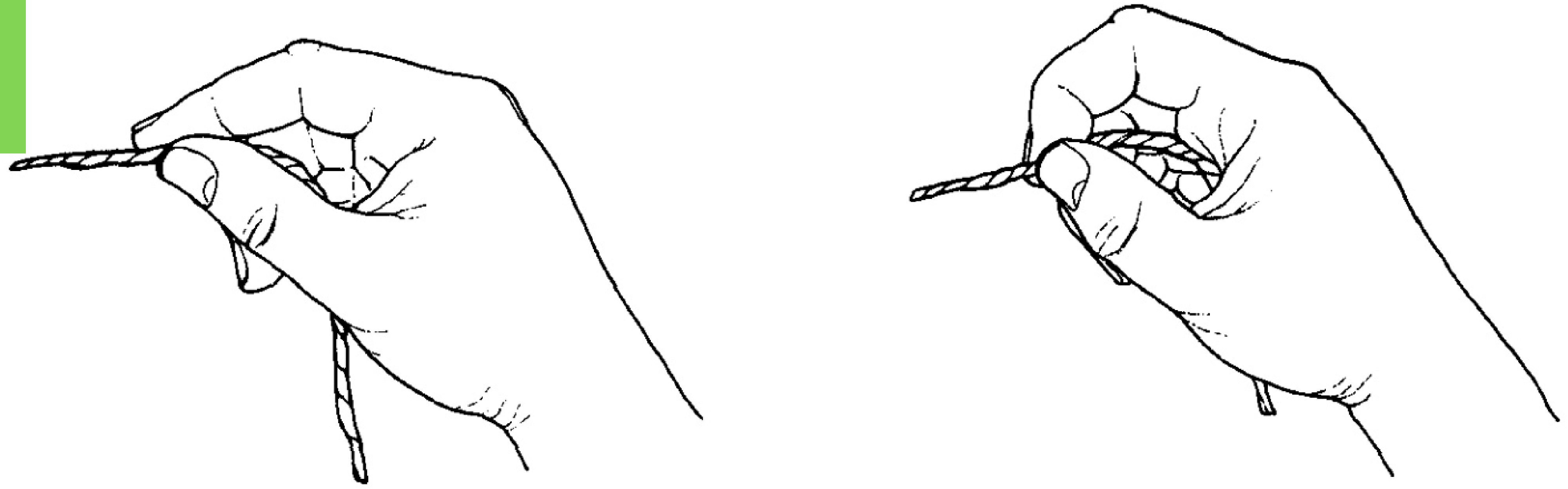


Fig. 4. Pinch: (a) *thumb and index extended,* (b) *thumb and index flexed. These represent terminal positions for digits when executing this pattern of movement.*

24. Tip Pinch

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Elliott and Connolly Primitives Capture Grasp Transitions

20. Writing Tripod

23. Adduction Grip

Digital Step

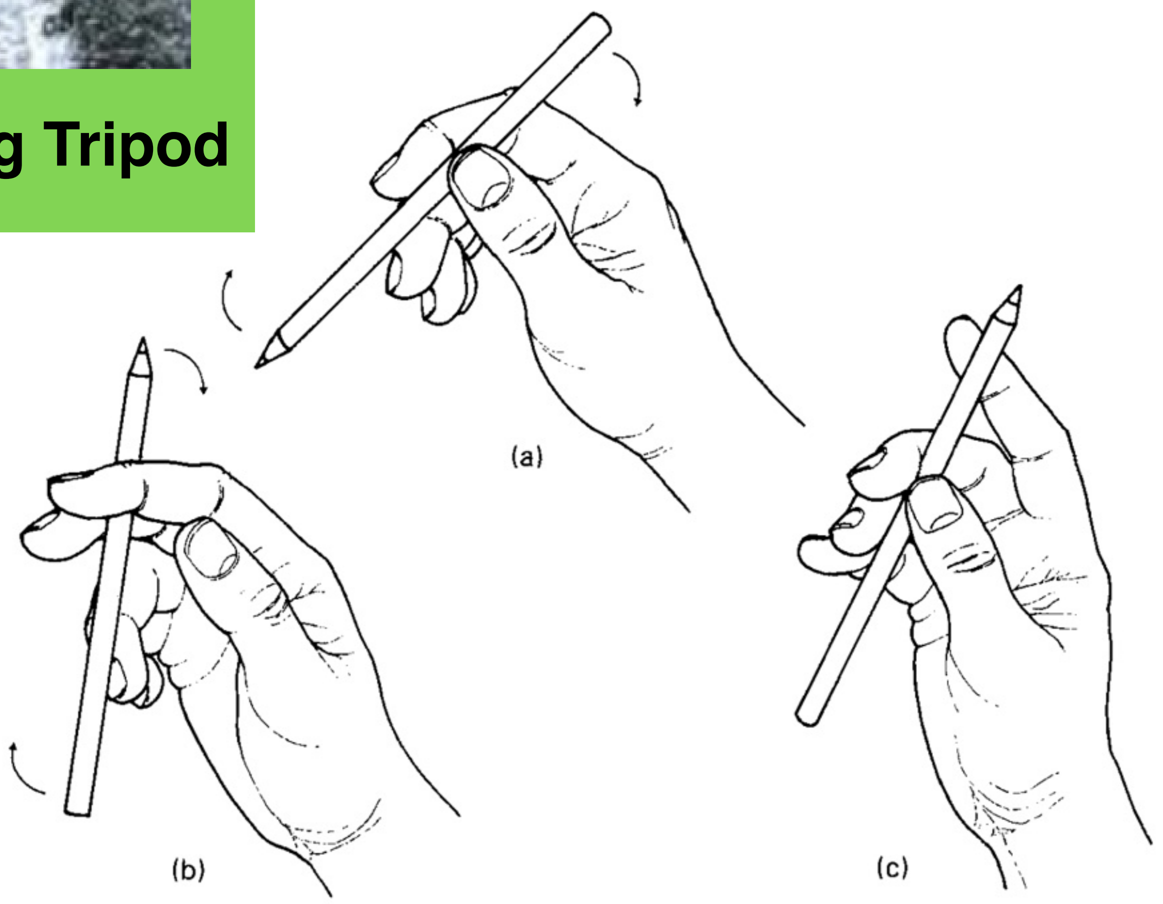

Fig. 13. Interdigital Step: from (a) to (b) the object is rotated by extension of ulnar digits, especially digit 3. Flexed thumb passes under rotating object to assume its position at (b). From (b) to (c), thumb and ulnar digits flex to grasp object and index extends and may lose contact with it. From (c) to (a), index flexes to preserve position of object against thumb, while ulnar digits flex to reposition below object in readiness for next cycle.

32. Ventral

6. Prismatic 4-finger

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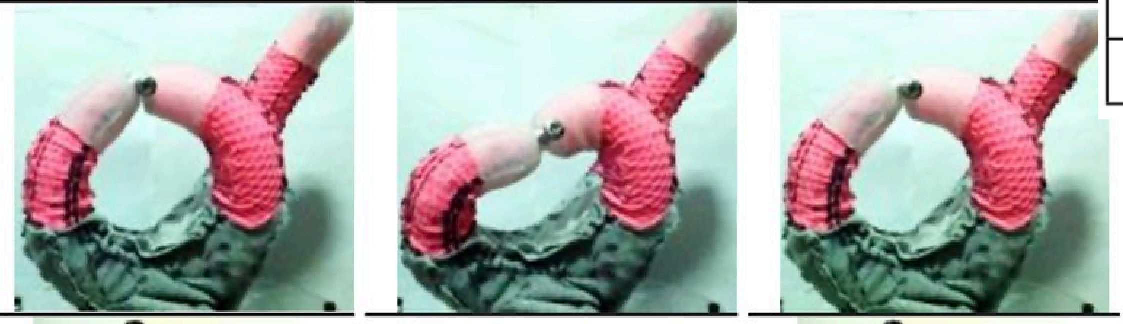
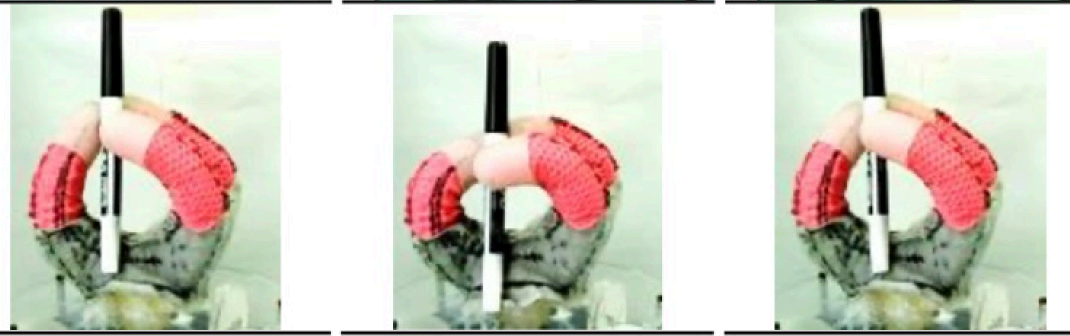
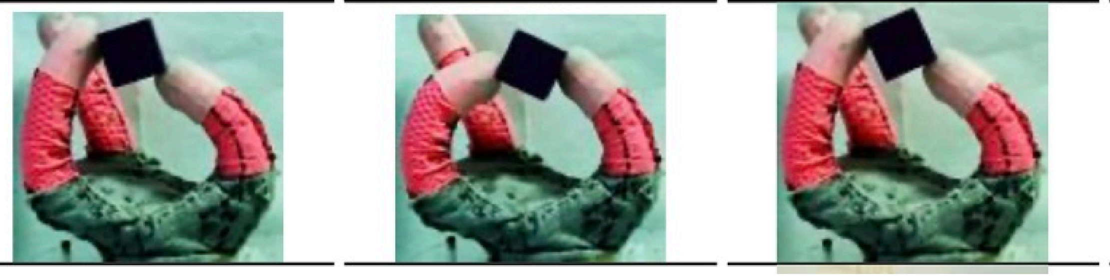
Measuring Dexterity

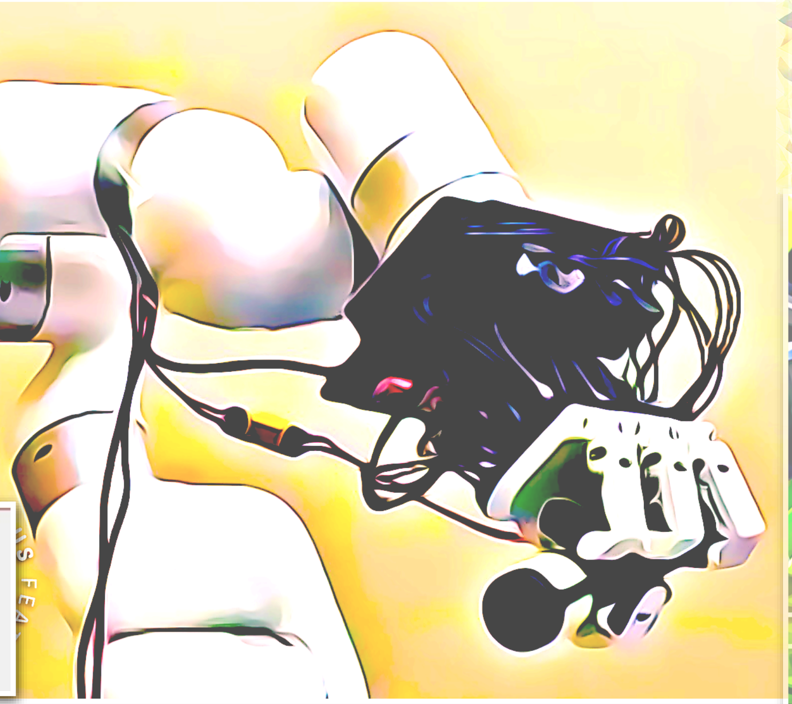
Elliott and Connolly Benchmark

Manipulation Pattern	Object	YCB ID
Pinch (P)	Bolt & Nut	46, 47
Dynamic Tripod (DT)	Small Marker	41
Squeeze (S)	Syringe	N/A
Twiddle (T)	Bolt & Nut	46, 47
Rock (R)	Cup (yellow)	64
Rock II (RII)	Small Marker	41
Radial Roll (RR)	Marble (green)	62
Index Roll (IR)	Marble (green)	62
Full Roll (FR)	Wood Block	69
Rotary Step (RS)	Cup (yellow)	64
Interdigital Step (IS)	Small Marker	41
Linear Step (LS)	Large Marker	40
Palmar Slide (PS)	Large Marker	40

Pattern	Criteria	Sub-Class	Category	Success/ Failure	Sequence
Pinch (P)	Object is held between two fingers. Both fingers are flexed simultaneously in order to translate the object along the ventro-dorsal axis, towards the palm. Fingers are then simultaneously extended to bring the object back to its starting position.	N/A	Δ_z(NA)	Success	
Dynamic Tripod (DT)	Object is held between three fingers. All three fingers are simultaneously flexed and extended, in repetitive motions, in order to translate the object along the ventro-dorsal axis. Application: writing.	N/A	Δ_z(NA)	Success	
Radial Roll (RR)	Object is held between the distal phalanx of one finger (stabilizing finger) and along the side of the proximal phalanx of another finger (manipulating finger). The manipulating finger is flexed and extended in order to roll the object along the length of the stabilizing finger.	Rolling	Δ_z(A) θ_x(A)	Success	
Index Roll (IR)	Object is held between the distal phalanxes of two fingers. One finger is then repetitively flexed and extended in order to roll the object along the length of the other finger.	Rolling	Δ_z(A) θ_x(A)	Success	
Full Roll (FR)	Object is held between distal phalanxes of two fingers. One finger is then repetitively flexed and extended in order to pivot object about a stationary point on the other finger.	N/A	θ_x(NA)	Success	

13 manipulation patterns

measure rotation angle, travel distance



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Ryan Coulson, Chao Li, Carmel Majidi, and Nancy S. Pollard, The Elliott and Connolly Benchmark: A Test for Evaluating the In-Hand Dexterity of Robot Hands, Humanoids 2021

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Measuring Dexterity

What does a hand designed for Elliott & Connolly look like?

Ryan Coulson, Chao Li, Carmel Majidi, and Nancy S. Pollard, The Elliott and Connolly Benchmark: A Test for Evaluating the In-Hand Dexterity of Robot Hands, Humanoids 2021

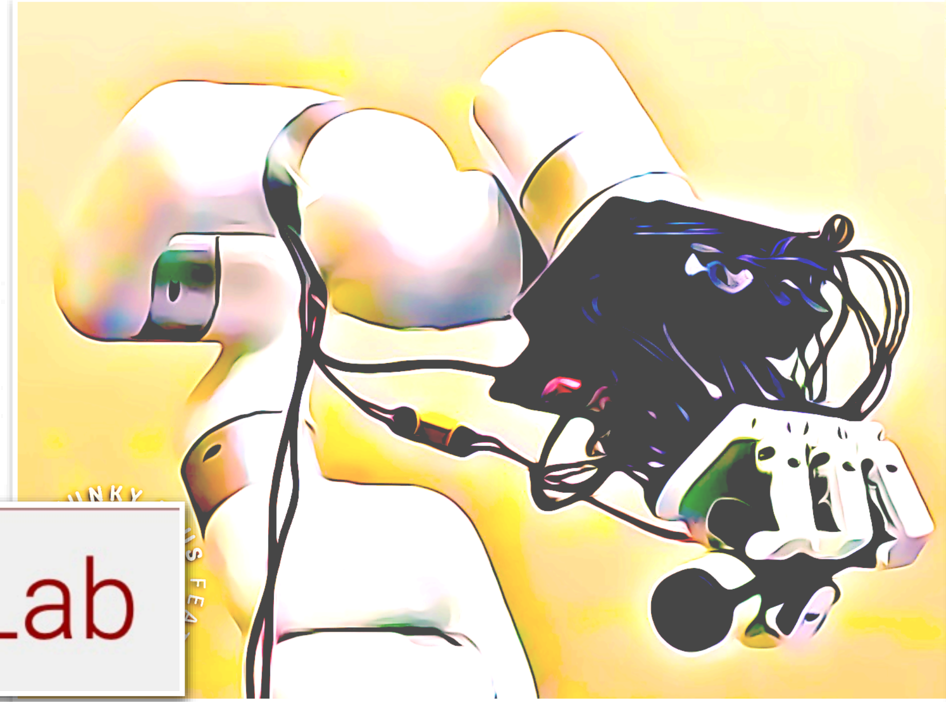
This talk

- Measuring Dexterity
    - dexterity involves creating change with intention / in-hand manipulation patterns (rock, roll, twiddle, step…) can be observed in grasp transitions
- **Contacts Everywhere**
- Design for Dexterous Manipulation

Contacts Everywhere

Kamakura Taxonomy

Kamakura N, Matsuo M, Ishii H, Mitsuboshi F, Miura Y. Patterns of static prehension in normal hands. American Journal of Occupational Therapy. 1980



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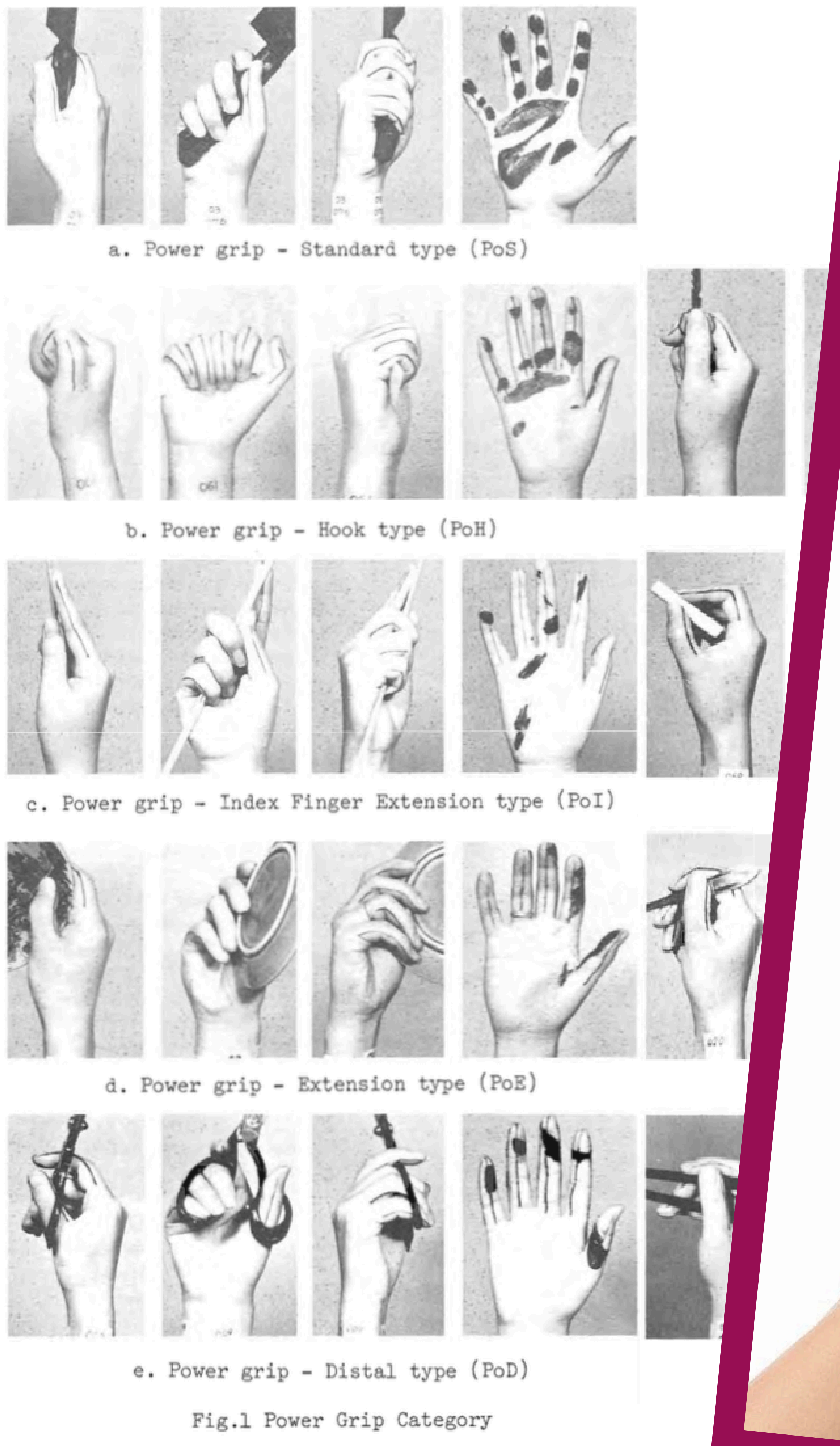
Contacts Every

amakura
axonomy



Kamakura N, Matsuo M, Ishii H, Mitsuboshi F, Miura Y. Patterns of static prehension in normal hands. American Journal of Occupational Therapy. 1980

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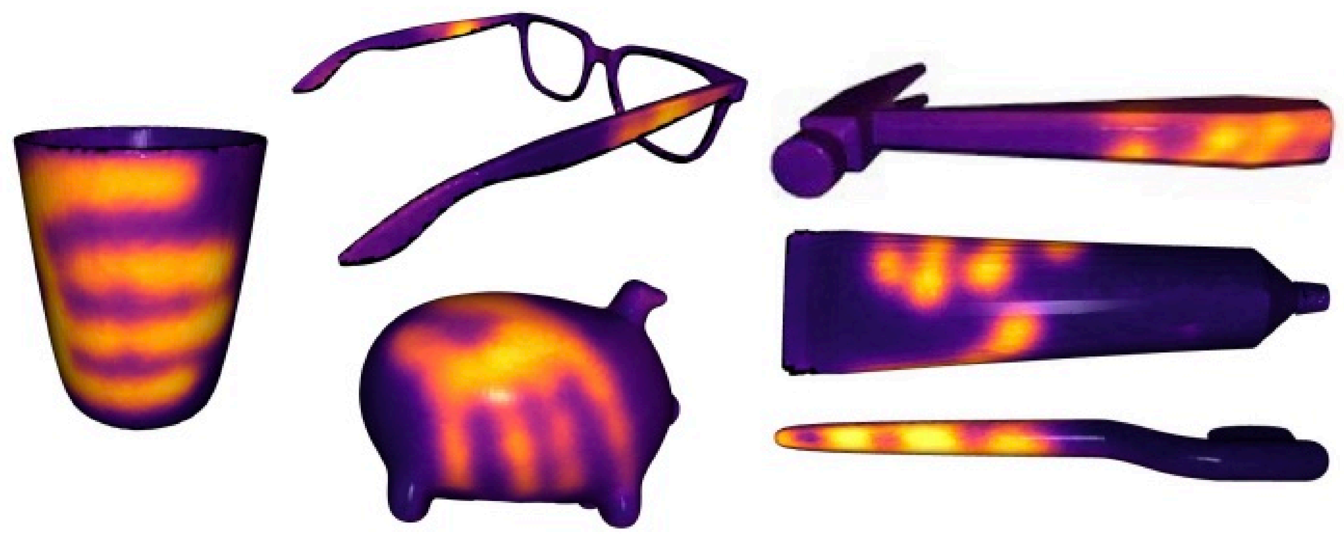
Contacts Everywhere

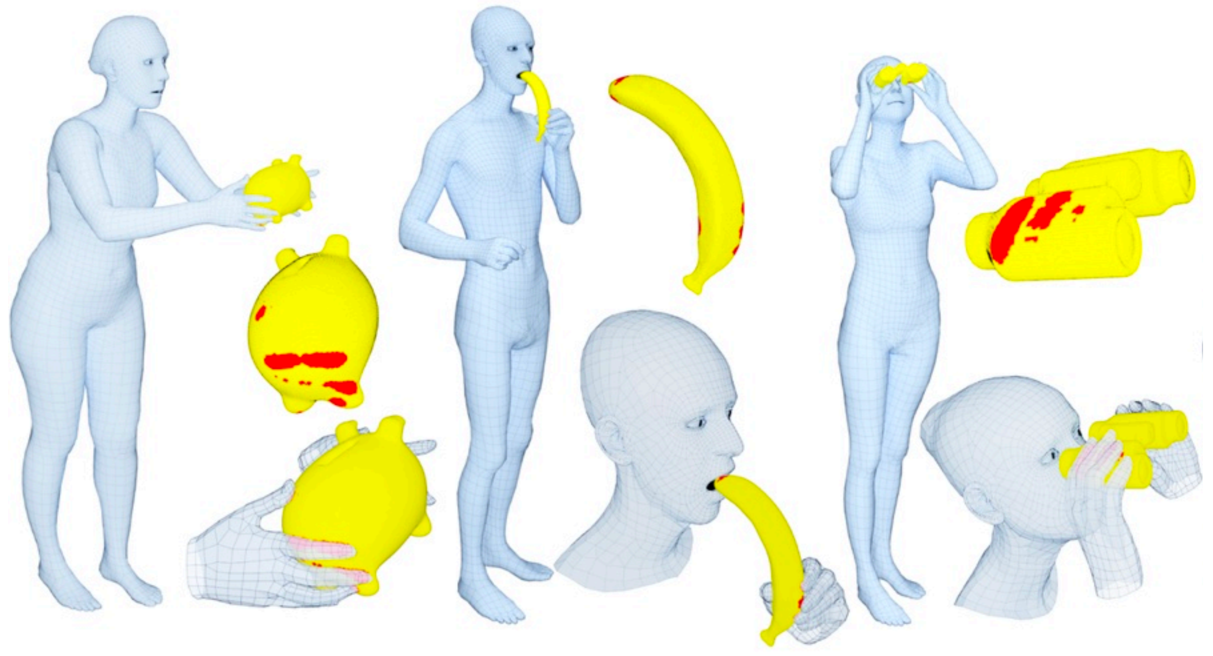
Contact databases

ContactDB



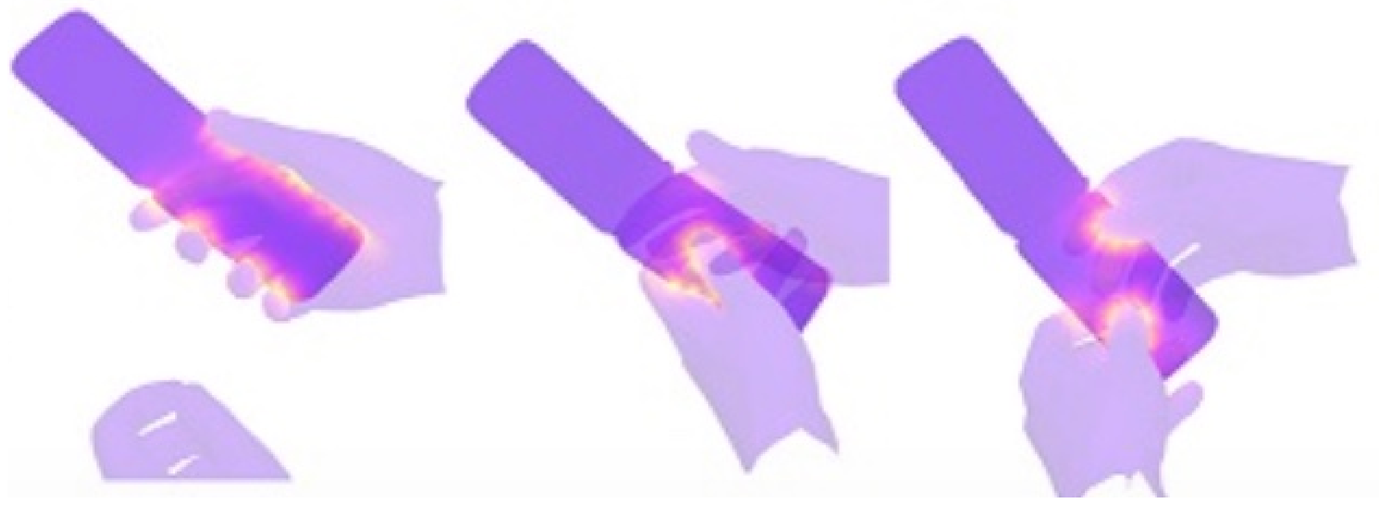
[Brahmbhatt et. al, 2019]

GRAB



[Taheri et. al, 2020]

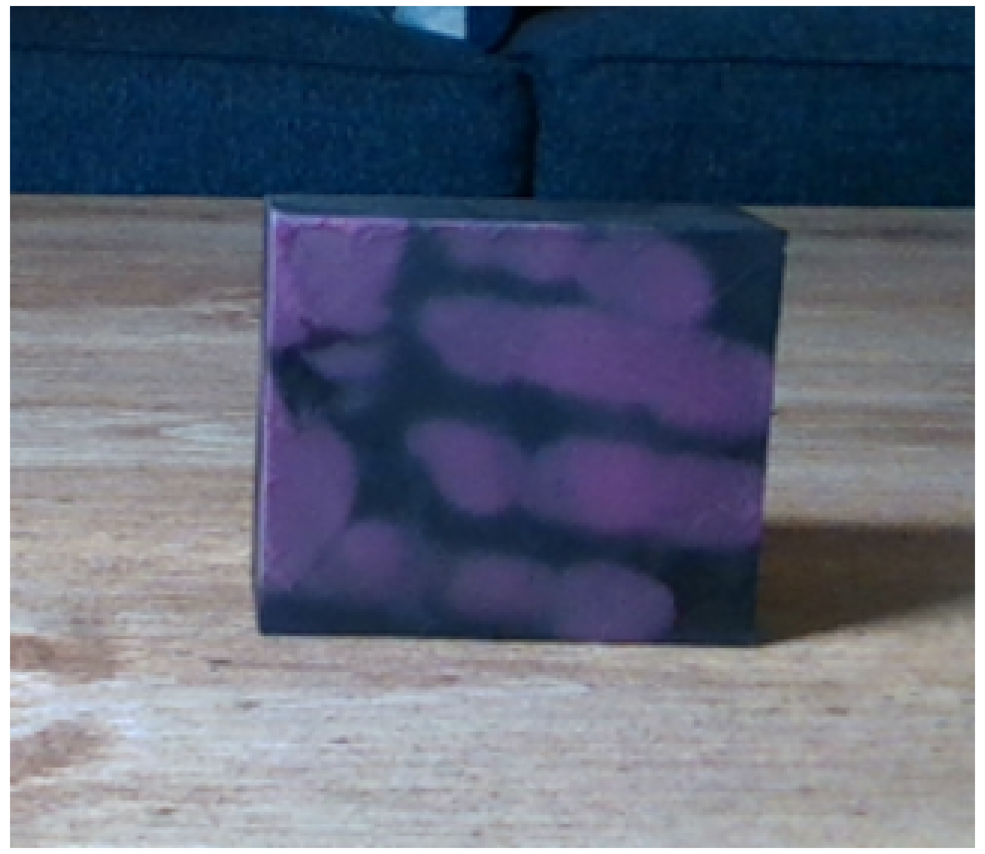
ARCTIC



[Fan et. al, 2023]

Contacts Everywhere

Measuring contact on the object



Thermochromatic pigment

Arjun Lakshmipathy, Dominik Bauer, and Nancy Pollard. Contact Tracing: A Low Cost Reconstruction Framework for Surface Contact Interpolation, IROS 2021.

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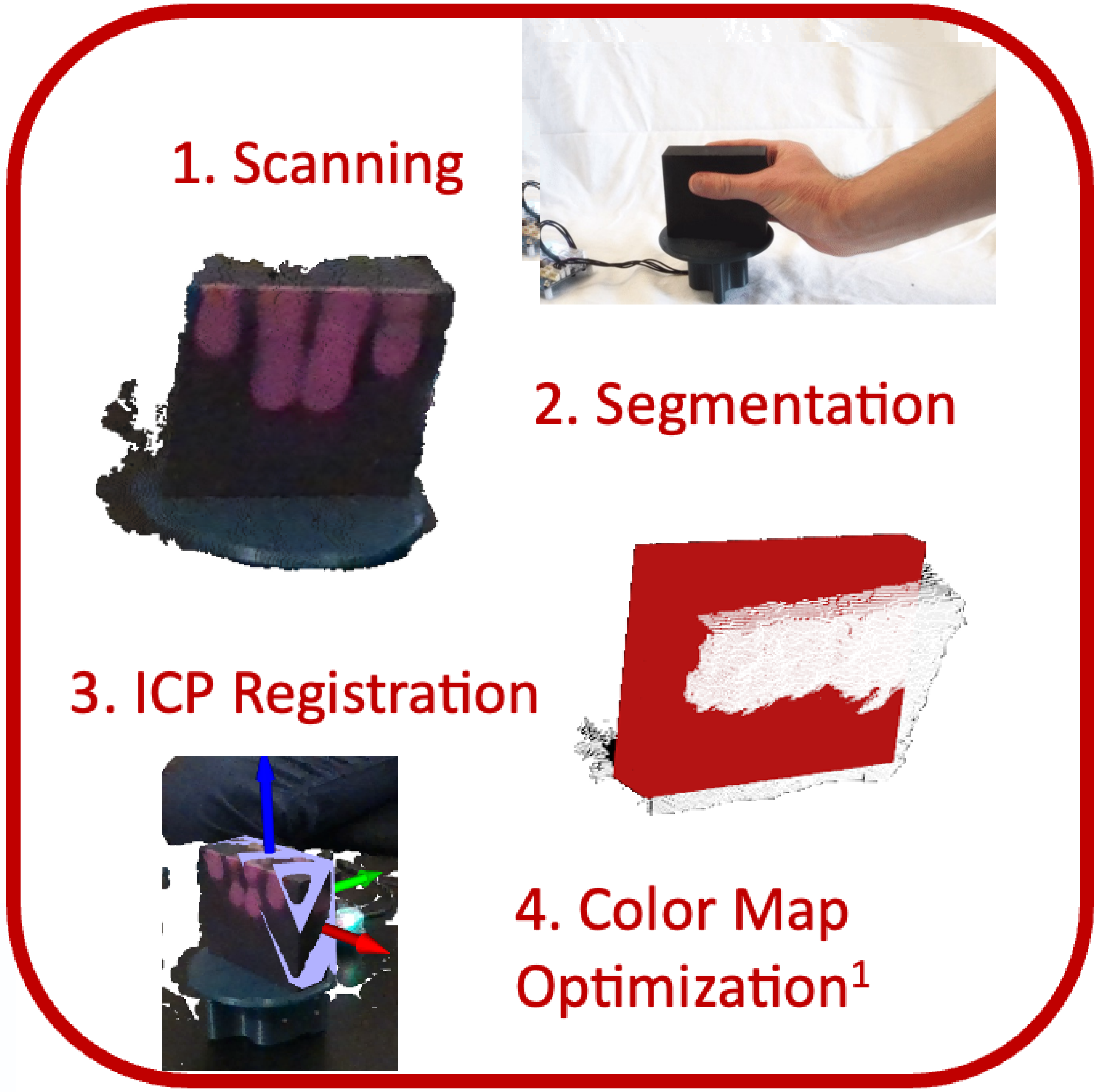
Contacts Everywhere

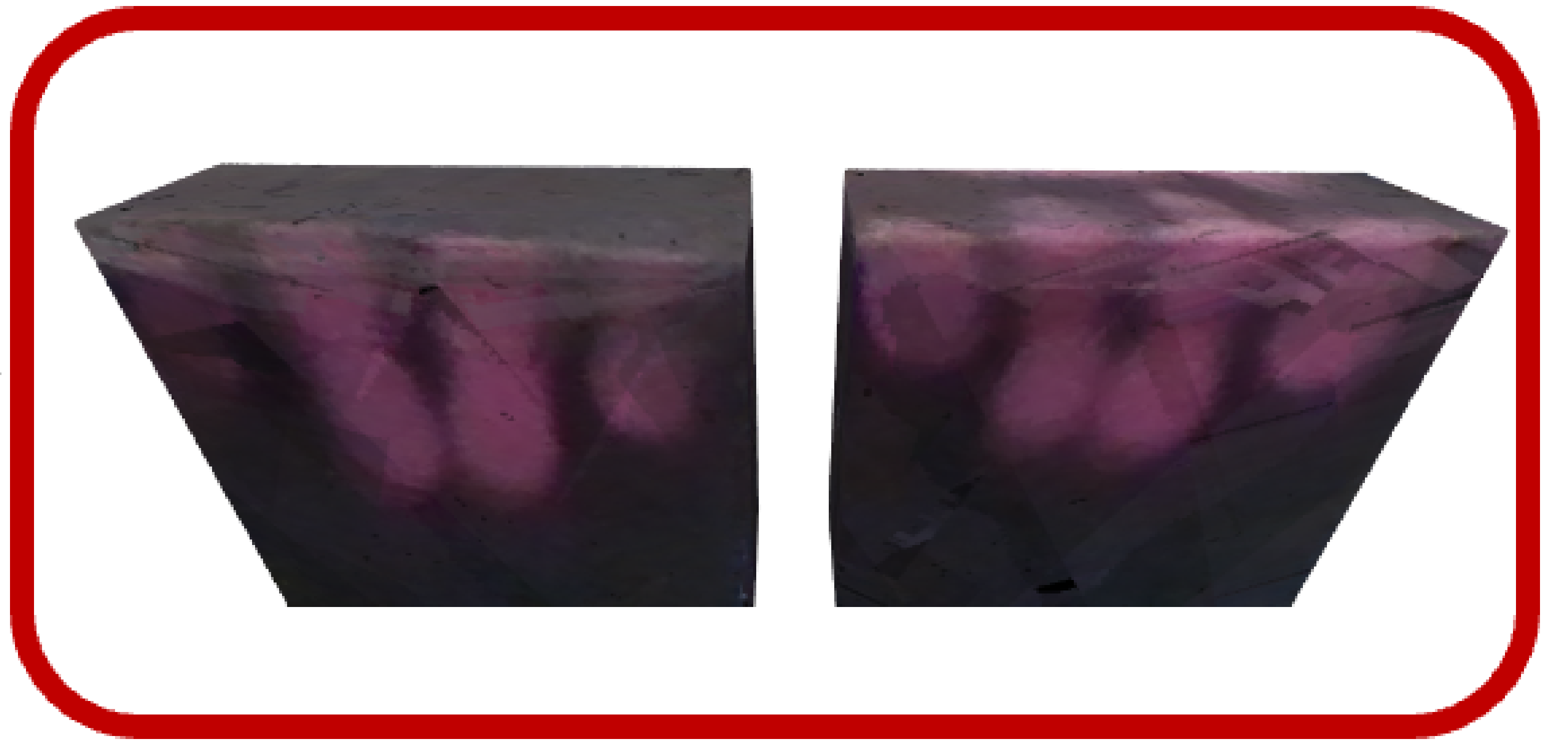
Measuring contact on the object

INPUTS x2

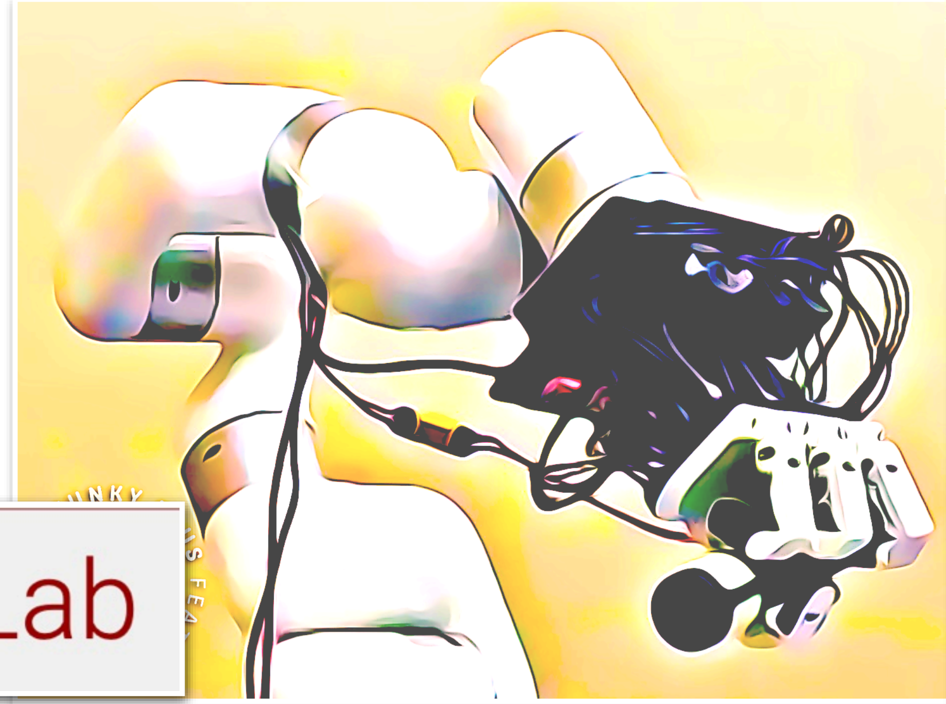


Standard image processing

OUTPUTS

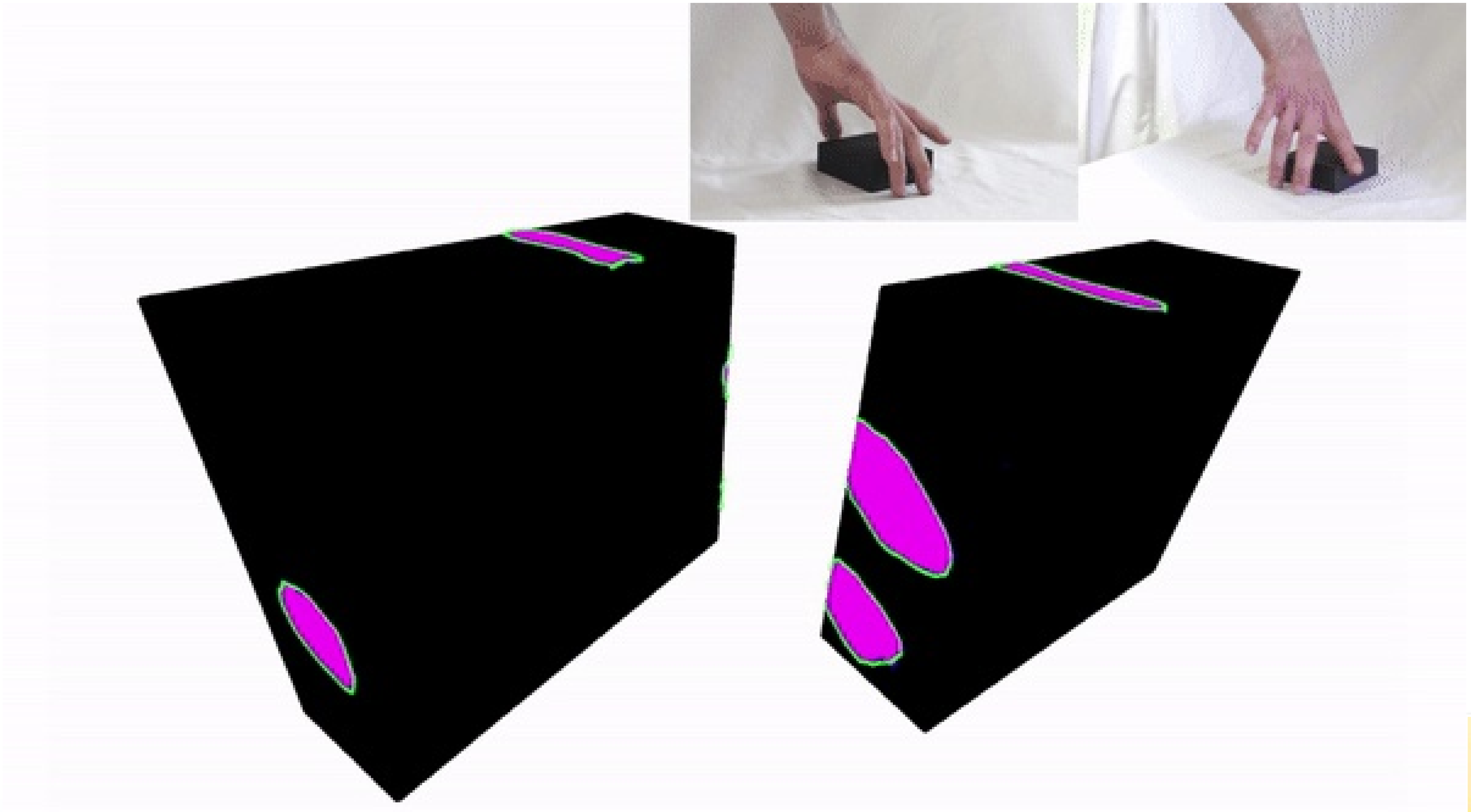


Arjun Lakshmipathy, Dominik Bauer, and Nancy Pollard. Contact Tracing: A Low Cost Reconstruction Framework for Surface Contact Interpolation, IROS 2021.



Contacts Everywhere

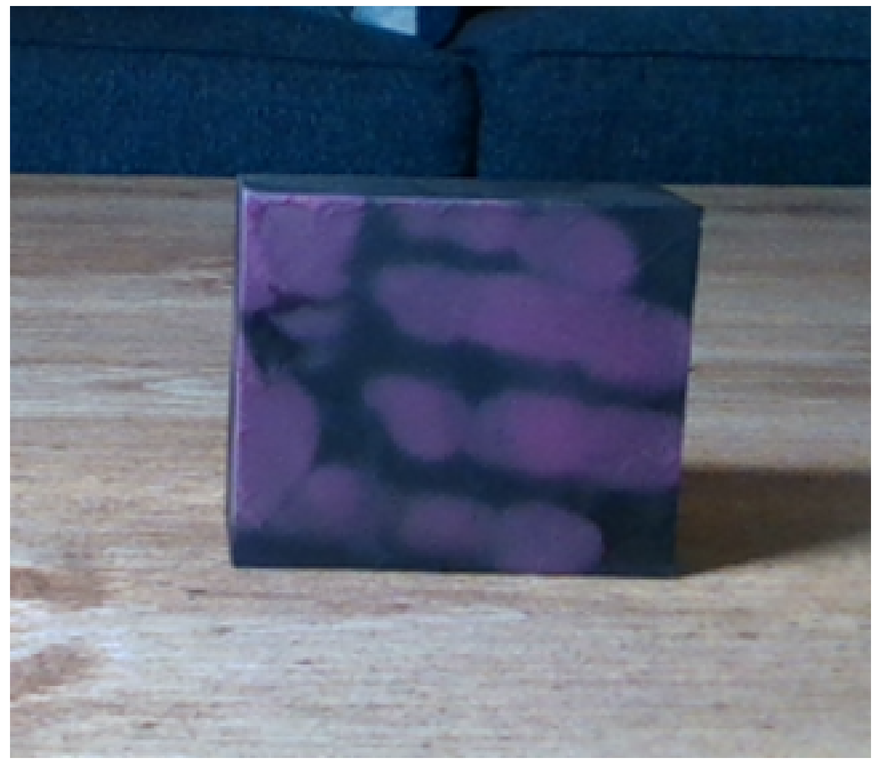
Measuring contact on the object

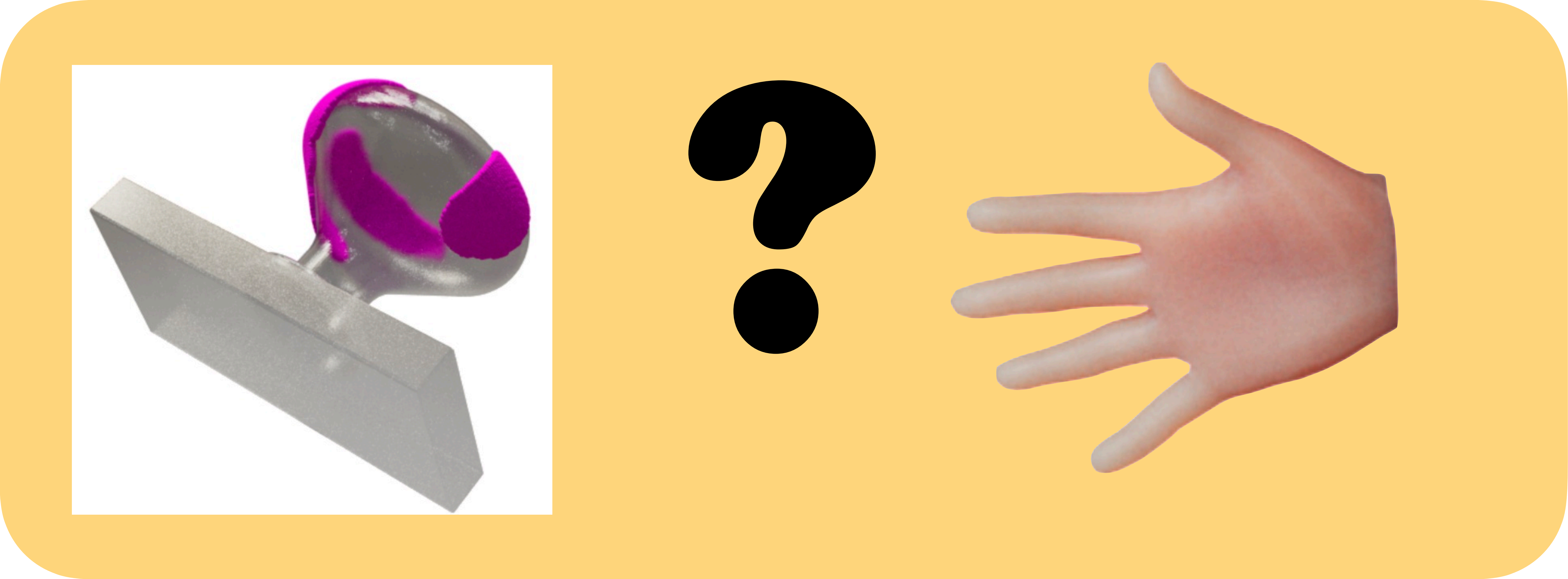


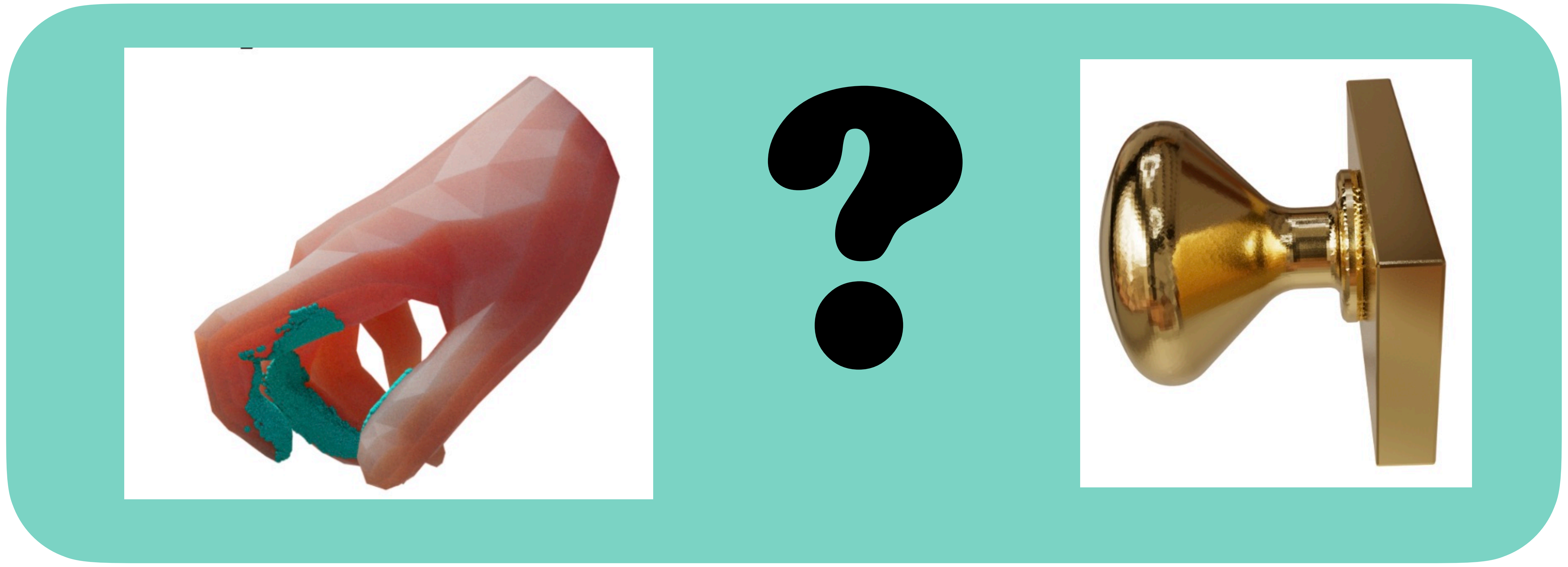
Arjun Lakshmipathy, Dominik Bauer, and Nancy Pollard. Contact Tracing: A Low Cost Reconstruction Framework for Surface Contact Interpolation, IROS 2021.

Contacts Everywhere

How should we transfer contact between surfaces?







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Contacts Everywhere

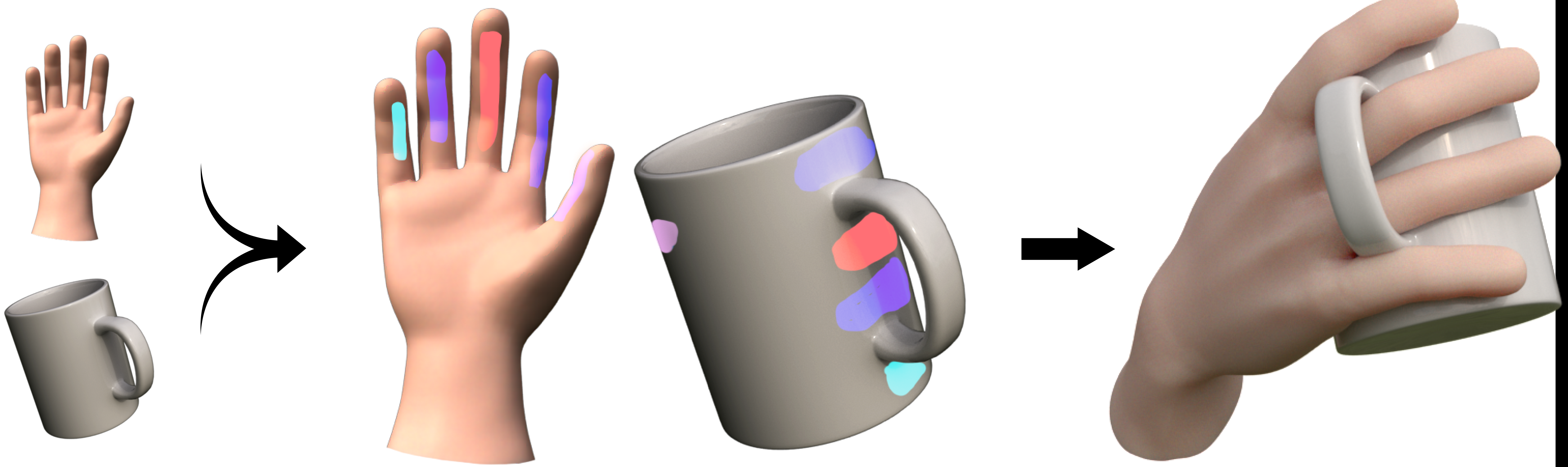
Our Solution: A local intrinsic geometric representation

Arjun Lakshmipathy, Nicole Feng, Yu Xi Lee, Moshe Mahler, and Nancy S. Pollard. Contact Edit: Artist Tools for Intuitive Modeling of Hand-Object Interactions, SIGGRAPH 2023.

Arjun Lakshmipathy, Nicole Feng, Yu Xi Lee, Moshe Mahler, and Nancy S. Pollard. Contact Edit: Artist Tools for Intuitive Modeling of Hand-Object Interactions, SIGGRAPH 2023.

Contacts Everywhere

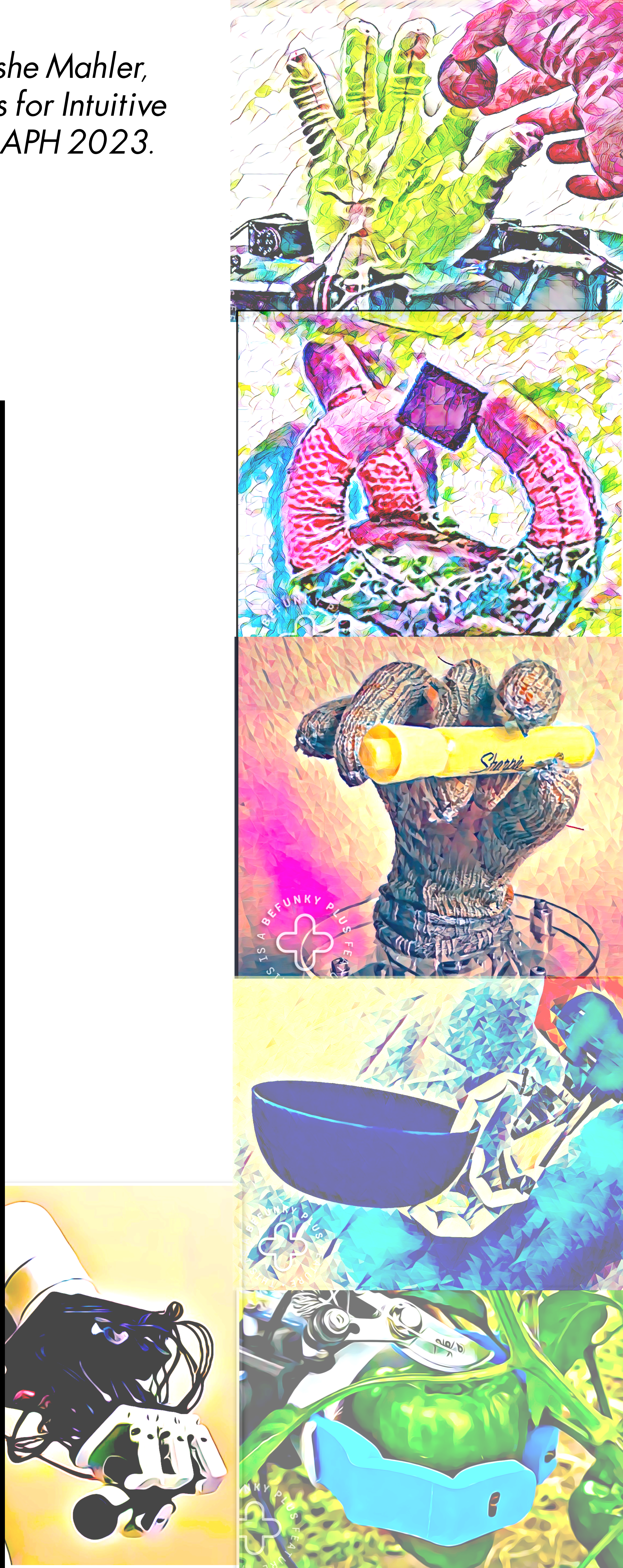
Creating with contact



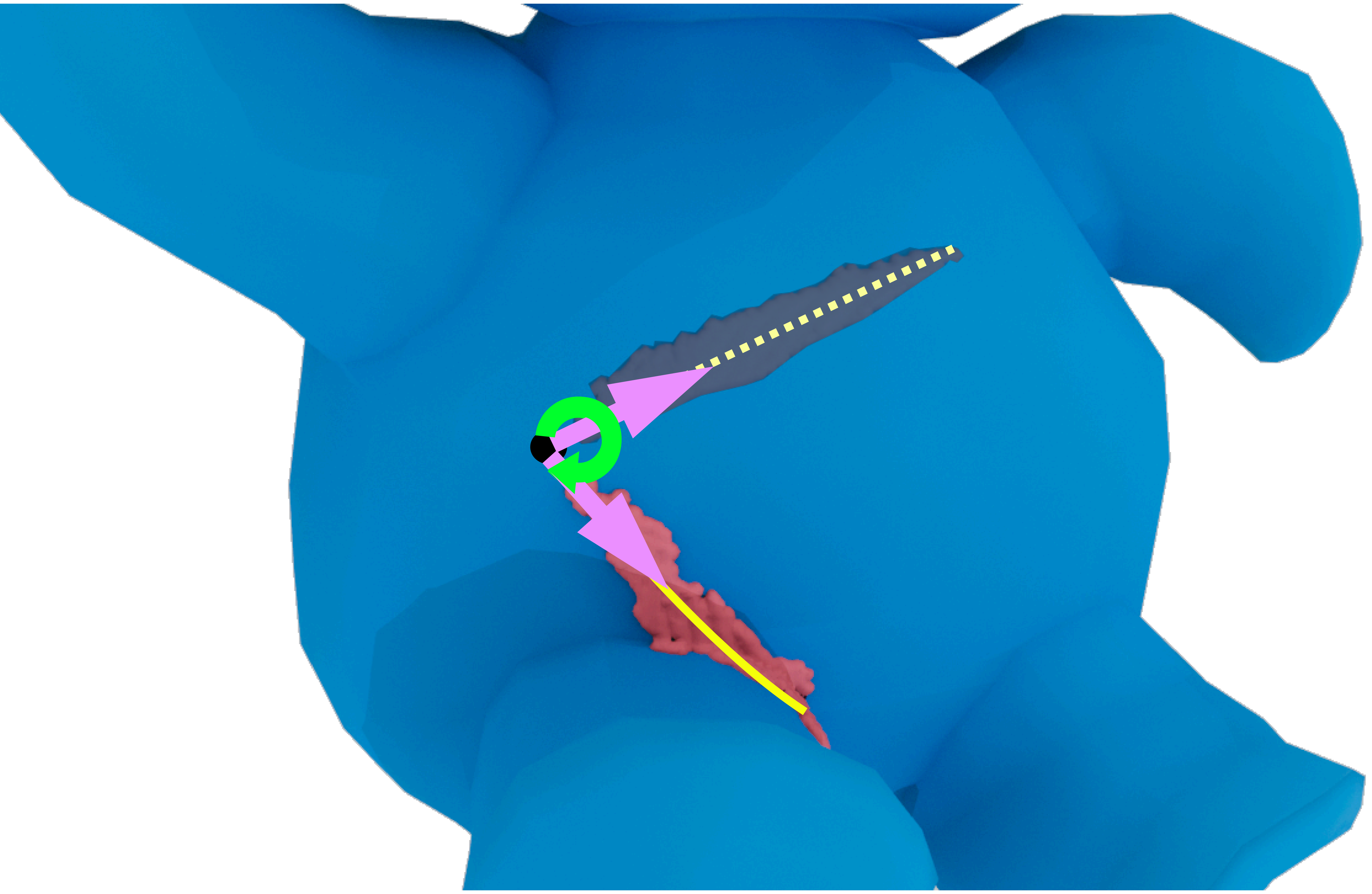
input

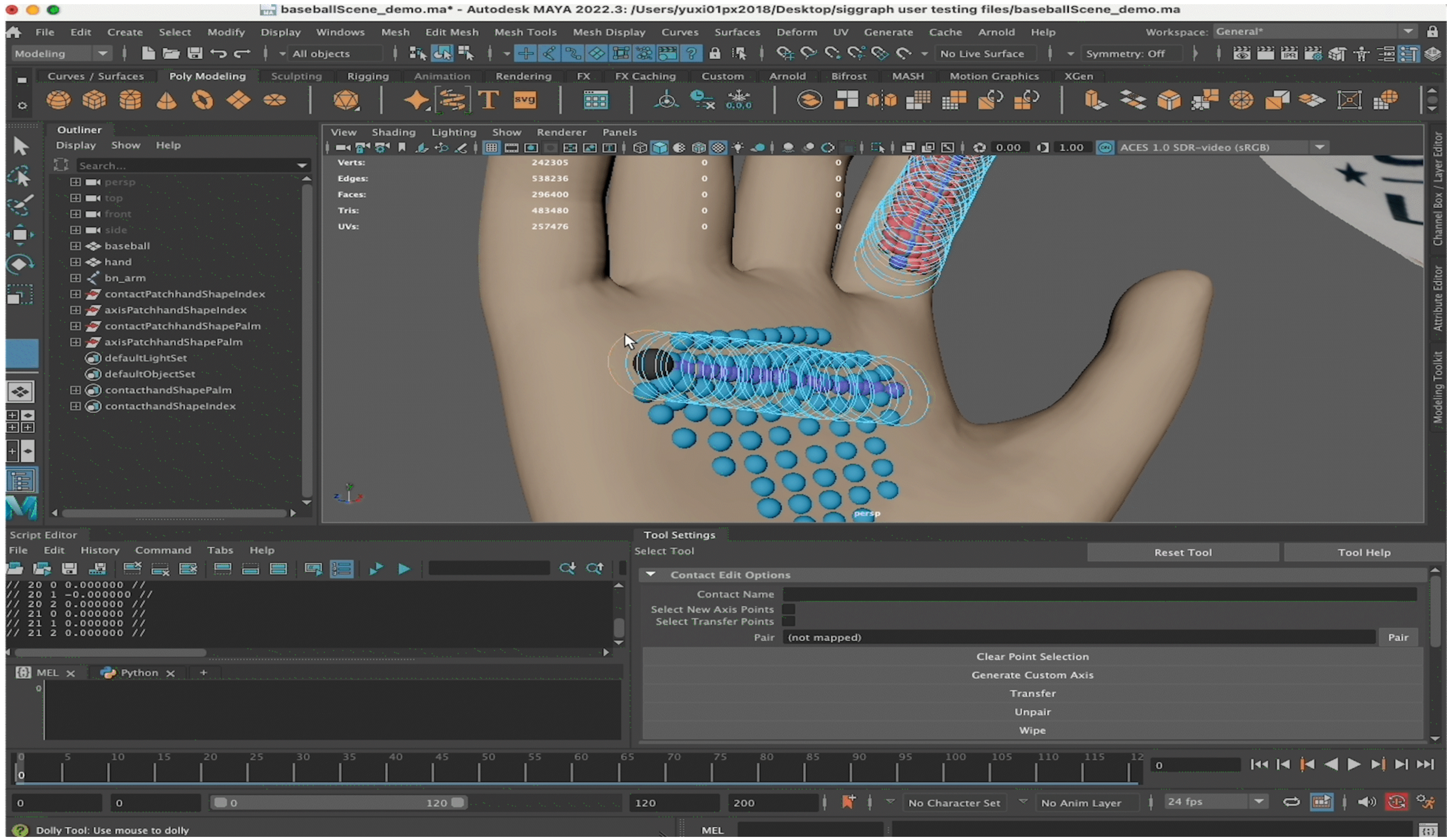
Contact Edit

final pose

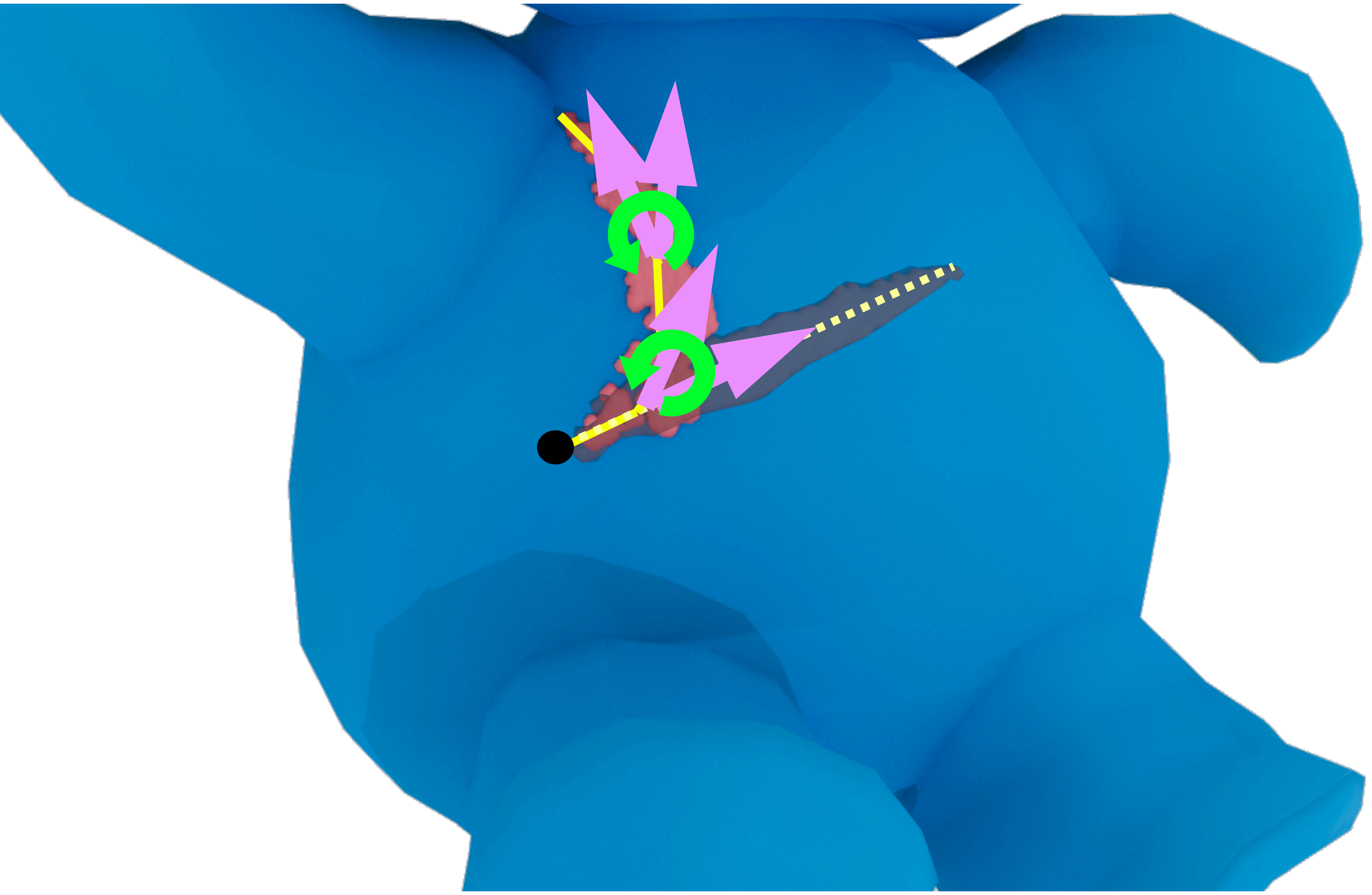


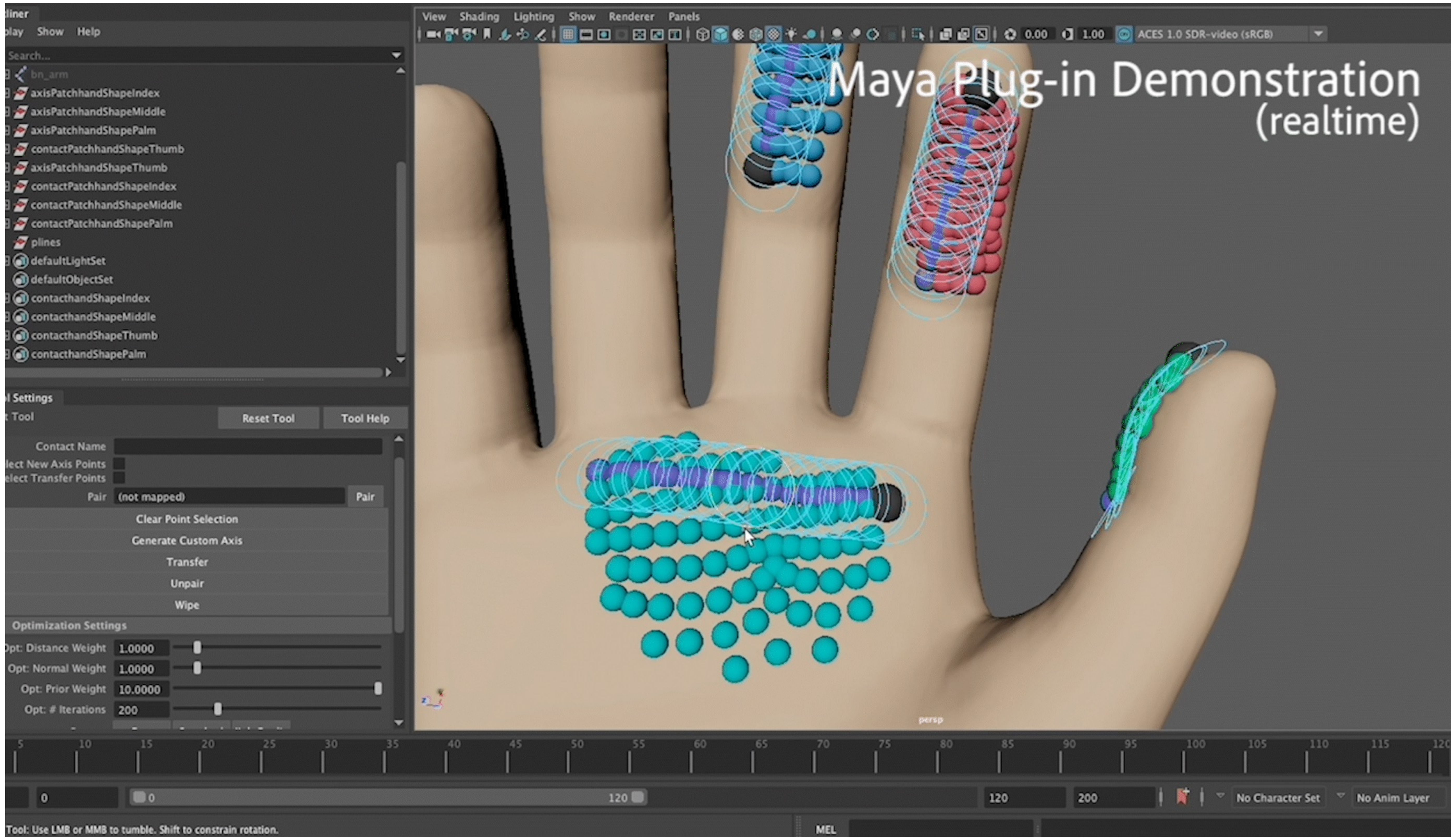
Contact Area Rotation



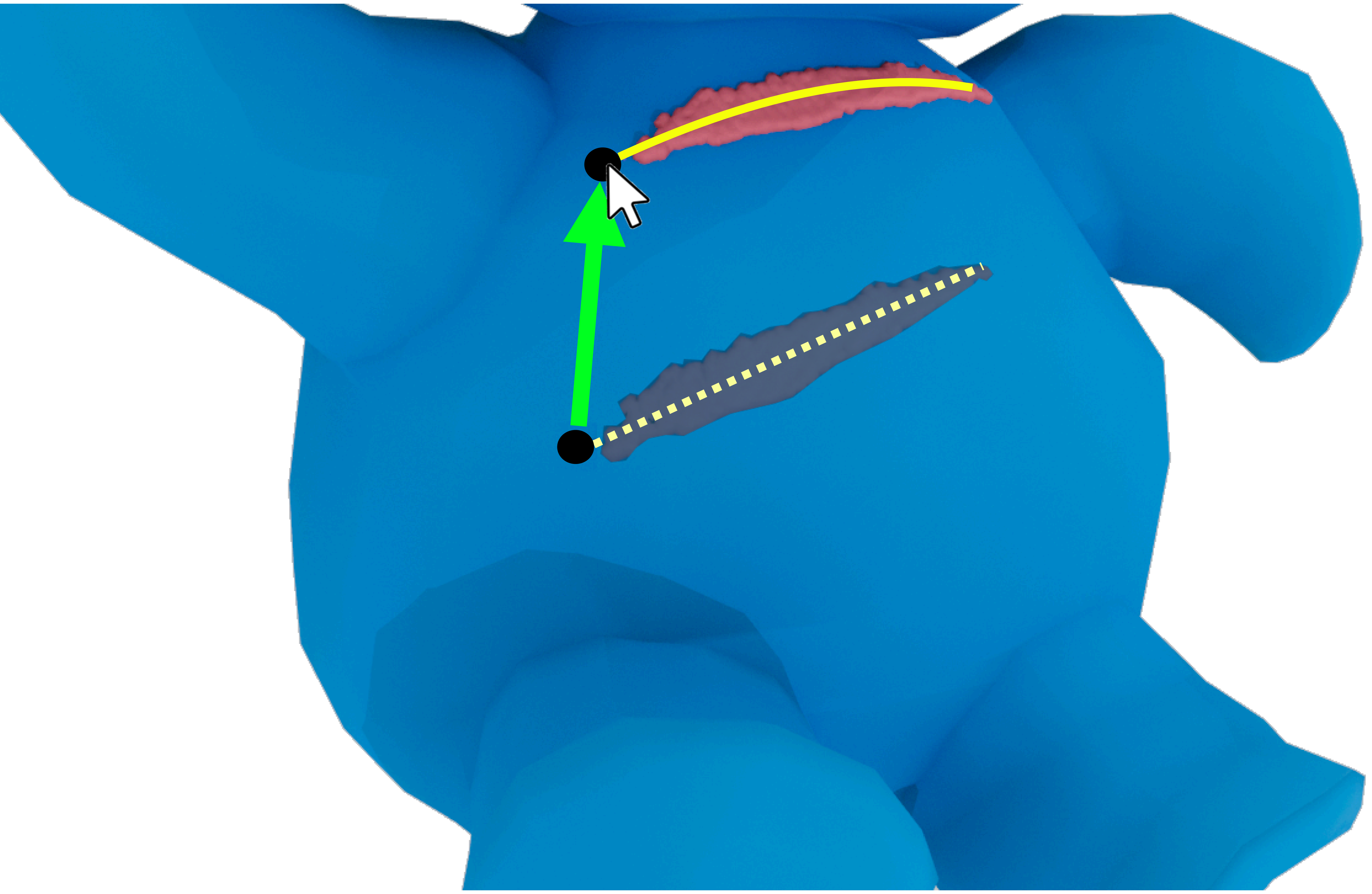


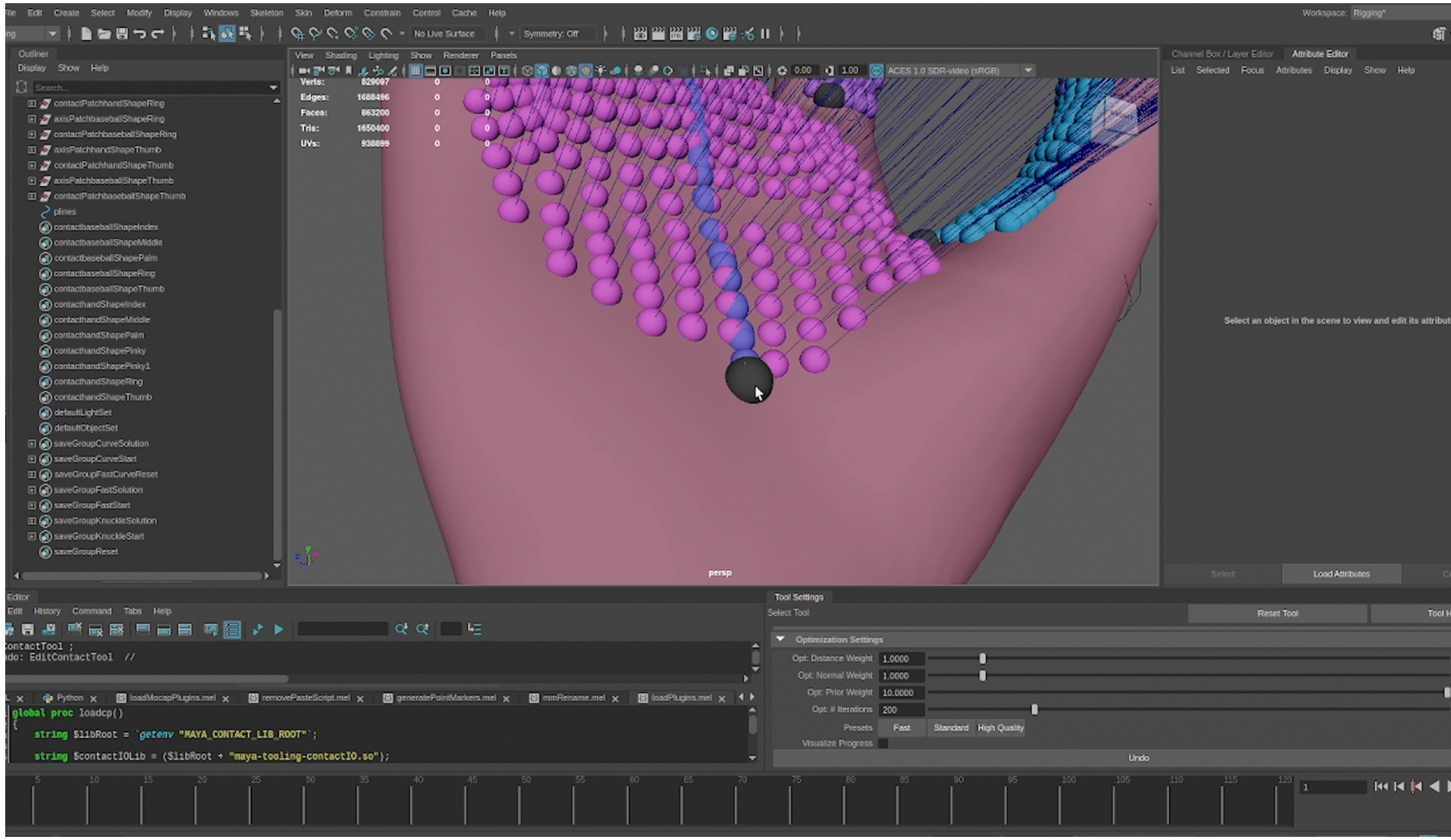
Contact Area Deformation



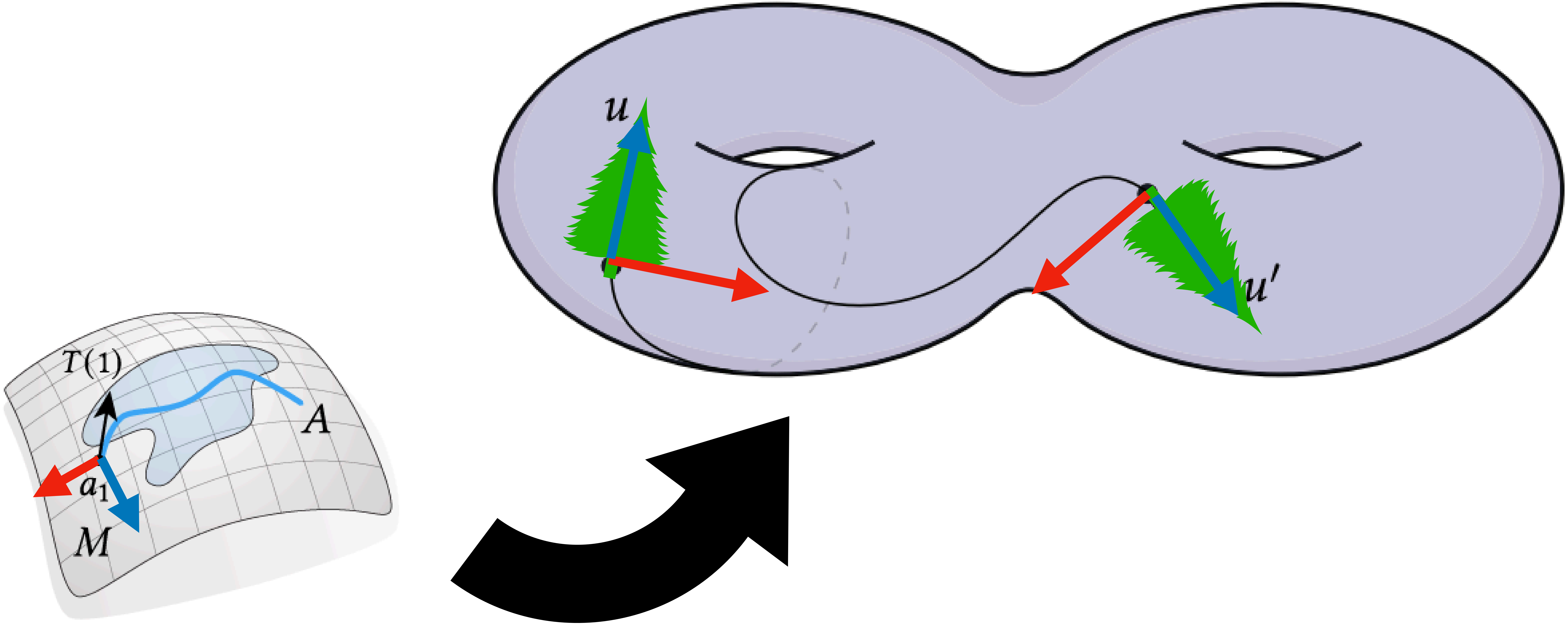


Contact Area Translation

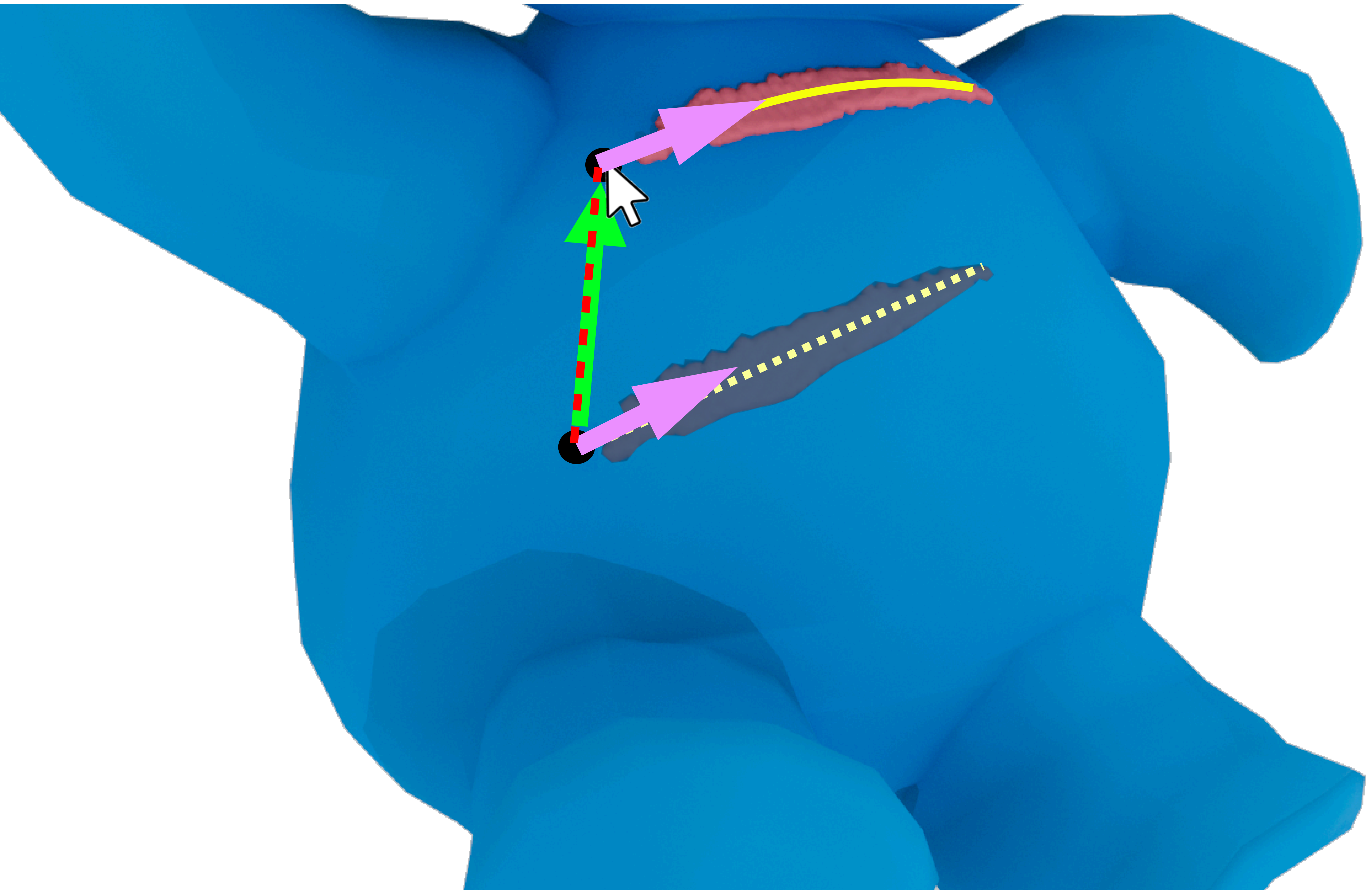


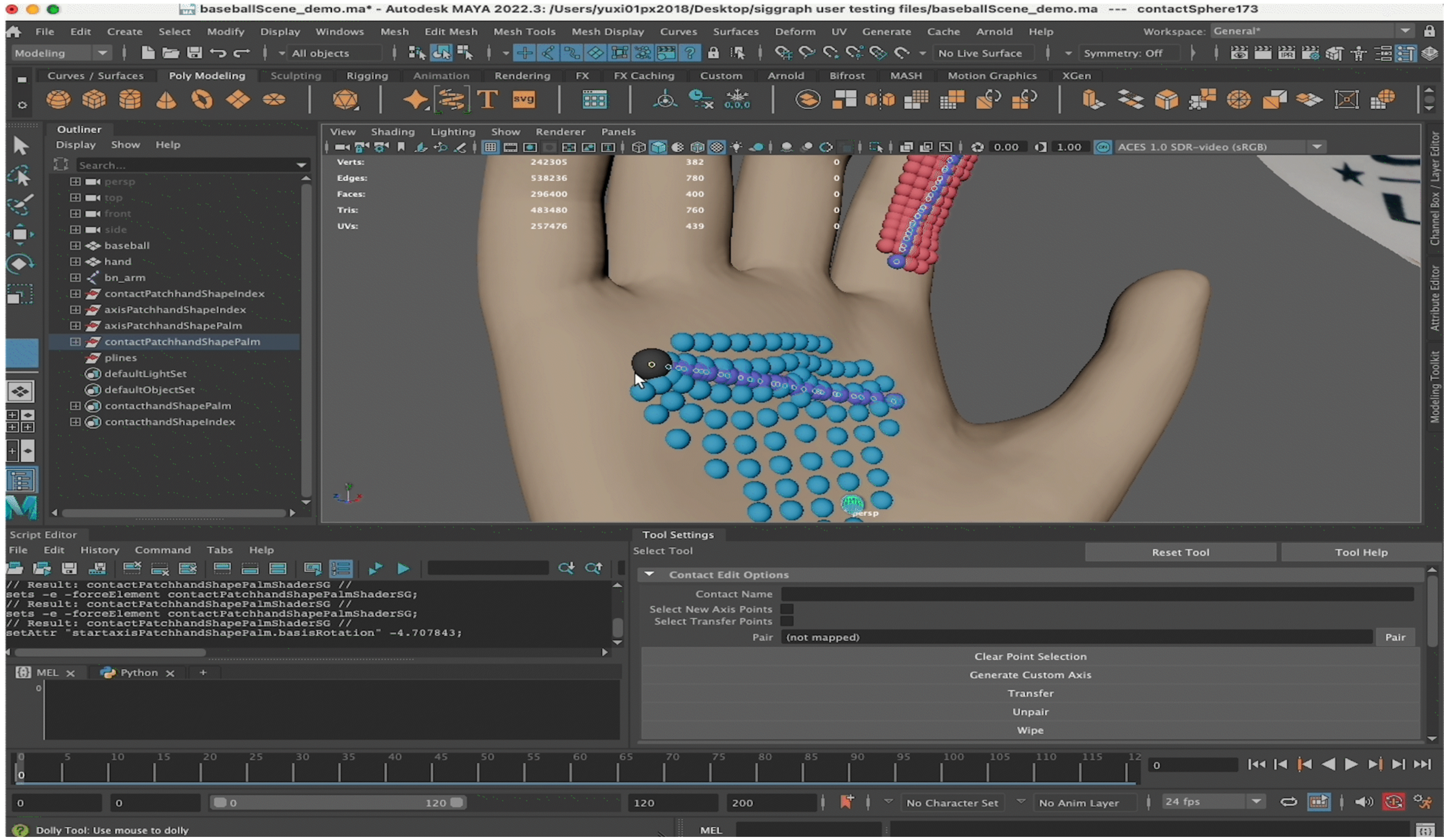


An Important Caveat with Translation

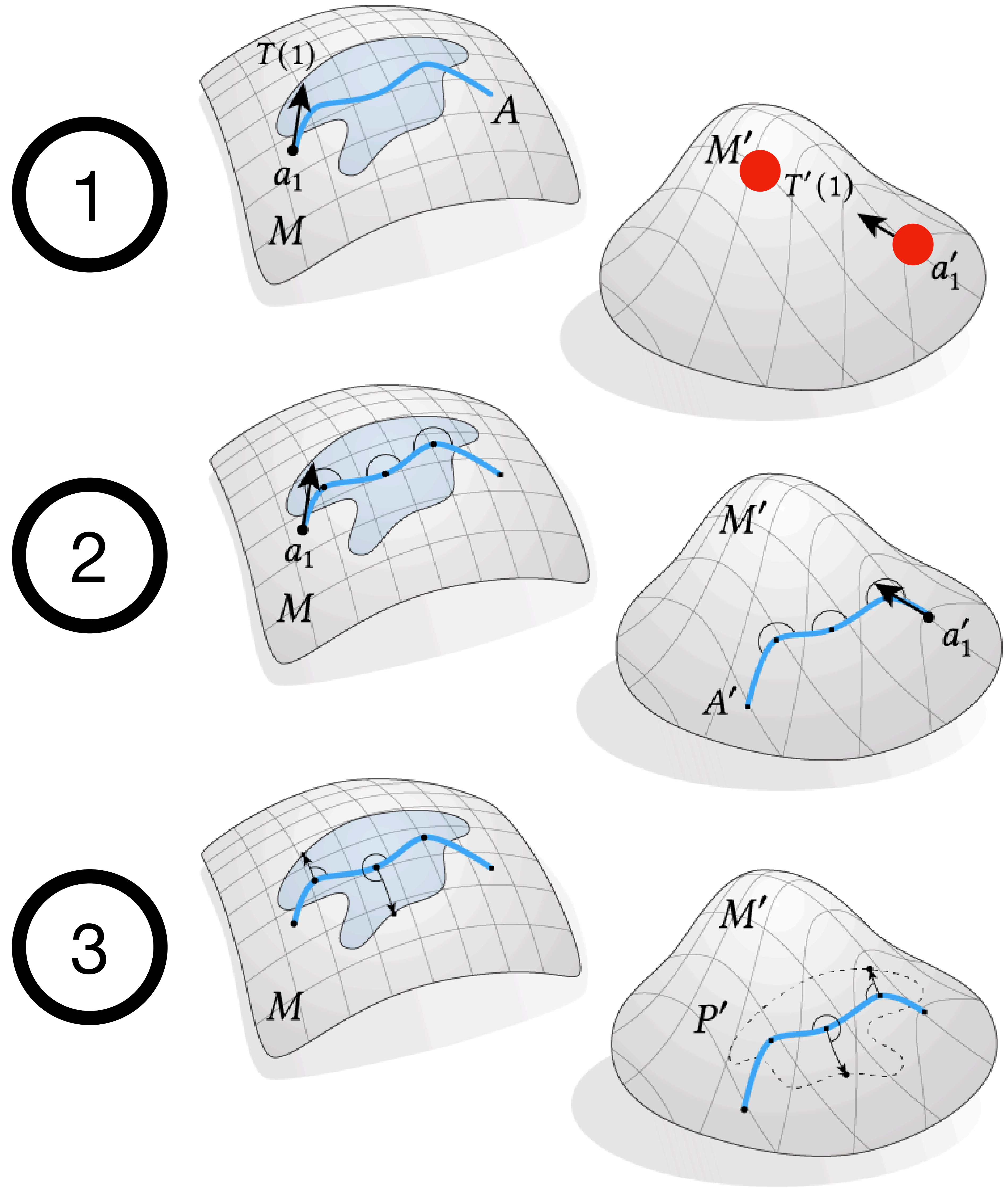


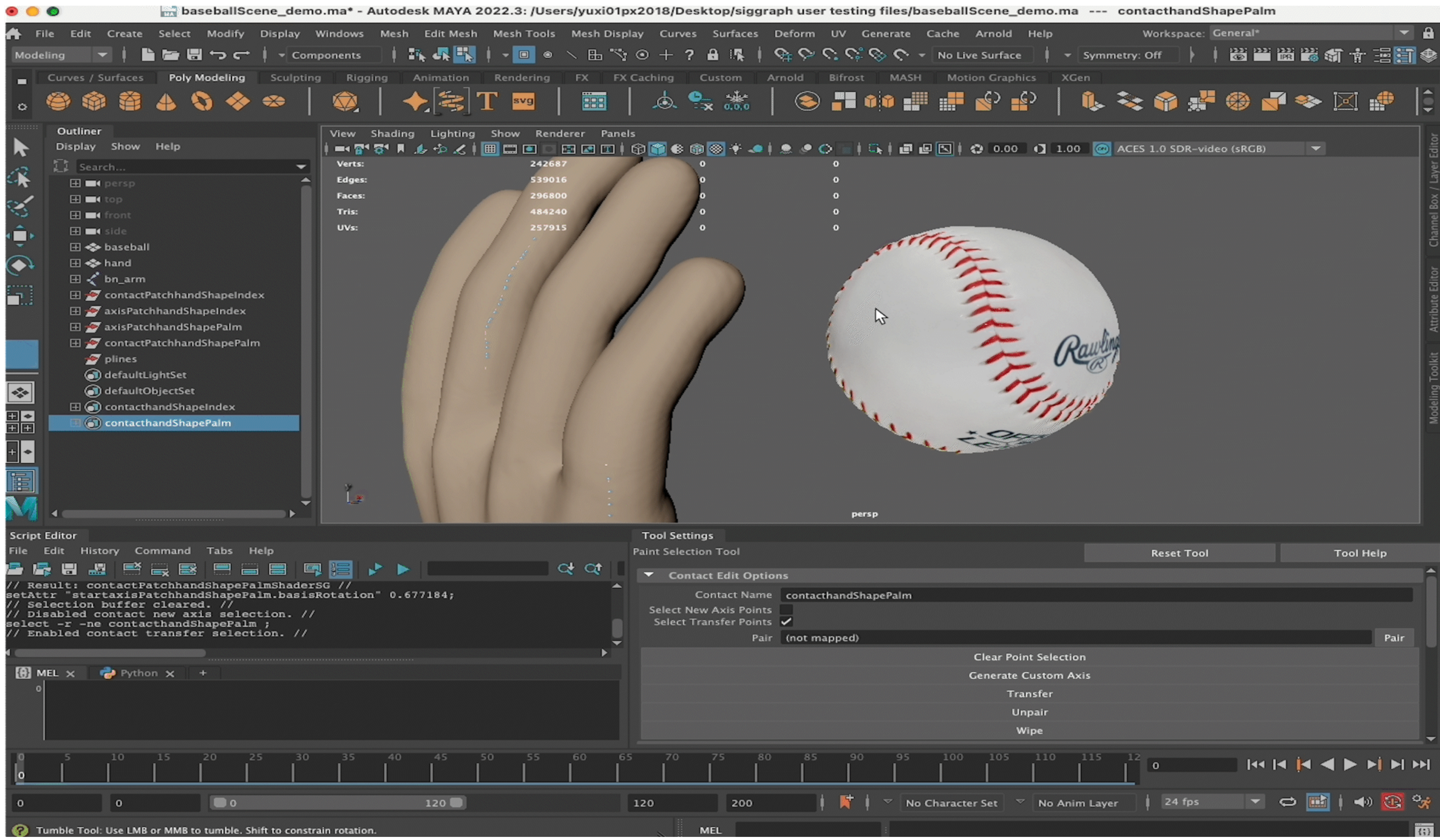
Actual Contact Area Translation





Contact Area Transfer

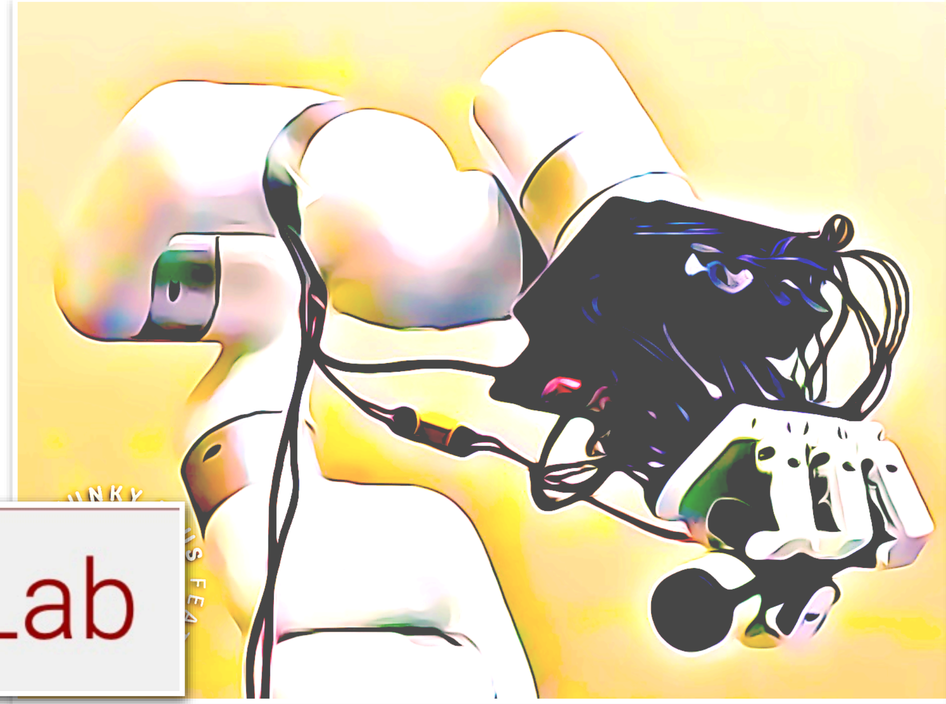




Arjun Lakshmipathy, Nicole Feng, Yu Xi Lee, Moshe Mahler, and Nancy S. Pollard. Contact Edit: Artist Tools for Intuitive Modeling of Hand-Object Interactions, SIGGRAPH 2023.

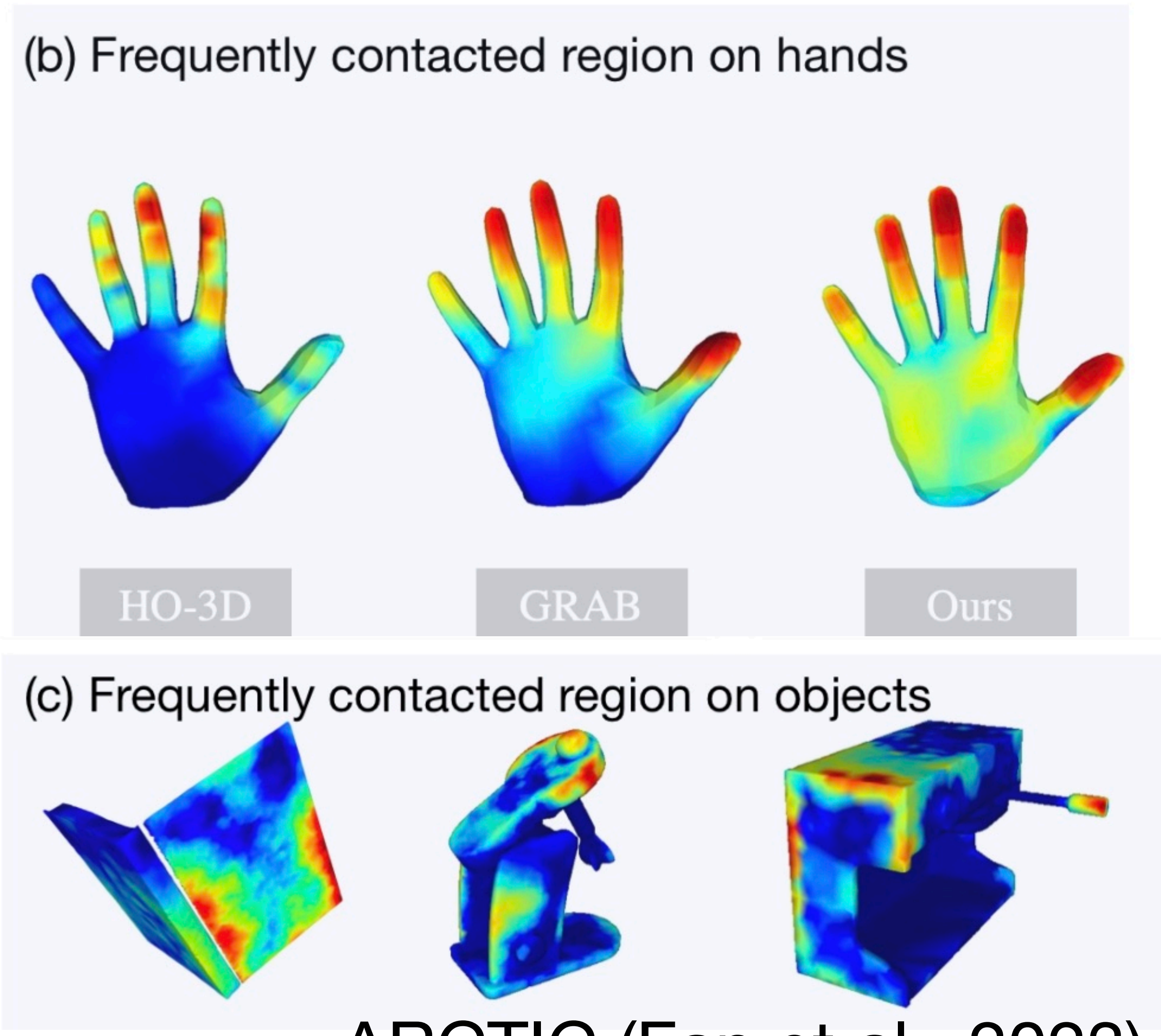
Contacts Everywhere

Creations of various artists



Contacts Everywhere

Observations



ARCTIC (Fan et al., 2023)

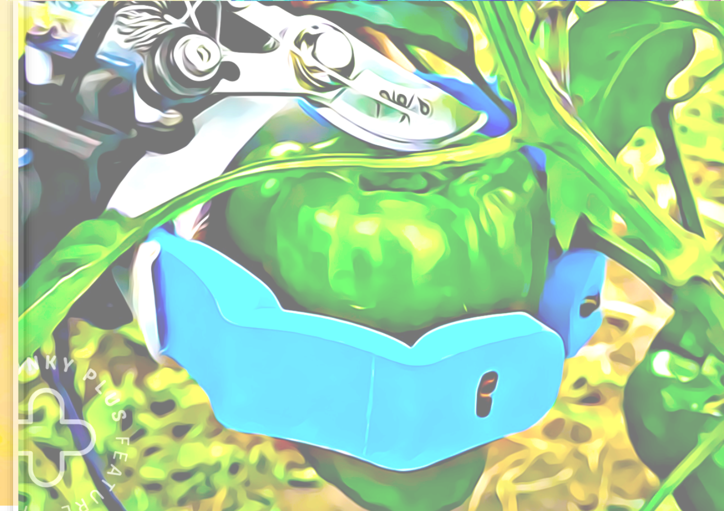
- Contacts can
  - form large areas
  - reach much of the hand surface
  - persist and change over time (sliding, rolling)

- Artists enjoyed direct control of contacts for specifying hand poses

- We may consider contact areas as potential first class elements for design, planning, and control

This talk

- Measuring Dexterity
    - dexterity involves creating change with intention / in-hand manipulation patterns (rock, roll, twiddle, step…) can be observed in grasp transitions
- Contacts Everywhere
    - everyday activities involve contact all over the hand / we can measure contact areas and plan grasps with large area contacts in mind
- **Design for Dexterous Manipulation**



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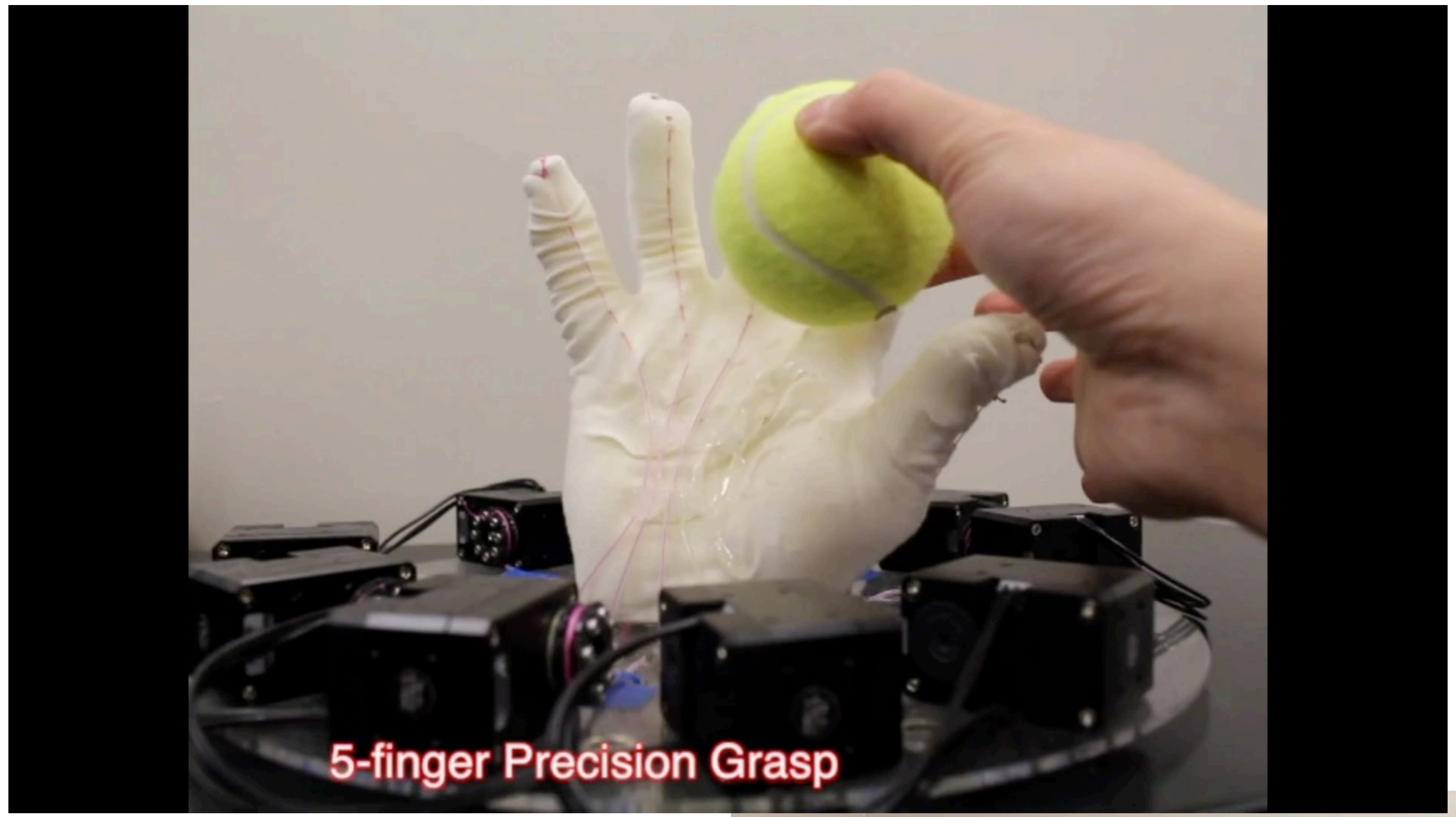
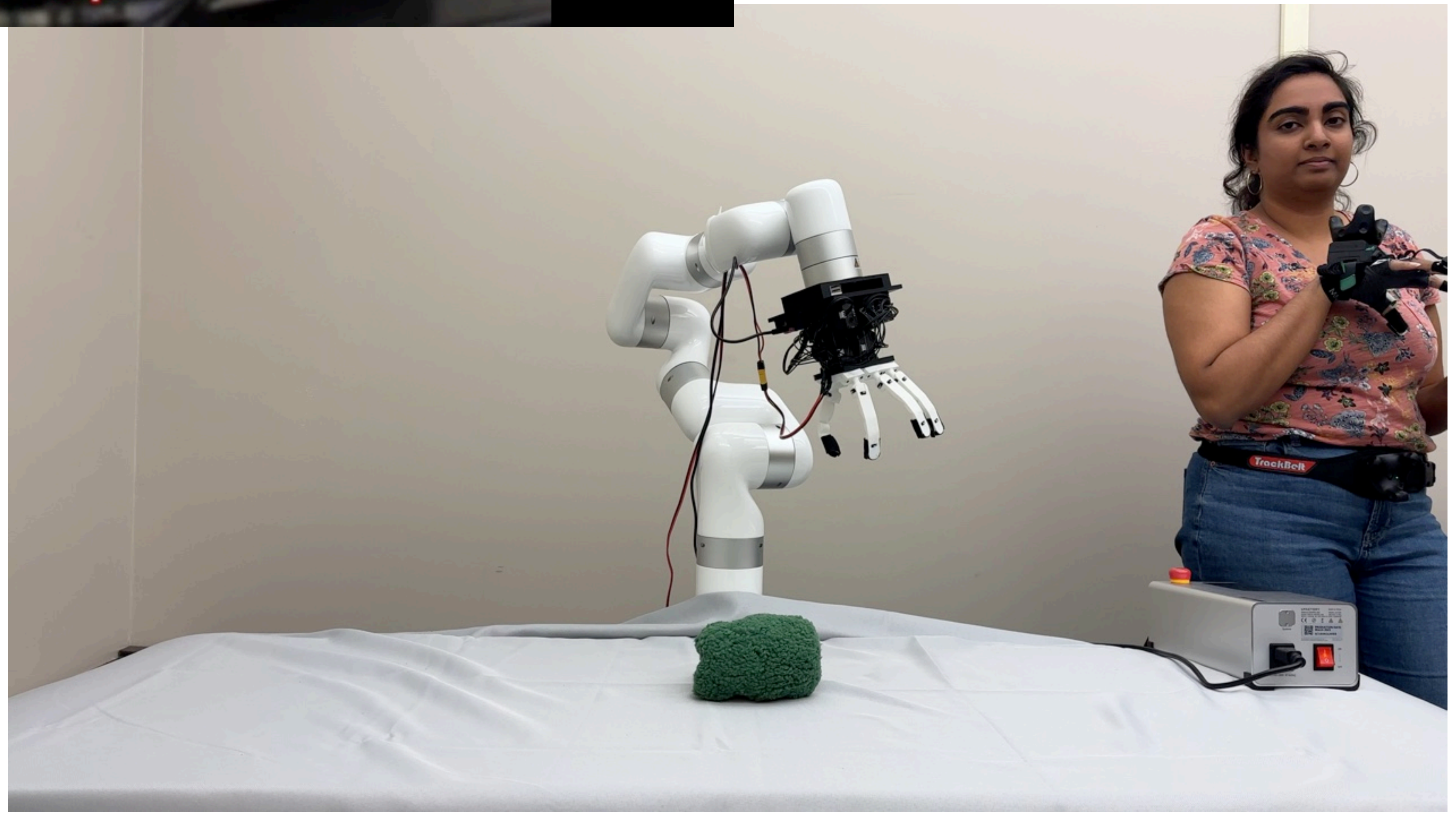
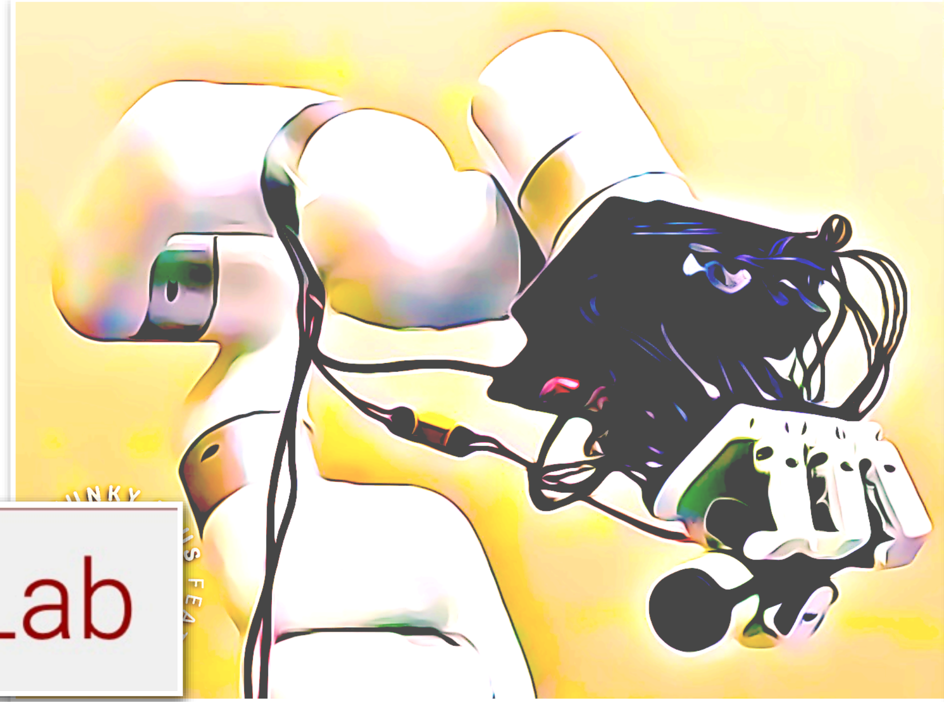
Design for Dexterous Manipulation

Design for Dexterous Manipulation

(1) The Advantage of Soft







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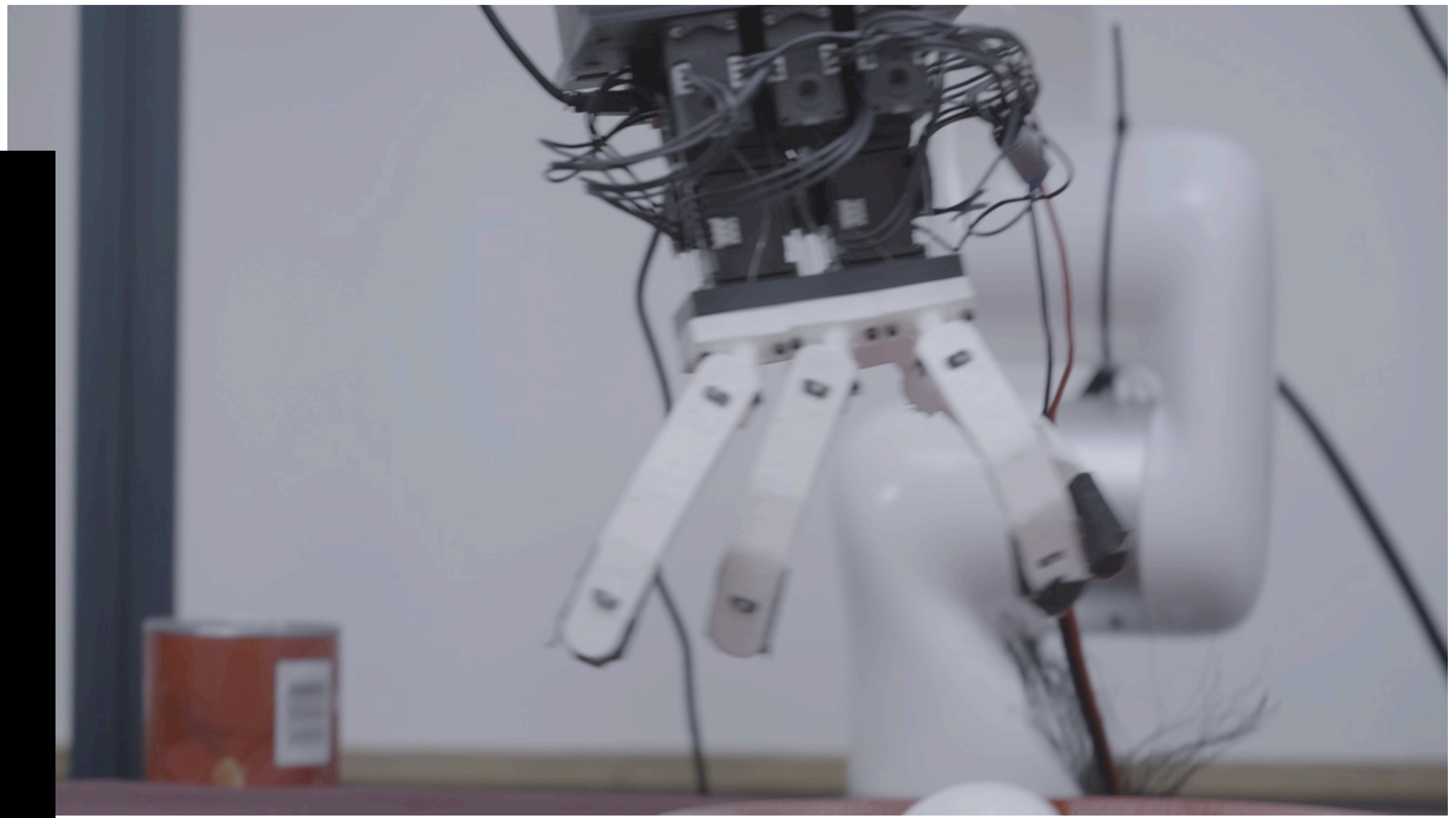
Design for Dexterous Manipulation

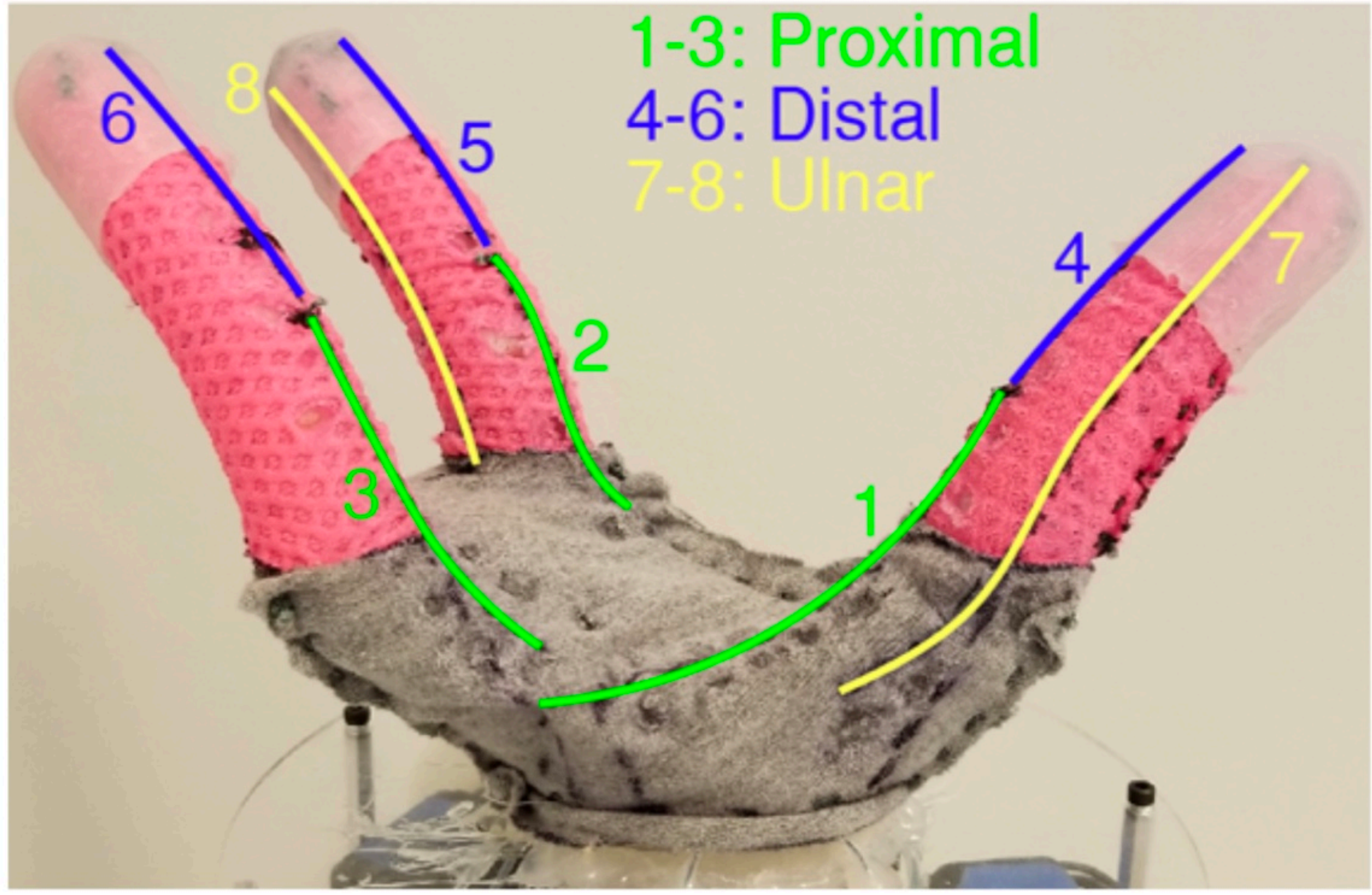
(1) The Advantage of Soft

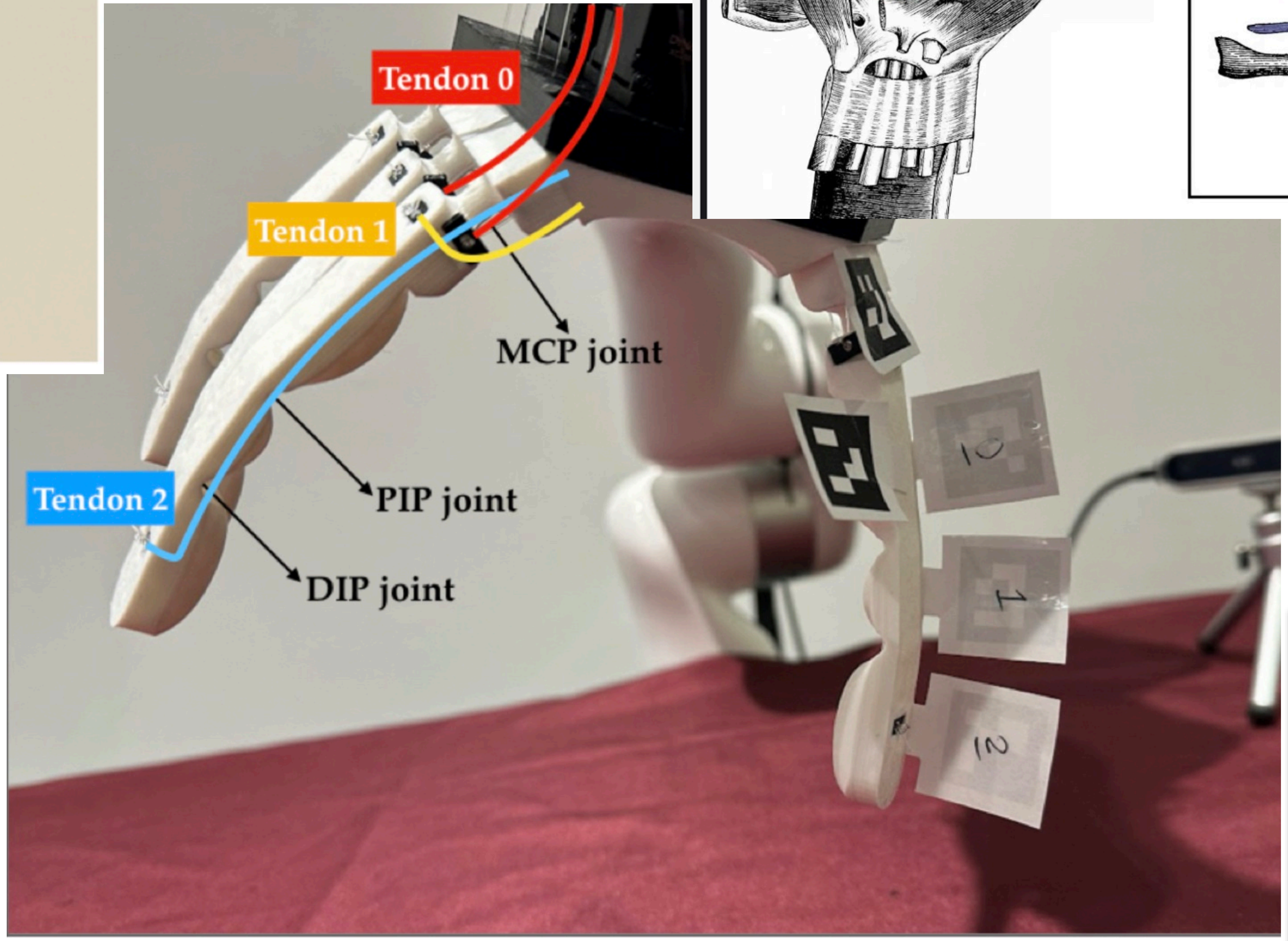


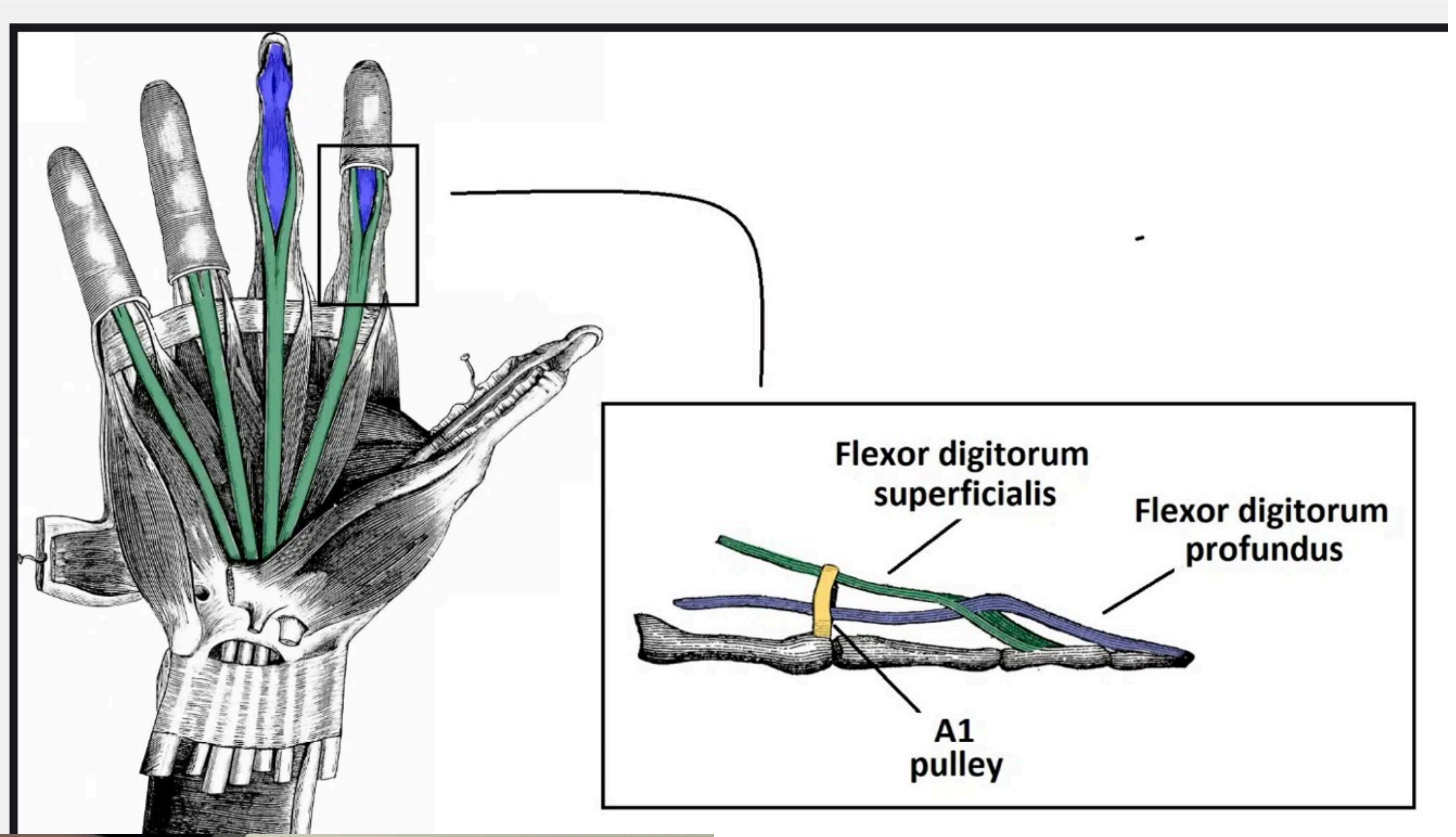
M. Kazemi, J.-S. Valois, J. A. Bagnell, and N. Pollard, 2014. Human-Inspired Force Compliant Grasping Primitives, Autonomous Robots, 37(2), 209--225, 2014.

Design for Dexterous Manipulation

(2) The Need for Two Flexors







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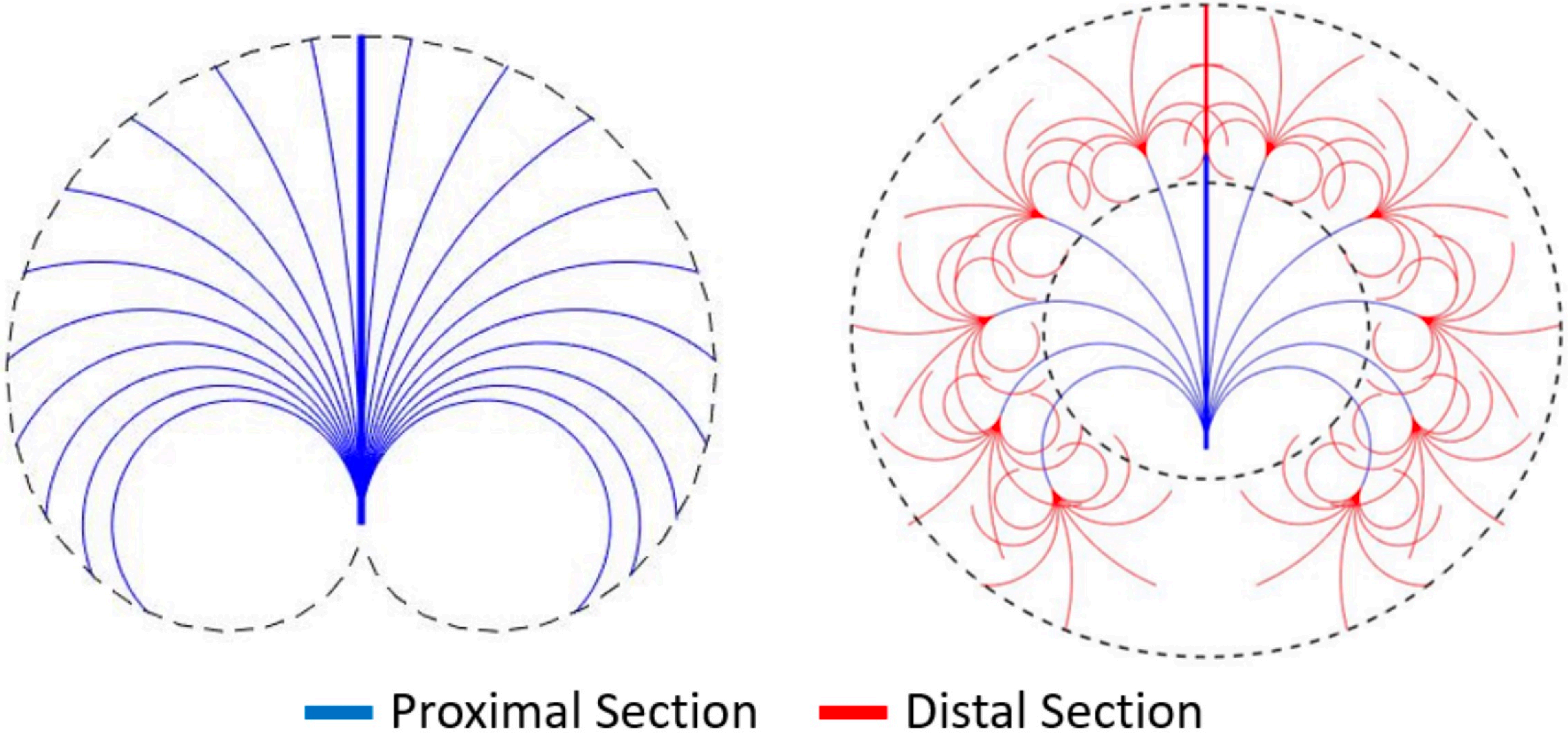
Design for Dexterous Manipulation

(2) The Need for Two Flexors



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Design for Dexterous Manipulation

(3) The Simplicity of Additive Manufacturing

D. Bauer, C. Bauer, J. P. King, D. Moro, K.-H. Chang, S. Coros, and N. Pollard, 2020. [Design and Control of Foam Hands for Dexterous Manipulation](), International Journal of Humanoid Robotics, Volume 17, Issue 01, February 2020.

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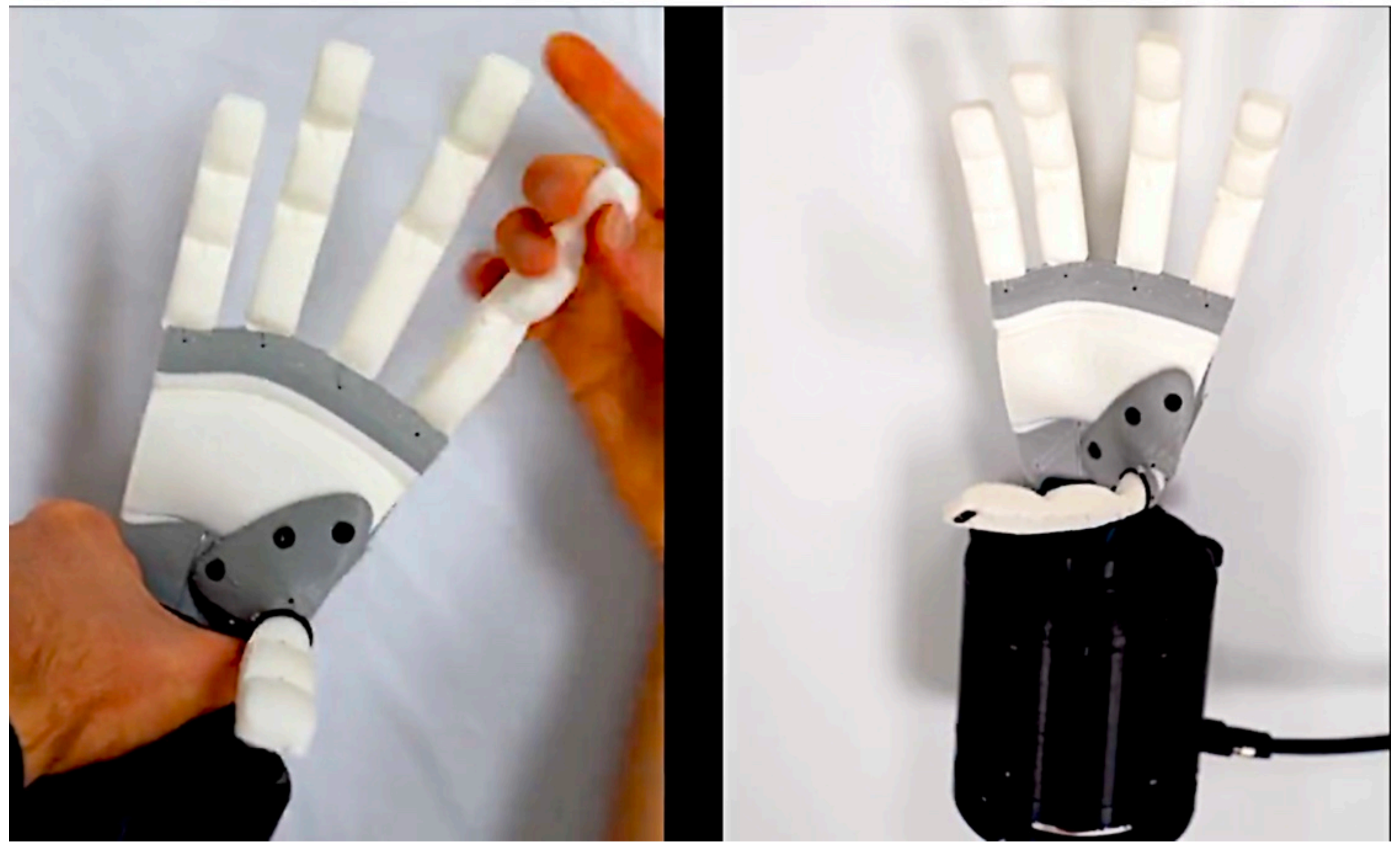
(3) The Simplicity of Additive Manufacturing

D. Bauer, C. Bauer, A. Lakshmipathy, R. Shu, and N. S. Pollard. Towards Very Low-Cost Iterative Prototyping for Fully Printable Dexterous Soft Robotic Hands, ROBOSOFT 2022.



D. Bauer, C. Bauer, and N. Pollard. Soft Robotic End-Effectors in the Wild: A Case Study of a Soft Manipulator for Green Bell Pepper Harvesting, In AI for Agriculture and Food Systems (AAIAFS) Workshop, AAAI 2023.

Design for Dexterous Manipulation

(4) Field Reliability

D. Bauer, C. Bauer, and N. Pollard. Soft Robotic End-Effectors in the Wild: A Case Study of a Soft Manipulator for Green Bell Pepper Harvesting, In AI for Agriculture and Food Systems (AAIAFS) Workshop, AAAI Conference on Artificial Intelligence. Washington, DC, February 2023.

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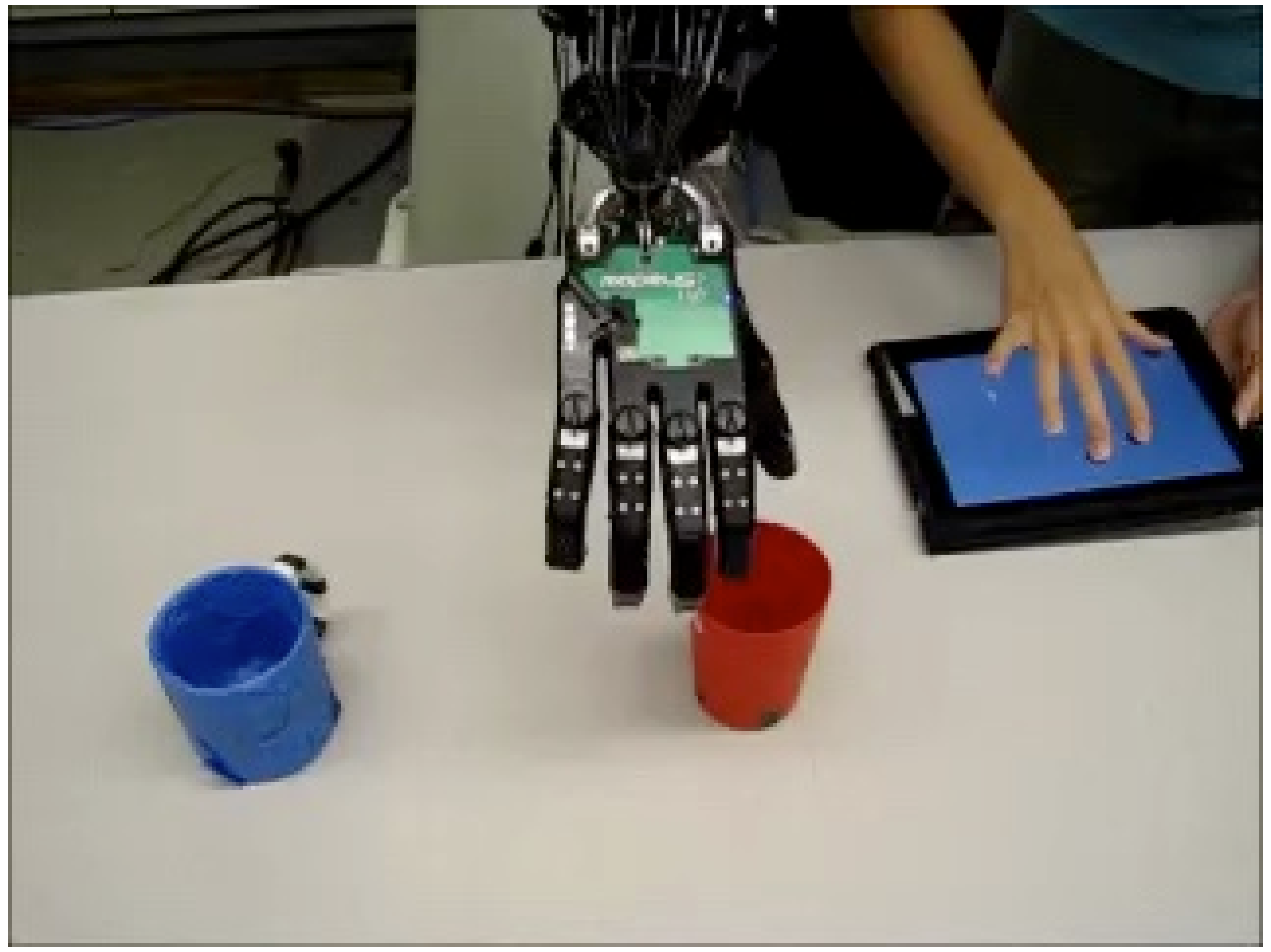
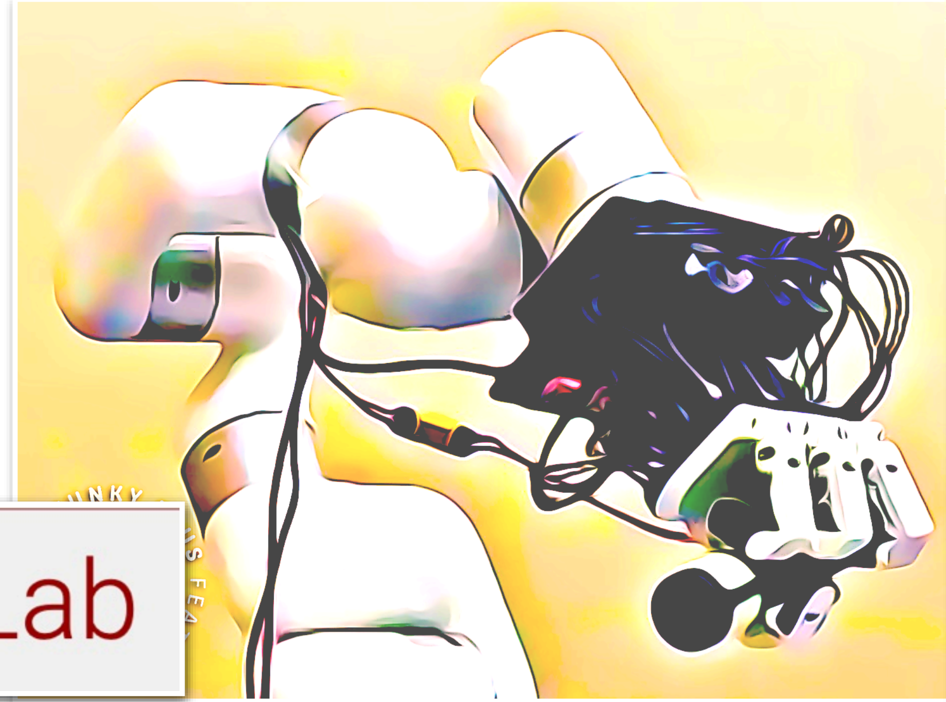
Design for Dexterous Manipulation

(5) Teleoperation as a Design Tool



Y. P. Toh, S. Huang, J. Lin, M. Bajzek, G. Zeglin, and N. S. Pollard,. Dexterous TeleManipulation with a Multi-Touch Interface, Humanoids 2012

Pragna Mannam, Kenneth Shaw, Dominik Bauer, Jean Oh, Deepak Pathak, and Nancy Pollard. Designing Anthropomorphic Soft Hands through Interaction, Humanoids 2023



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Design for Dexterous Manipulation
Summary

1. Passive **Compliance** Aids Dexterity
2. **Two Flexors** Are Needed for Fine Manipulation
3. **Customization** w/ Additive Manufacturing has Hardly Been Explored
4. Soft Hands Can Be **Reliable** in the Field
5. **Teleoperation** is a Great Tool for Design Iteration






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This talk

- Measuring Dexterity
  - dexterity involves creating change with intention / in-hand manipulation patterns (rock, roll, twiddle, step…) can be observed in grasp transitions
- Contacts Everywhere
  - everyday activities involve contact all over the hand / we can measure contact areas and plan grasps with large area contacts in mind
- Design for Dexterous Manipulation
  - soft hands can be robust, reliable, highly customizable, quick to prototype, … and dexterous

Putting it All Together

- General purpose benchmarks for dexterity
- Contact sensing
- Design from demonstration

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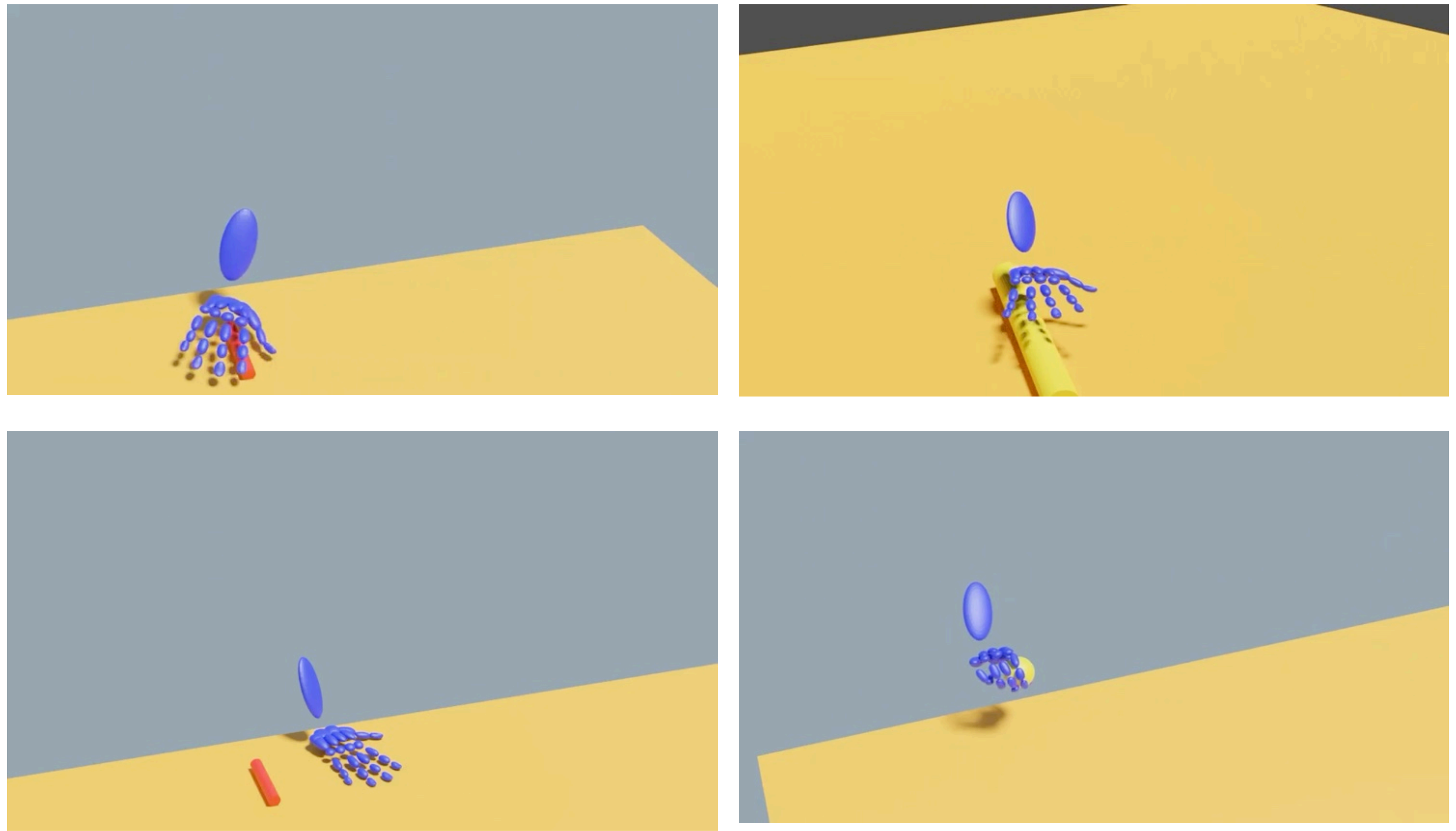
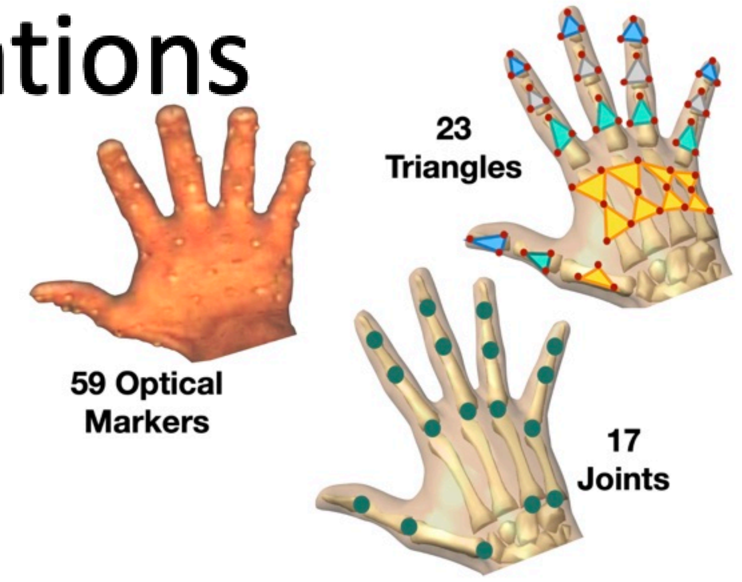
Putting it All Together



Task Demonstrations

Robot Hand Design



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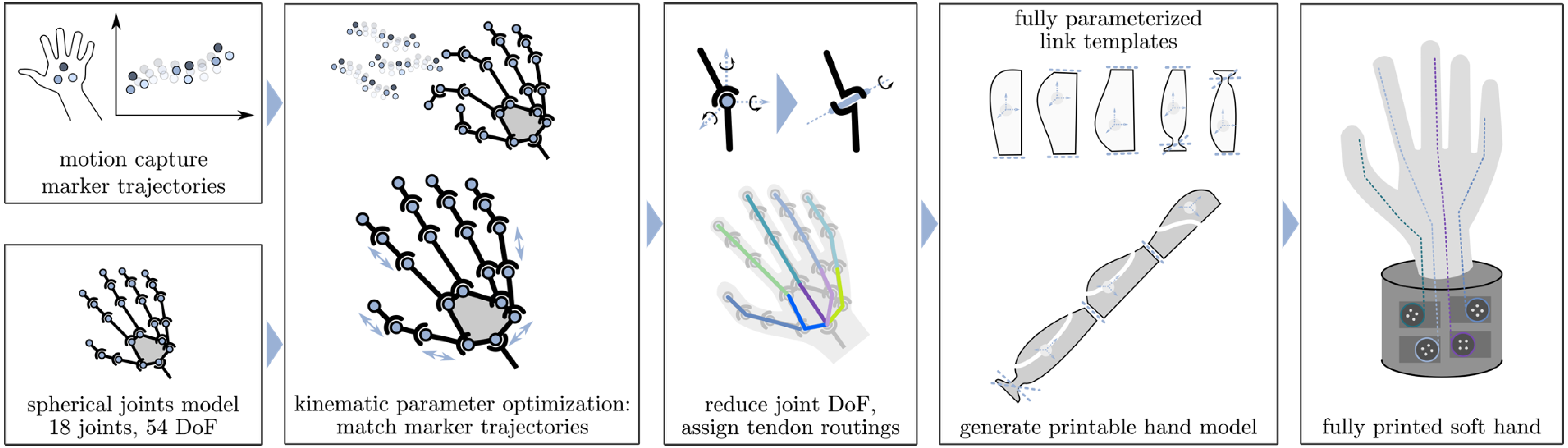

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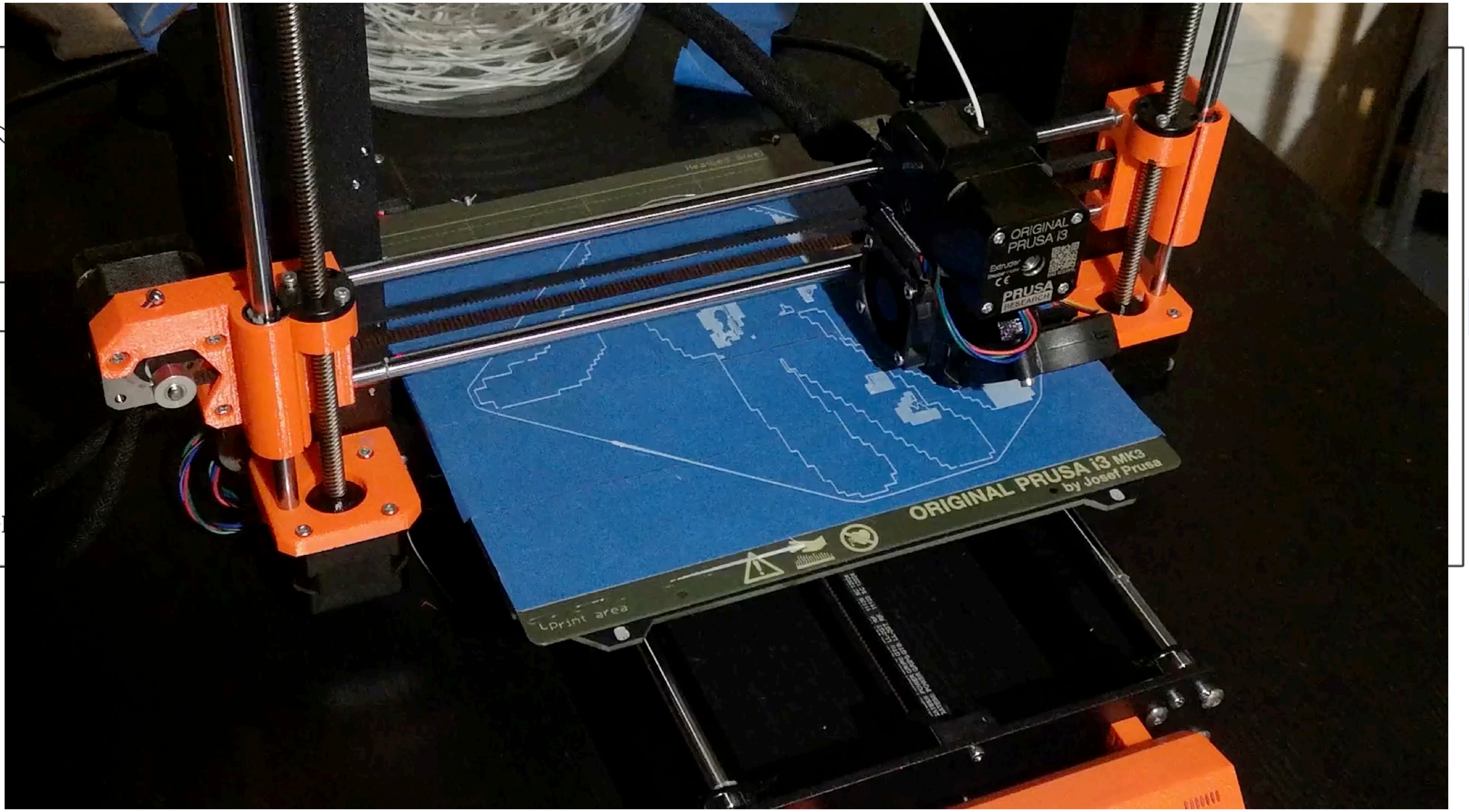

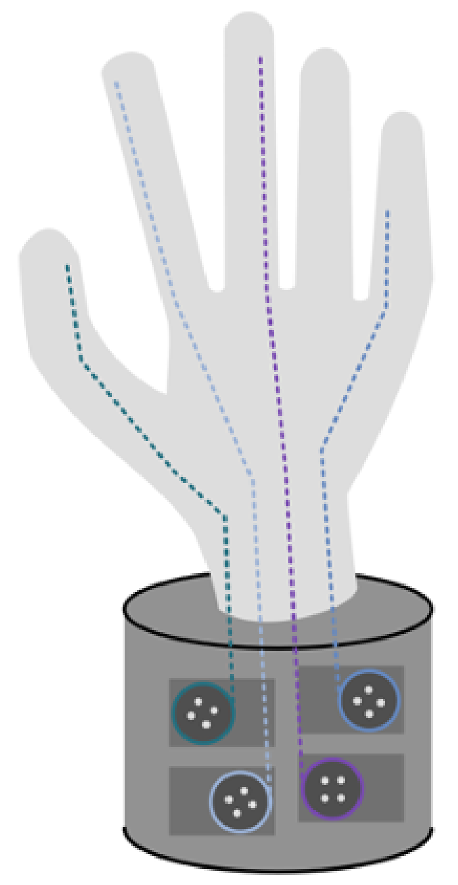

fully printed soft hand

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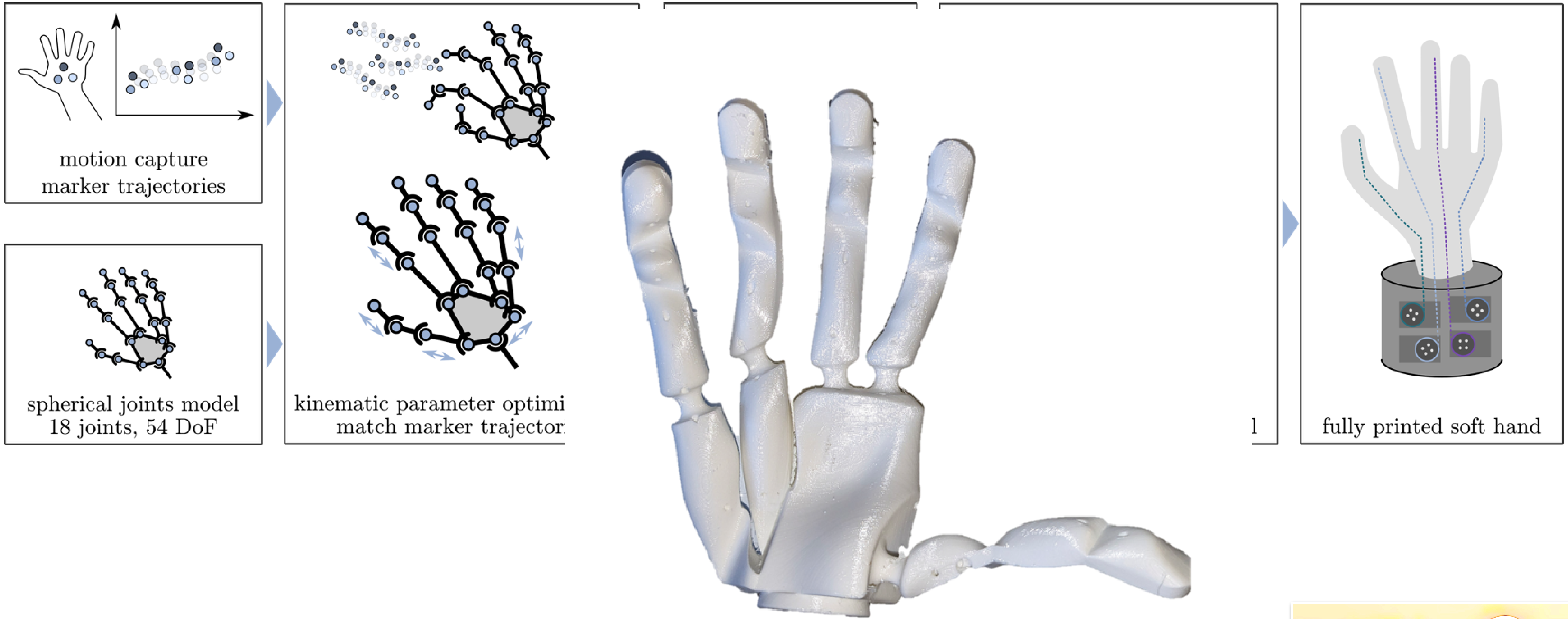

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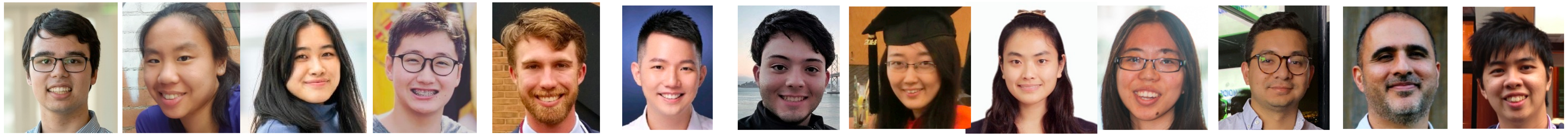
Acknowledgments



USDA National Institute of Food and Agriculture
U.S. DEPARTMENT OF AGRICULTURE

AIIRA
AI Institute for Resilient Agriculture

NASA

amazon

Meta

NSF U.S. National Science Foundation

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Center for Machine Learning and Health

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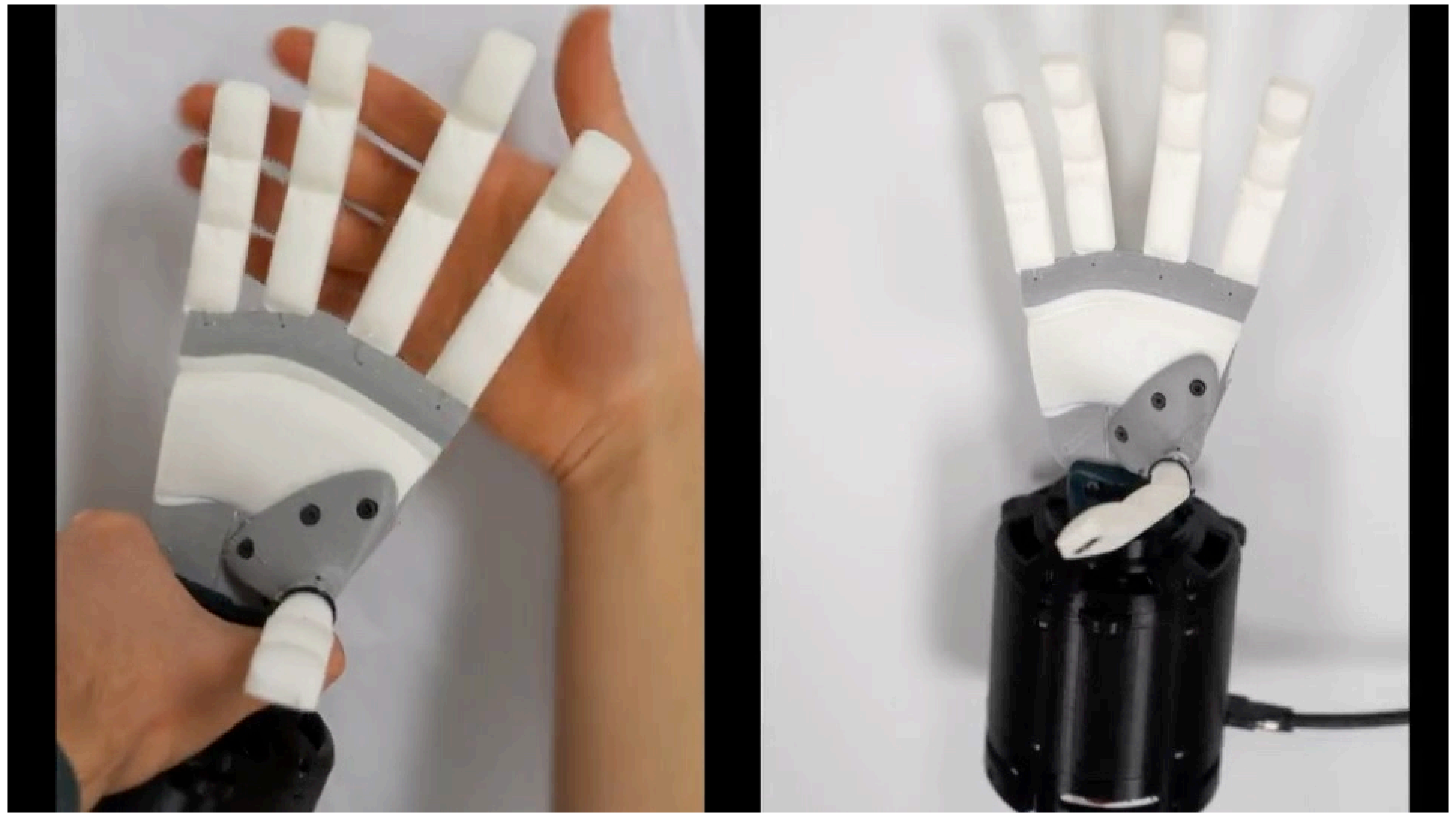
- 7DoF
- brushless DC (BLDC) electric motor (IQ Vertiq 220KV) operated at 24V
- built-in minimum jerk trajectory generator
- max pull out force 37N / finger
- NinjaTek Chinchilla (Shore Hardness 75A) — white
- NinjaTek Cheetah (Shore Hardness 95A) — grey
- total weight: 648g, soft hand excluding wrist: 94g
- $1000



23-06 220Kv Module

1 Features

Performance & Control

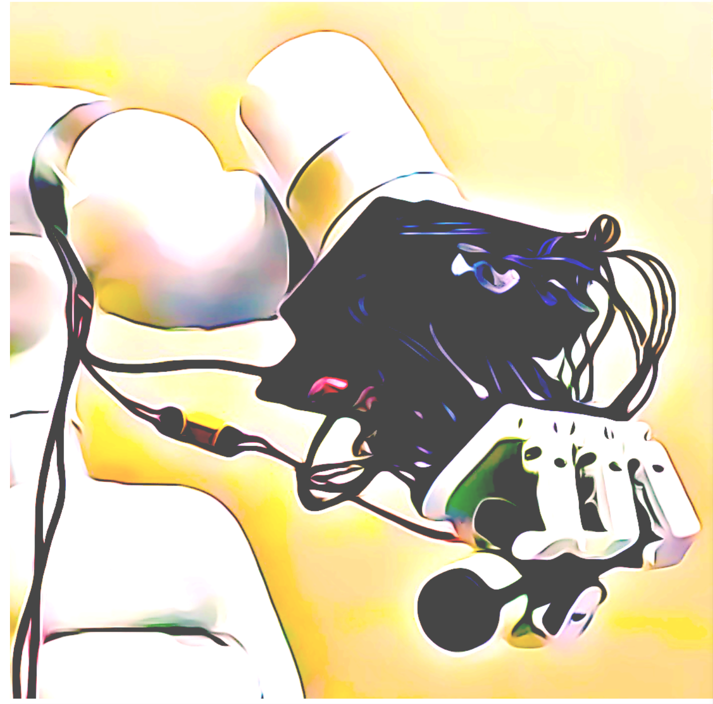
- Low power position control
- Multi-turn position control with tunable PID/FF
- Precise to 0.022°
- Field Estimated Control: Best-in-class efficiency
- Vibration minimization via anticogging software
- Closed-loop positioning, never skips or gets lost
- Built-in minimum jerk trajectories
- Built-in linear motion conversion
- Industry-leading response times
- Voltage, PWM, Coast, Brake modes
- No minimum speed
- Silent motion
- Backdrivable

3 Description

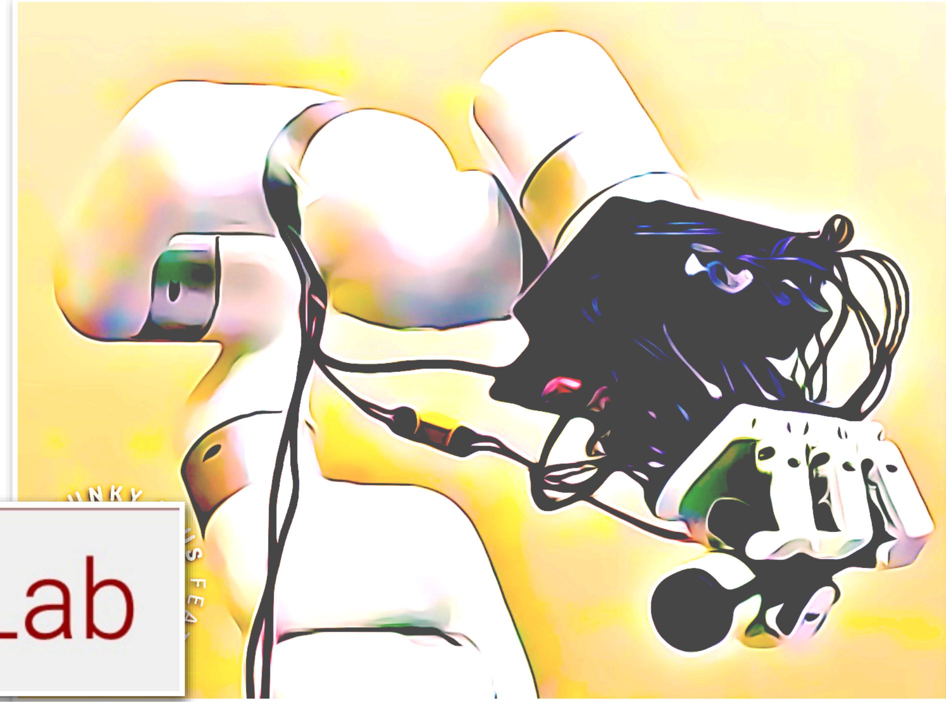
The 23-06 220Kv Module is an ultra-compact.

4 Motor Specifications

Description	Symbol	Value	Unit	Notes
Speed Constant	K_v	220	RPM/V	
Torque/EMF Constant	K_t	0.053	$\mathrm{N\,m\,A^{-1}}$	
Resistance	R	4.7	Ω	25°C
Mass	m	37.4	g	Without wires/accessories
Continuous Torque	τ_c	65	N mm	25°C ambient
Continuous Torque	τ_c	130	N mm	In airflow, 25°C ambient
Continuous Current	I_S	1.3	A	Motor current, 25°C ambient
Continuous Current	I_S	2.5	A	Motor current, in airflow, 25°C ambient
Pulsed Current	I_{SP}	5.3	A	Maximum supply voltage limited
No Load Speed	ω_0	199	$\mathrm{rad\,s^{-1}}$	$@V_{CC} = 10\,\mathrm{V}$
No Load Current	I_0	0.02	A	$@V_{CC} = 10\,\mathrm{V}$



- 12DoF
- DYNAMIXEL XC330-M288-T operated at 5V
- max pull out force 27N - 52N (6 different hands)
- NinjaTek Edge (Shore Hardness 83A)
- total weight 727g (v1)
- $1500



Specification

Model Name		XC330-M288-T
MCU		Cortex-M0+ (64 [MHz], 32bit)
Input Voltage	Min. [V]	3.7
	Recommended [V]	5.0
	Max. [V]	6.0
Performance Characteristics	Voltage [V]	5.0
	Stall Torque [N·m]	0.93
	Stall Current [A]	1.8
	No Load Speed [rpm]	81.0
	No Load Current [A]	0.08
Continuous Operation	Voltage [V]	-
	Torque [N·m]	-
	Speed [rpm]	-
	Current [A]	-
Resolution	Resolution [deg/pulse]	0.0879
	Step [pulse/rev]	4
	Angle [degree]	360
Position Sensor		Contactless absolute encoder (12Bit, 360 [deg]) Maker : ams(www.ams.com), Part No : AS5601
Operating Temperature	Min. [°C]	-5
	Max. [°C]	60
Motor		Coreless

DYNAMIXEL XC330-M288-T

DYNAMIXEL-X

$89.90

(No reviews yet)

Write a Review

SKU: 902-0173-000

Weight: 0.10 LBS

Shipping: Calculated at Checkout

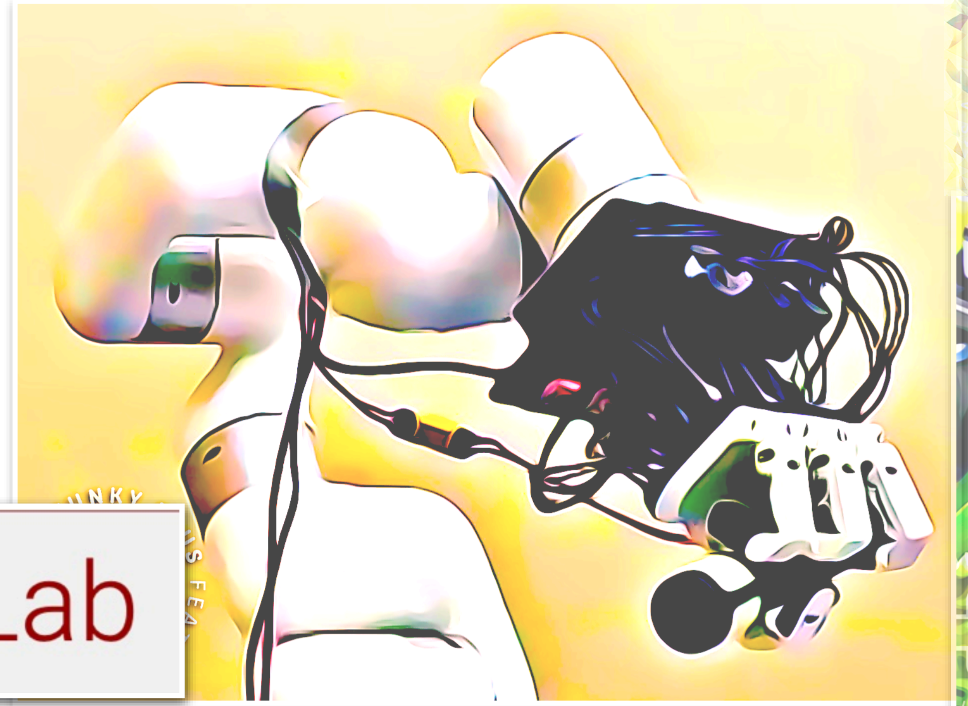
Ninjatek TPU Thermoplastic Polyurethane Materials

Chinchilla 75A

Edge 83A

Ninjaflex 85A

Cheetah 95A



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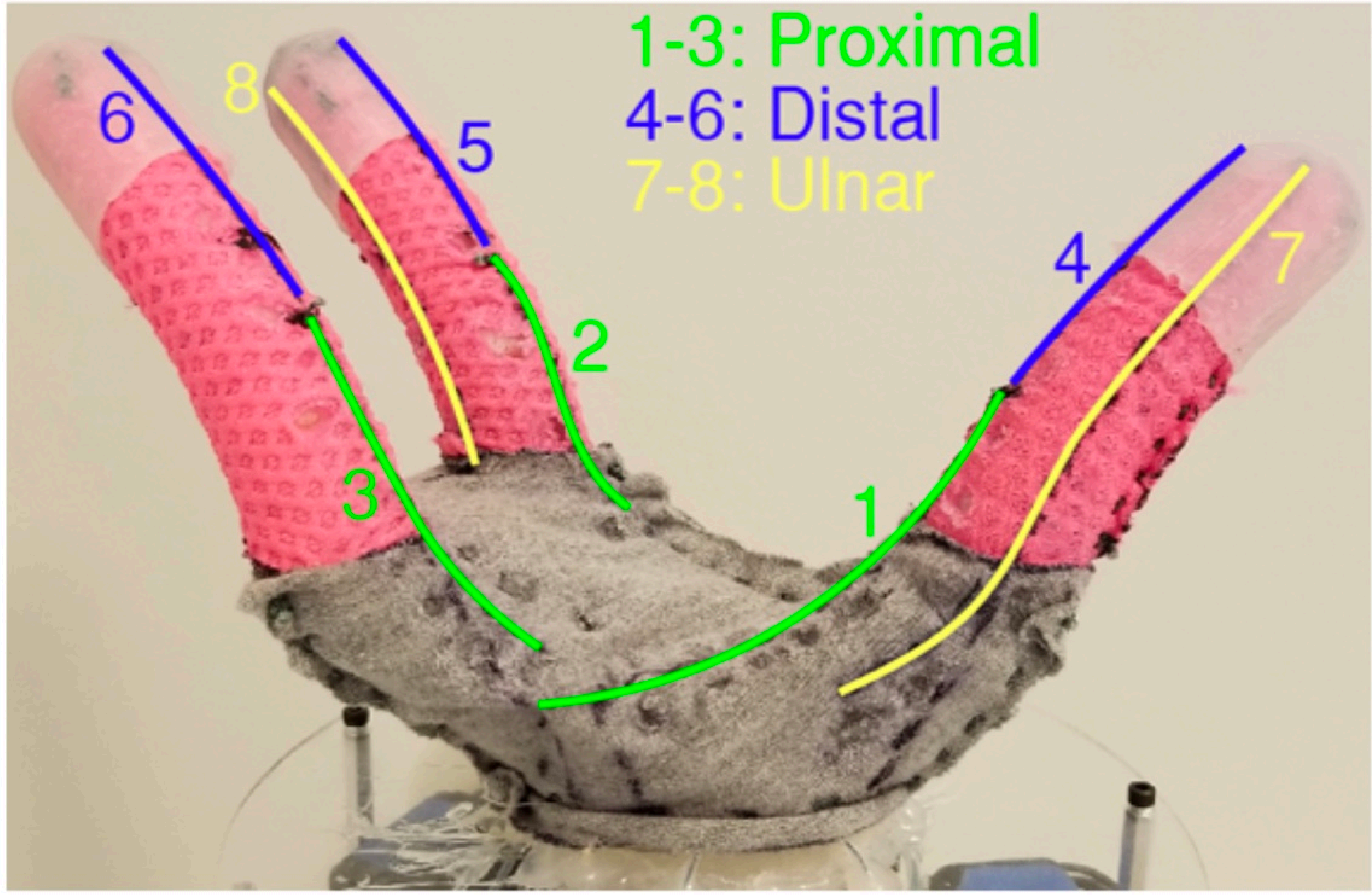
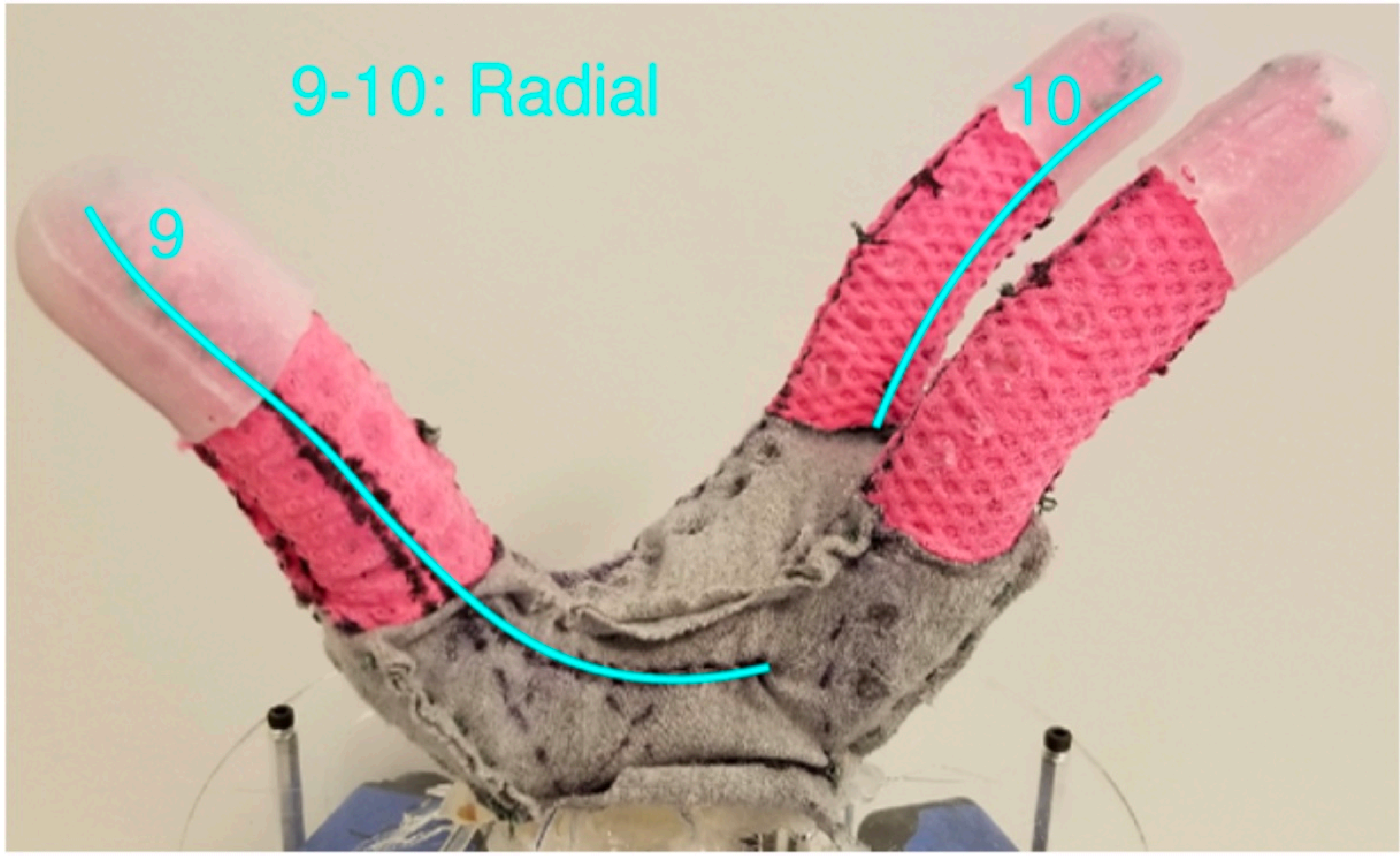
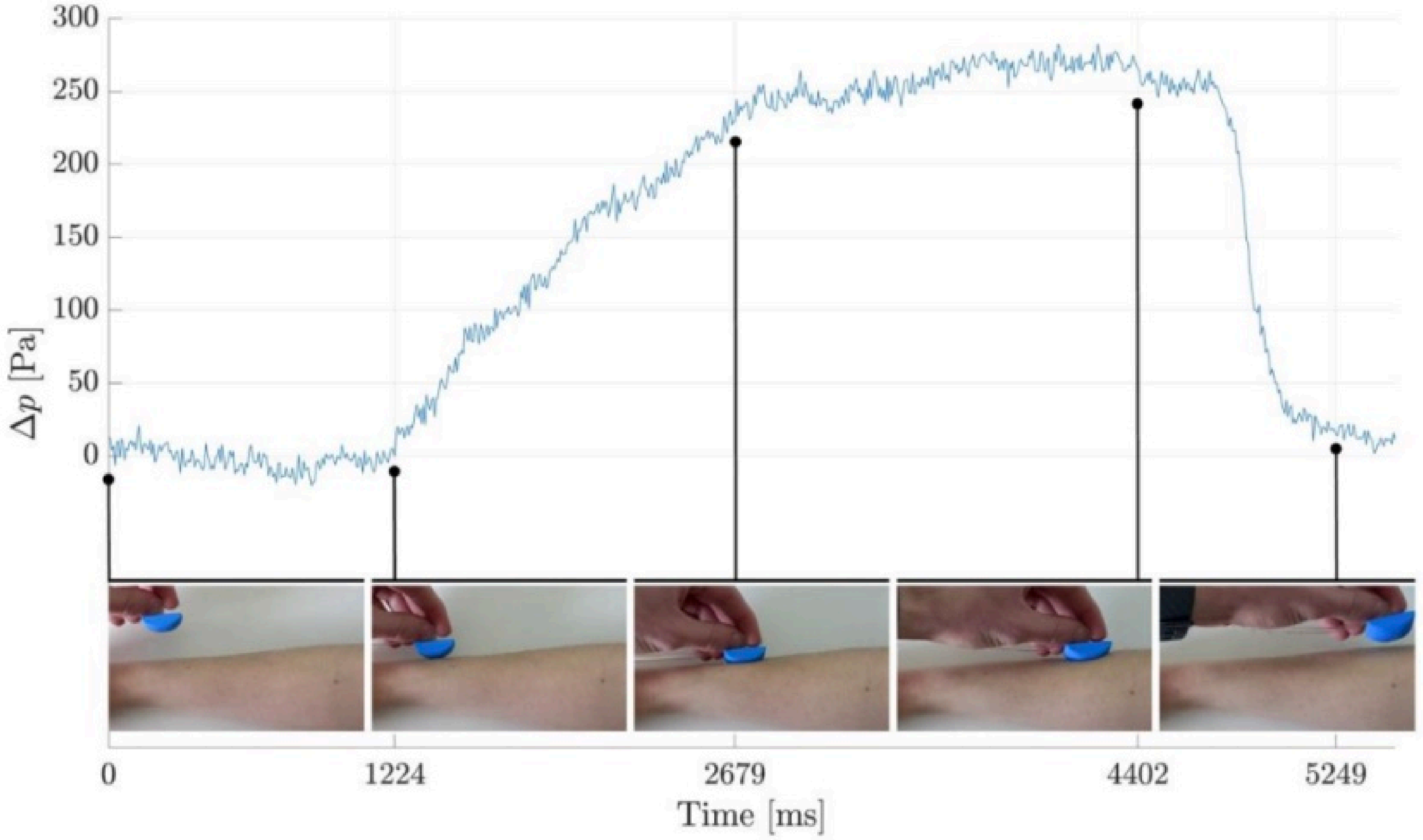
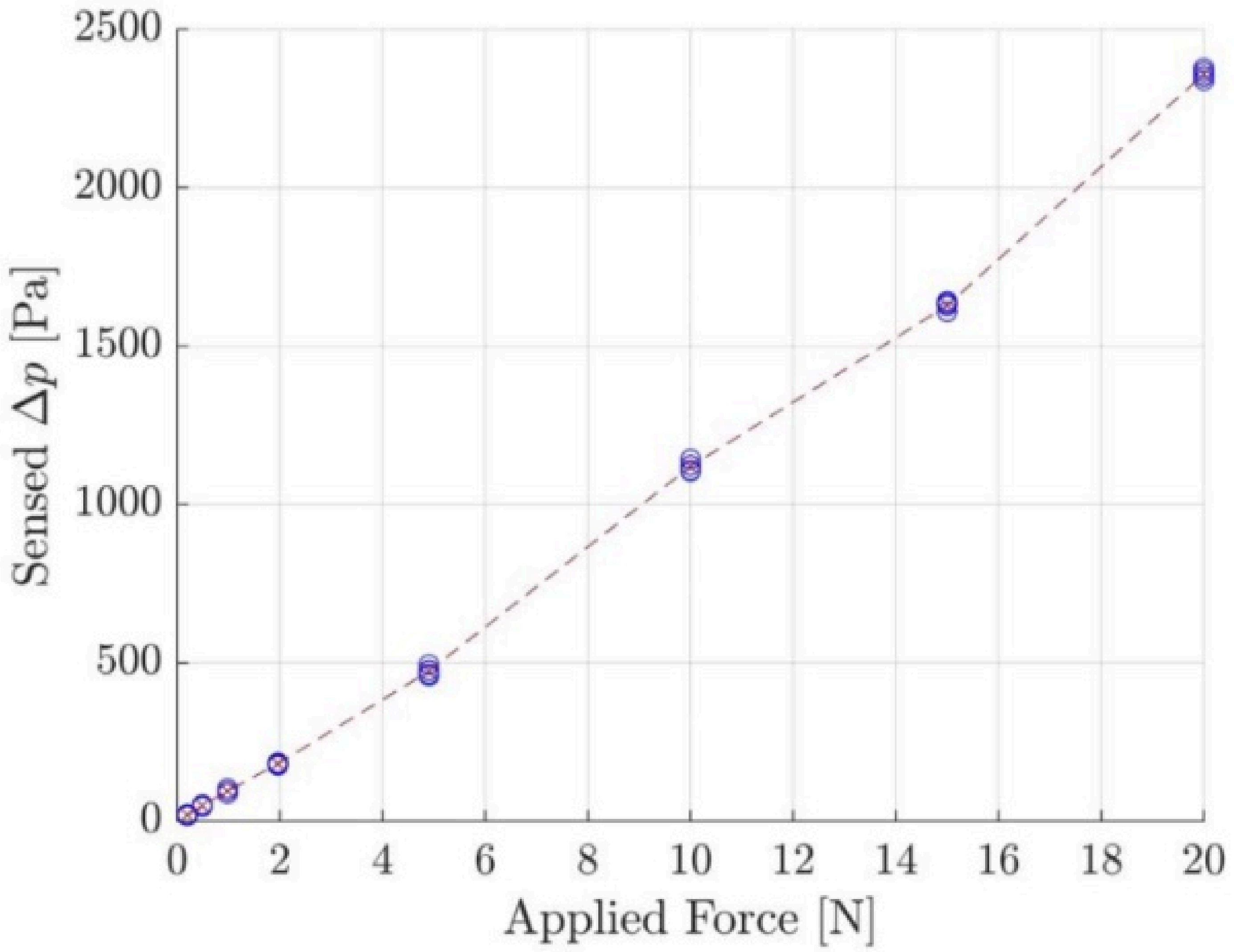
CMU Foam Hand III Details

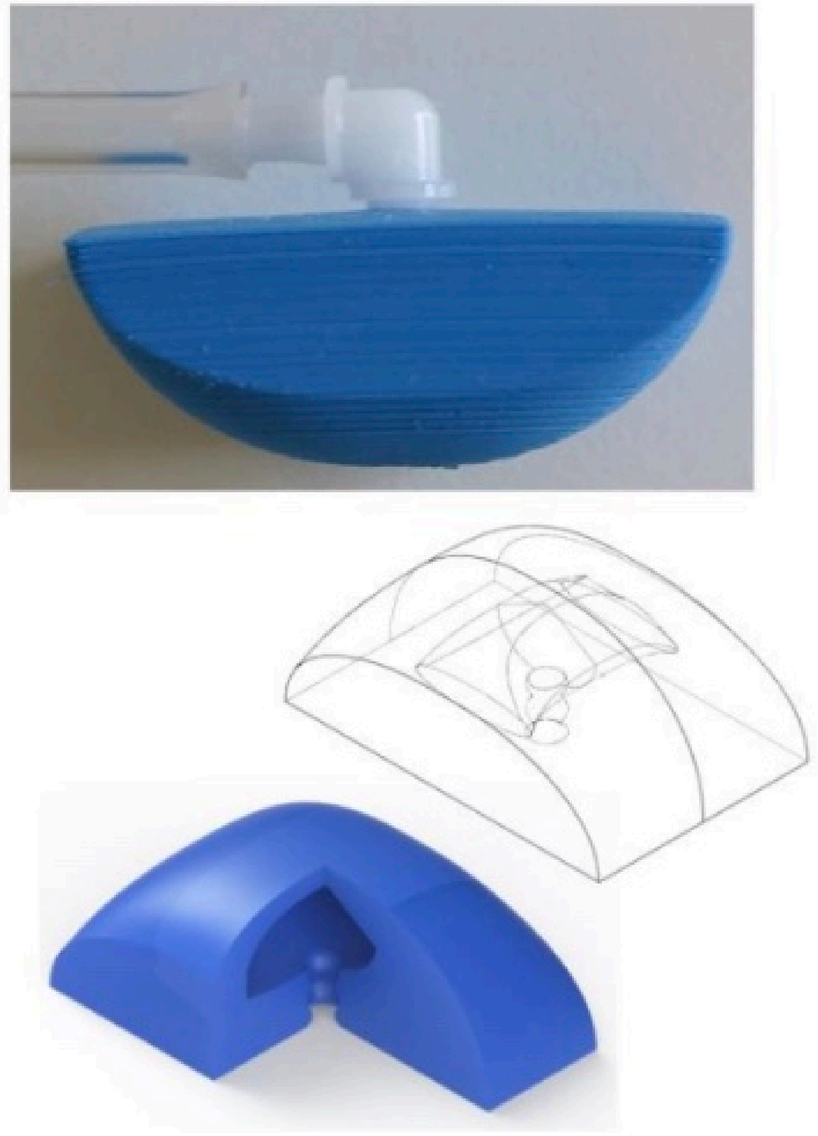




R. Coulson, C. Li, C. Majidi, and N. S. Pollard, The Elliott and Connolly Benchmark: A Test for Evaluating the In-Hand Dexterity of Robot Hands, Humanoids 2021







3D printed soft fingertip with cavity

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