Taxonomies, Synergies, and Benchmarks

16-848 Hands: Design and Control for Dexterous Manipulation
Spring 2024

THE PREHENSILE MOVEMENTS OF THE HUMAN HAND

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FIG. 5
As the lid is started the right hand is in a power grip posture.

FIG. 6
As the lid becomes loose the right hand assumes a precision grip posture.

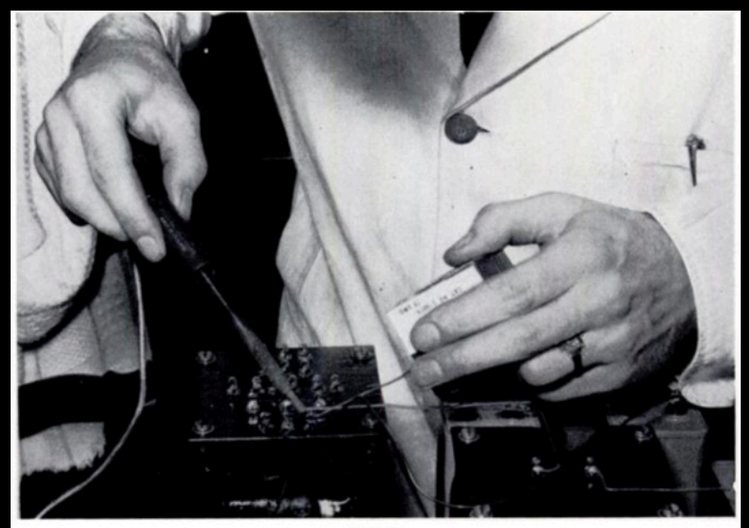

FIG. 7
The right hand is in a precision grip posture, the left in a power grip posture.

FIG. 1
A power grip posture.

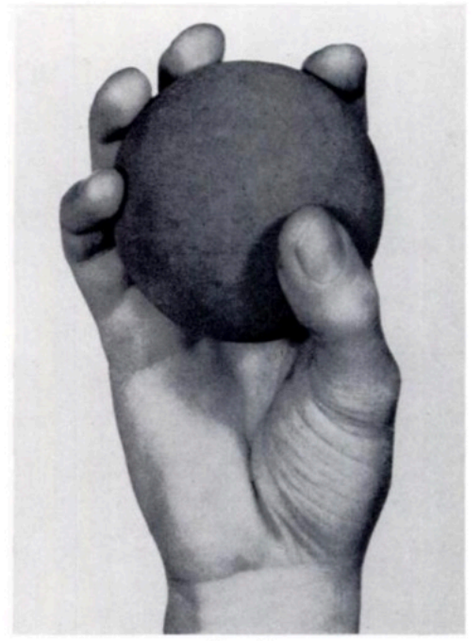

FIG. 2
A precision grip posture.

Power vs. Precision

Napier, John R. "The prehensile movements of the human hand." *The Journal of bone and joint surgery. British volume* 38, no. 4 (1956): 902-913.

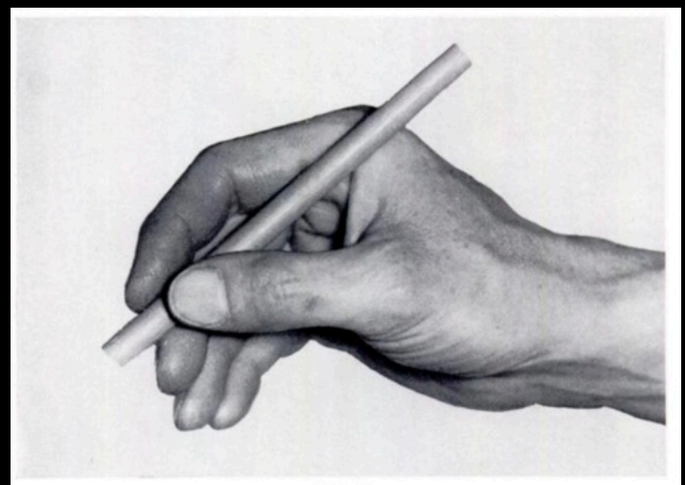

FIG. 3
Wooden rod held in a writing position.

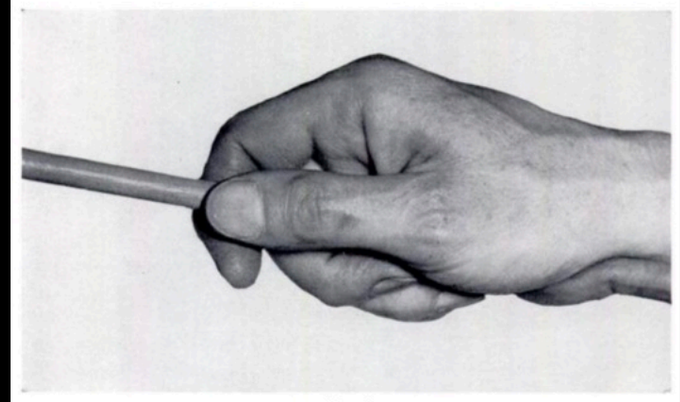

FIG. 4
Wooden rod held in a hammering position.

Taxonomies

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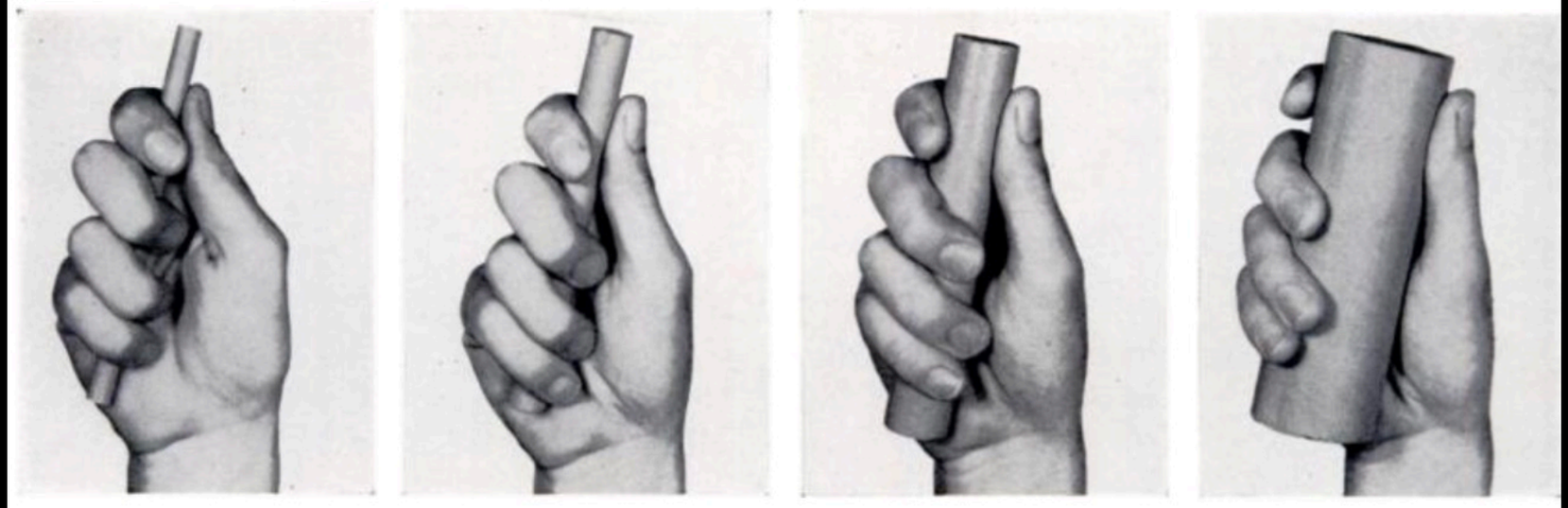


FIG. 8
An arbitrarily chosen series of postures illustrating some of the phases of the power grip complex.

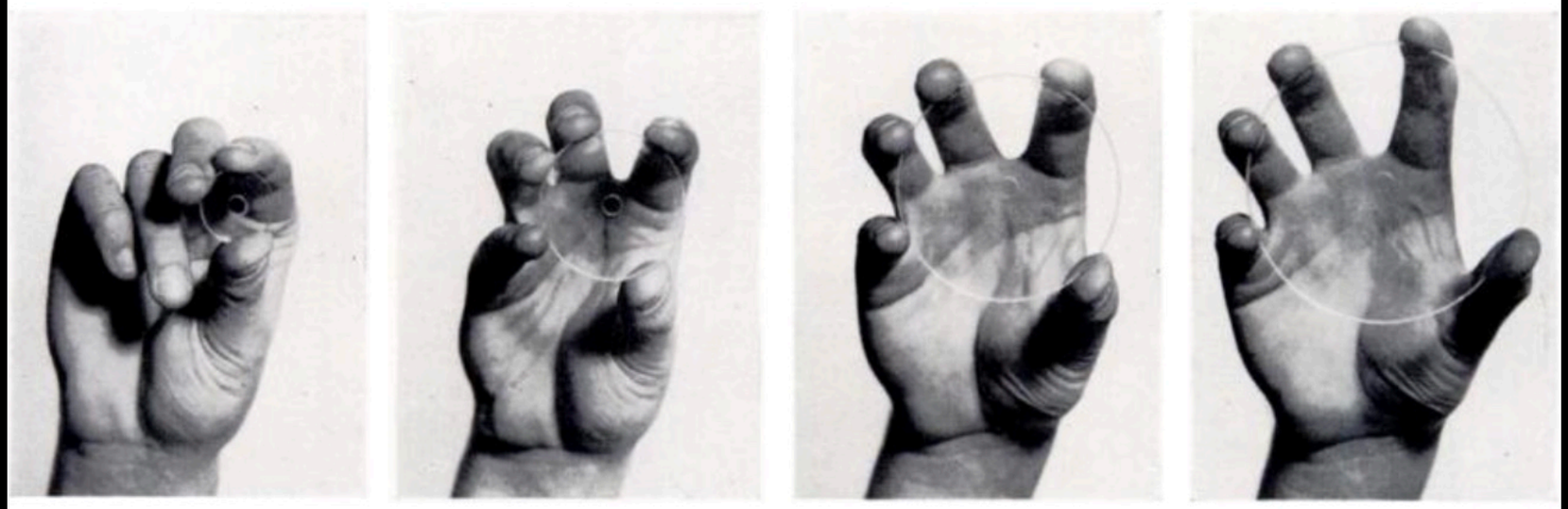


FIG. 9
An arbitrarily chosen series of postures illustrating some of the phases of the precision grip complex.

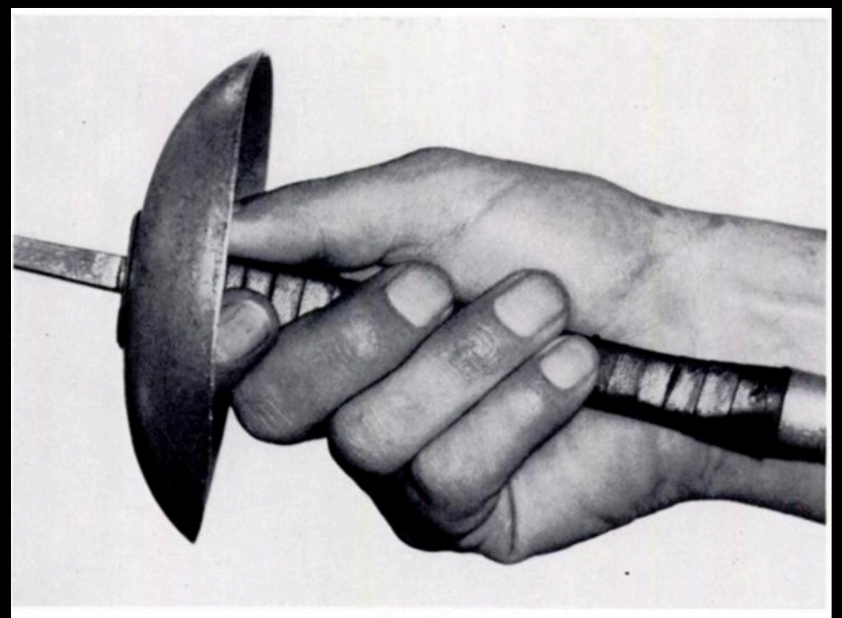
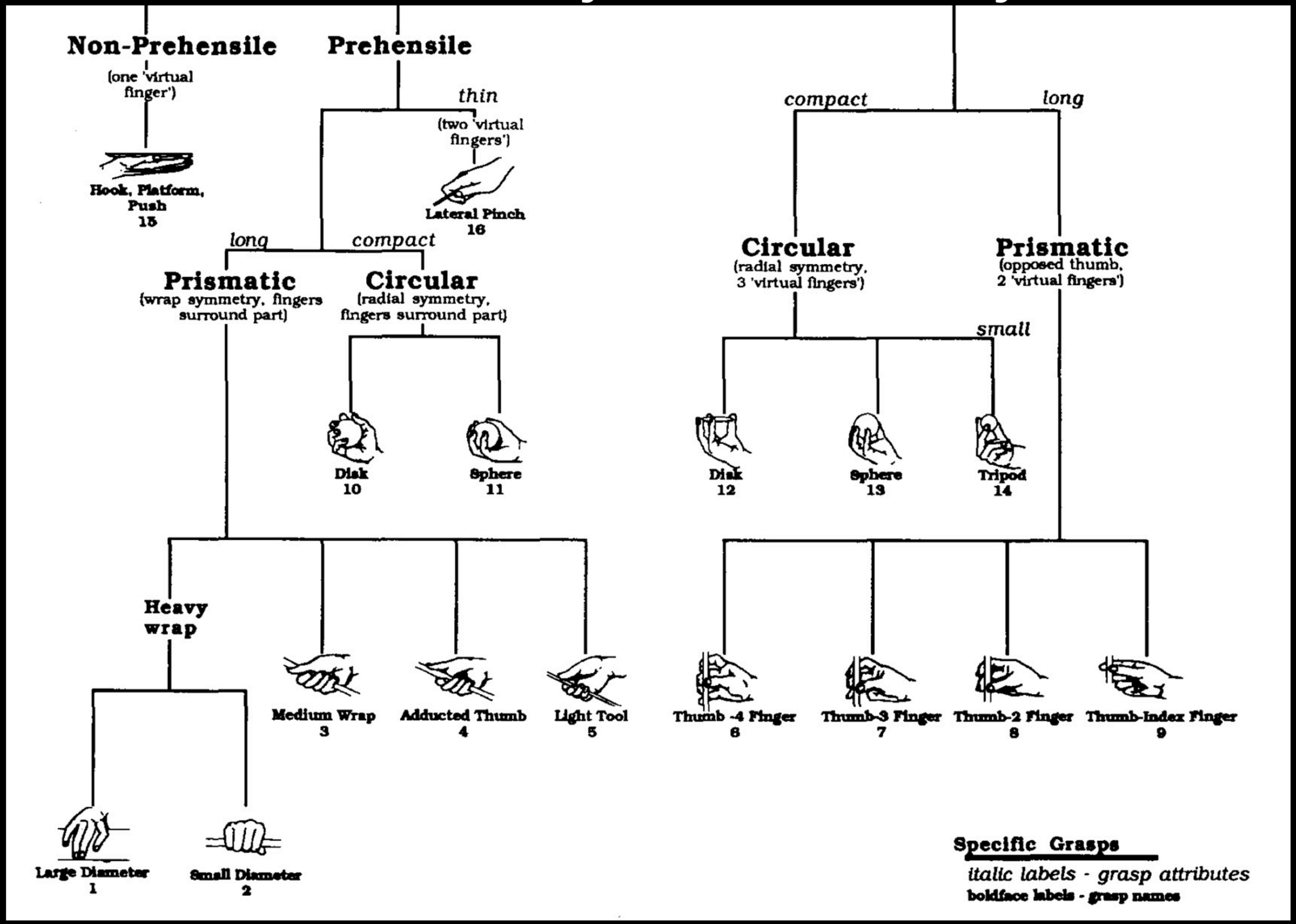


FIG. 10
A power grip posture in which the element of precision plays a large part. (The subject of this photograph is a fencing master.)

Power vs. Precision

Napier, John R. "The prehensile movements of the human hand." *The Journal of bone and joint surgery. British volume* 38, no. 4 (1956): 902-913.

Cutkosky Taxonomy



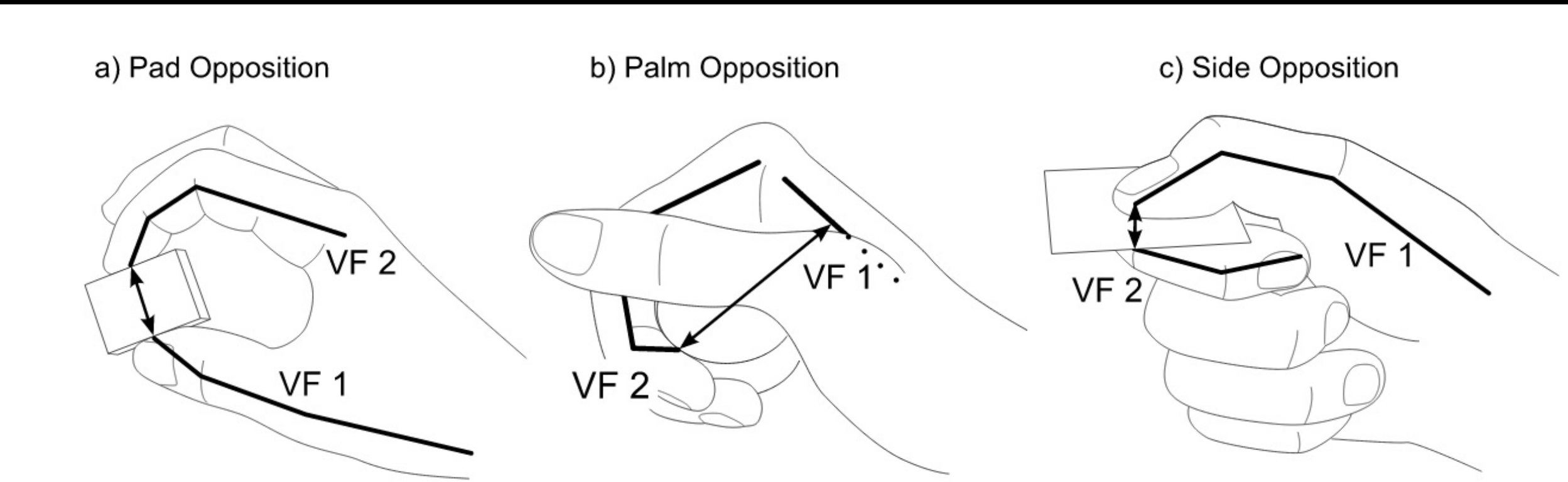
Cutkosky, Mark R. "On grasp choice, grasp models, and the design of hands for manufacturing tasks." *IEEE Transactions on robotics and automation* 5, no. 3 (1989): 269-279.

Kamakura Taxonomy

Kamakura, Noriko, Michiko Matsuo, Harumi Ishii, Fumiko Mitsuboshi, and Yoriko Miura. "Patterns of static prehension in normal hands." *The American journal of occupational therapy* 34, no. 7 (1980): 437-445.

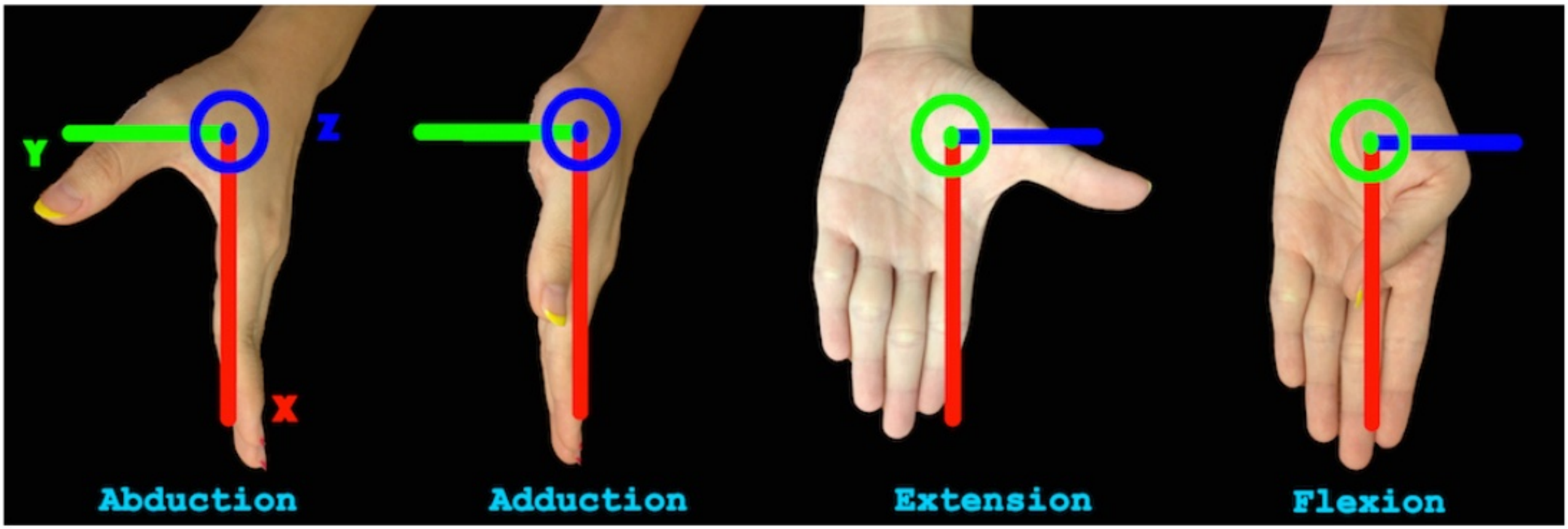
Kapandji Taxonomy

Iberall's Oppositions and Virtual Fingers

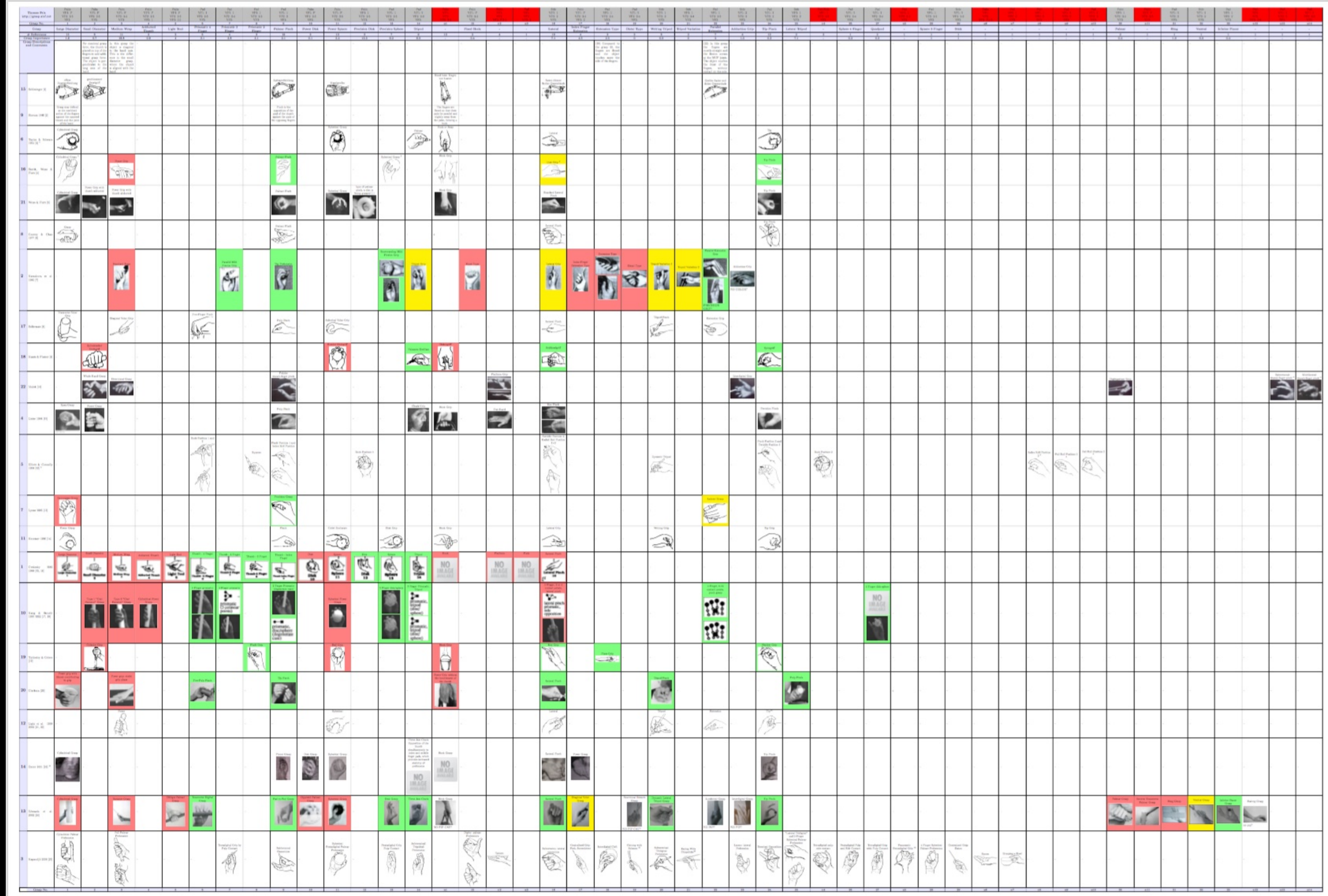


Iberall, Thea. "Human prehension and dexterous robot hands." *The International Journal of Robotics Research* 16, no. 3 (1997): 285-299.

Thumb Abduction / Adduction



Feix et al. Cumulative Taxonomy

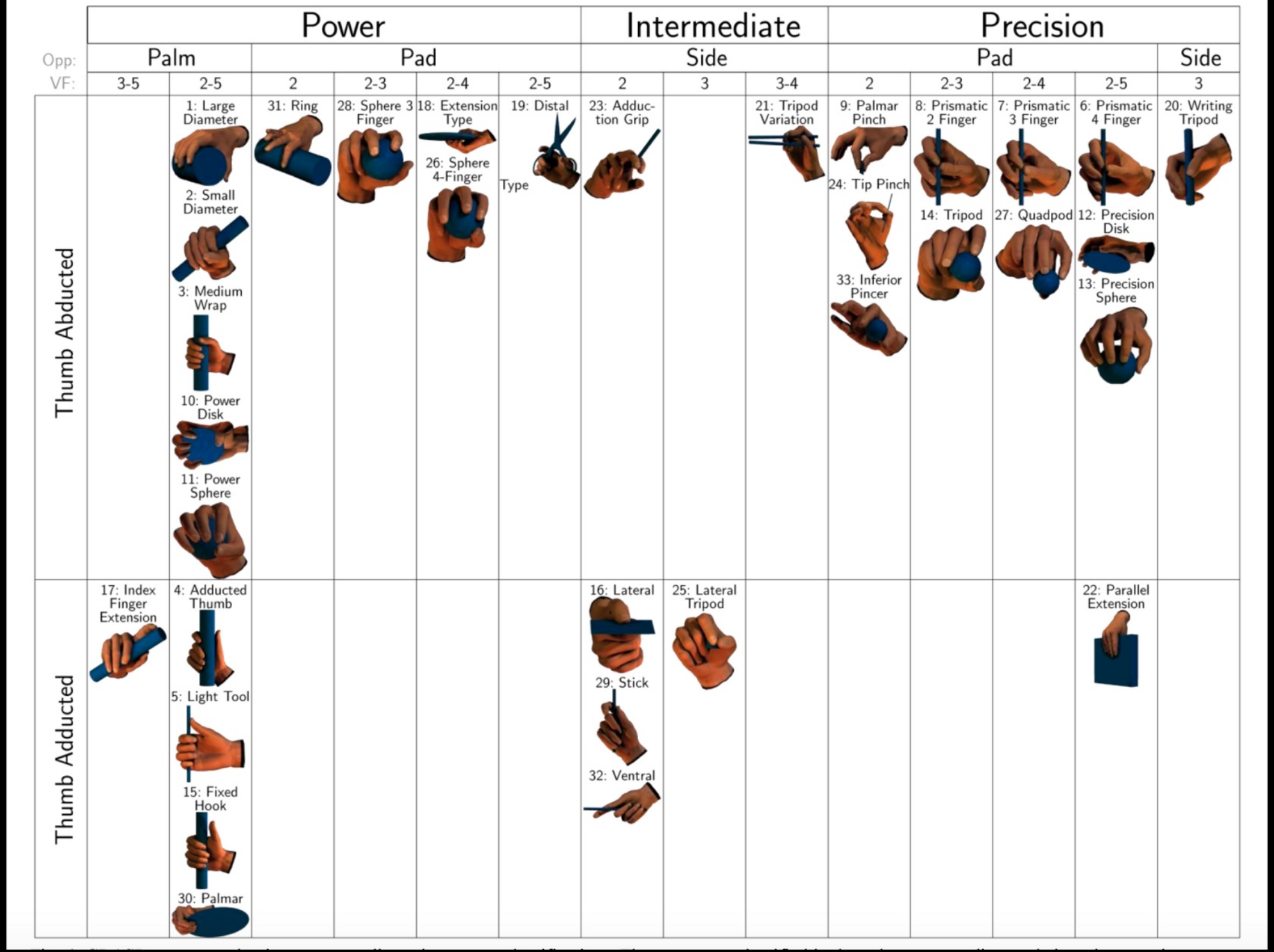


Feix et al. Cumulative Taxonomy

		Palm VF1: P VF2: 2-5 VF3:	Palm VF1: P VF2: 2-5 VF3:	Palm VF1: P VF2: 2-5 VF3:	Palm VF1: P VF2: 2-5 VF3: 1	Palm VF1: P VF2: 2-5 VF3: (1)	Pad VF1: 1 VF2: 2-5 VF3:	Pad VF1: 1 VF2: 2-4 VF3:	Pad VF1: 1 VF2: 2-3 VF3:	Pad VF1: 1 VF2: 2 VF3:	
Grasp No.		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
Grasp		**Large Diameter**	**Small Diameter**	**Medium Wrap**	**Adducted Thumb**	**Light Tool**	**Prismatic 4 Finger**	**Prismatic 3 Finger**	**Prismatic 2 Finger**	**Palmar Pinch**	**Pc**
# References		**15**	**8**	**11**	**2**	**2**	**6**	**4**	**3**	**18**	
Grasp Importance		**1.6**	**0.7**	**18.8**	**0.9**	**4**	**3.1**	**3.8**	**5.1**	**3.1**	
1	Cutkosky 1989	Large Diameter 	Small Diameter 	Medium Wrap 	Adducted Thumb 	Light Tool 	Thumb - 4 Finger 	Thumb - 3 Finger 	Thumb - 2 Finger 	Thumb - Index Finger 	
2	Kamakura et al. 1980	–	–	Standard Type 	–	–	–	Parallel Mild Flexion Grip 	–	Tip Prehension 	–
3	Kapandjii 2006	Cylindrical Palmar Prehension 	–	Full Palmar Prehension 	–	–	–	Tetradigital Grip by Pulp Contact 	–	Subterminal Opposition 	–

Fig. 2. Comparison of the grasp listings from 22 taxonomy publications found in literature. Due to the size (22 publications x 47 grasp columns) only an excerpt

Feix et al. Cumulative Taxonomy

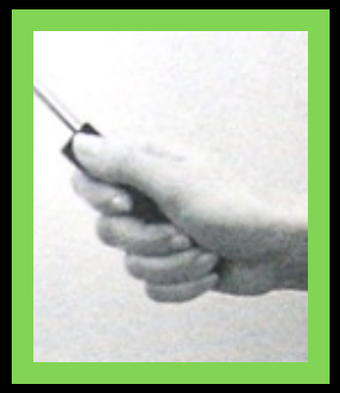


Feix, Thomas, Javier Romero, Heinz-Bodo Schmiedmayer, Aaron M. Dollar, and Danica Kragic. "The grasp taxonomy of human grasp types." *IEEE Transactions on human-machine systems* 46, no. 1 (2015): 66-77.

Feix et al. taxonomy in use

Raphael Deimel and Oliver Brock. A Novel Type of Compliant and Underactuated Robotic Hand for Dexterous Grasping. International Journal of Robotics Research 2015.

Cumulative Taxonomy: My Summary



1. Power grasps using the Palmar Gutter

2. Power grasps using Other Parts of the Palm

3. Power grasps with Lateral Stabilization

4. Precision grasps with Lateral Stabilization

5. Power grasps with Pad Opposition

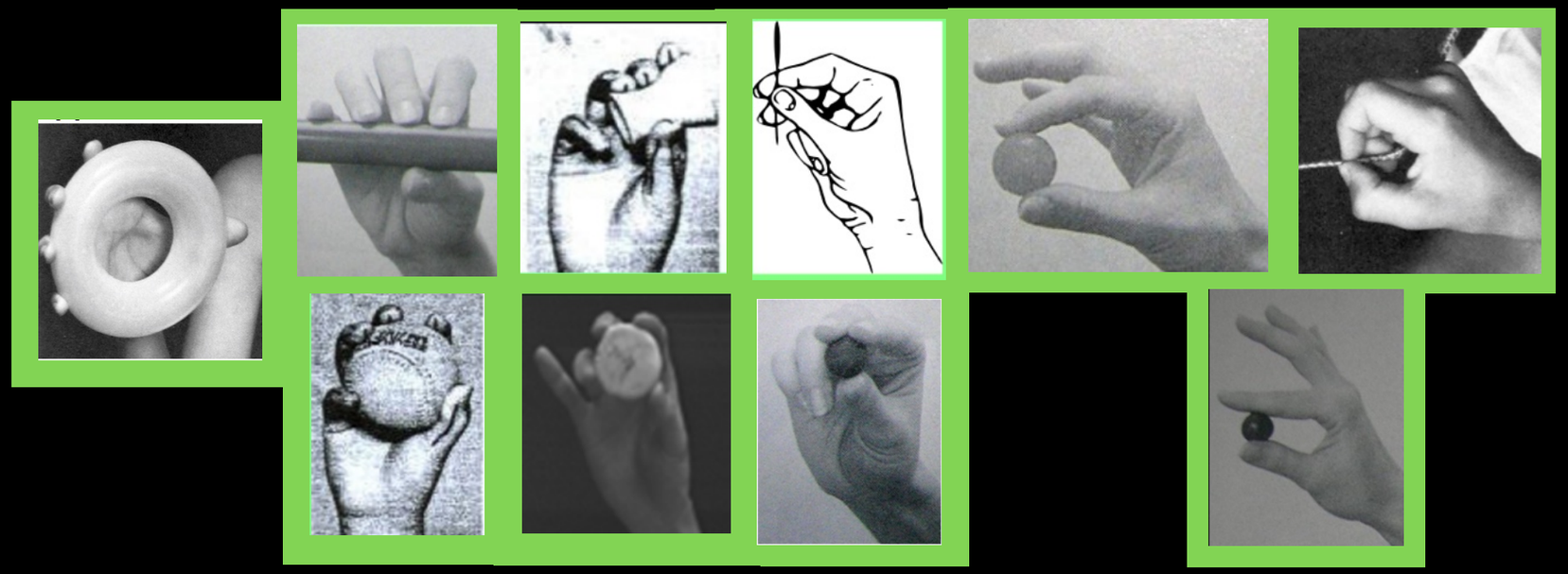
6. Precision Grasps with Pad Opposition

Feix et al. Cumulative Taxonomy: My Summary

Power palm

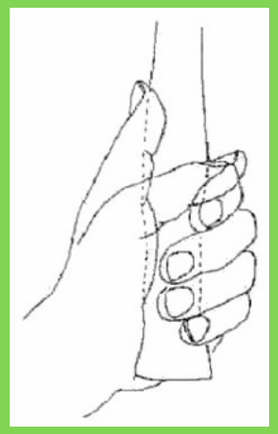
Lateral support

Pad opposition

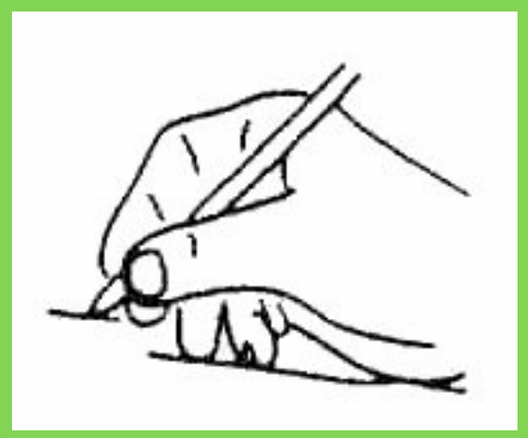


Feix et al. Cumulative Taxonomy — is this sufficient?

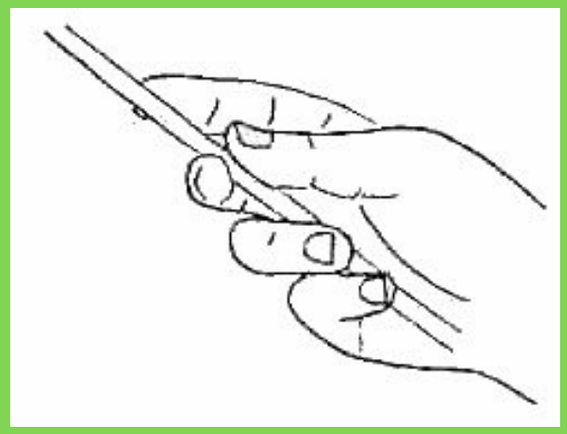
Taxonomy from a Surgeon



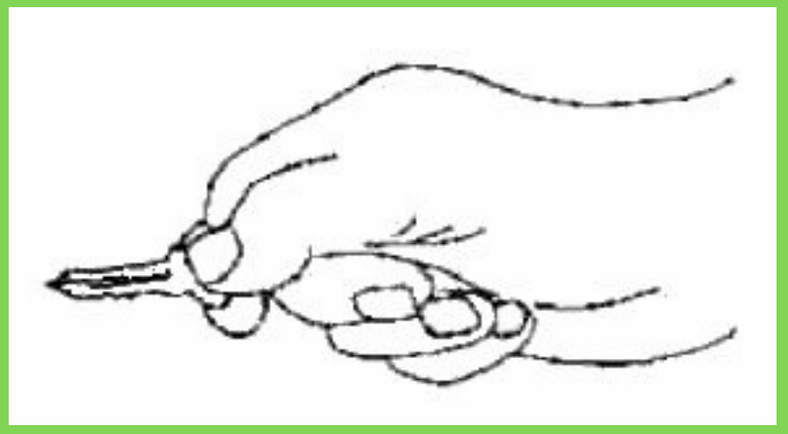
Power



External Precision

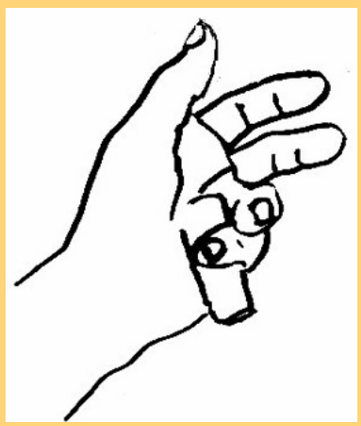


Internal Precision

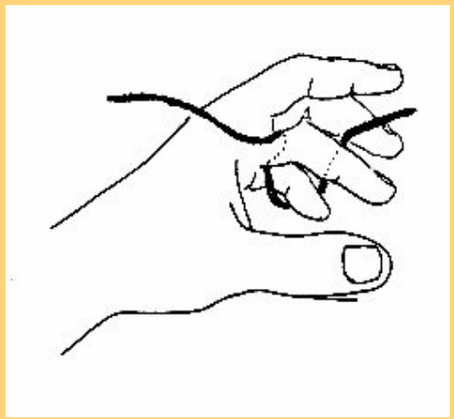


Pinch

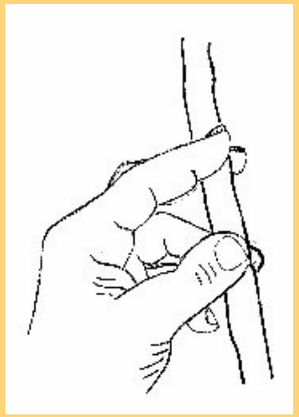
Power Variation



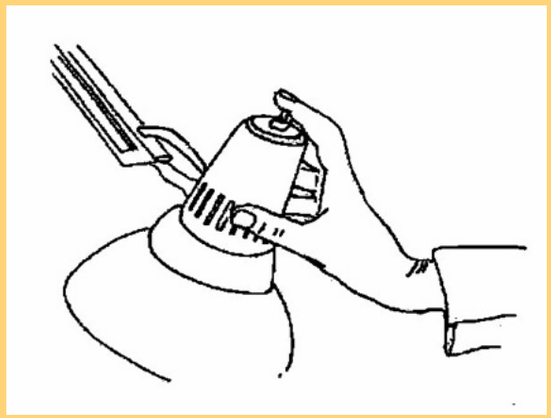
Ulnar Storage



Suture Storage



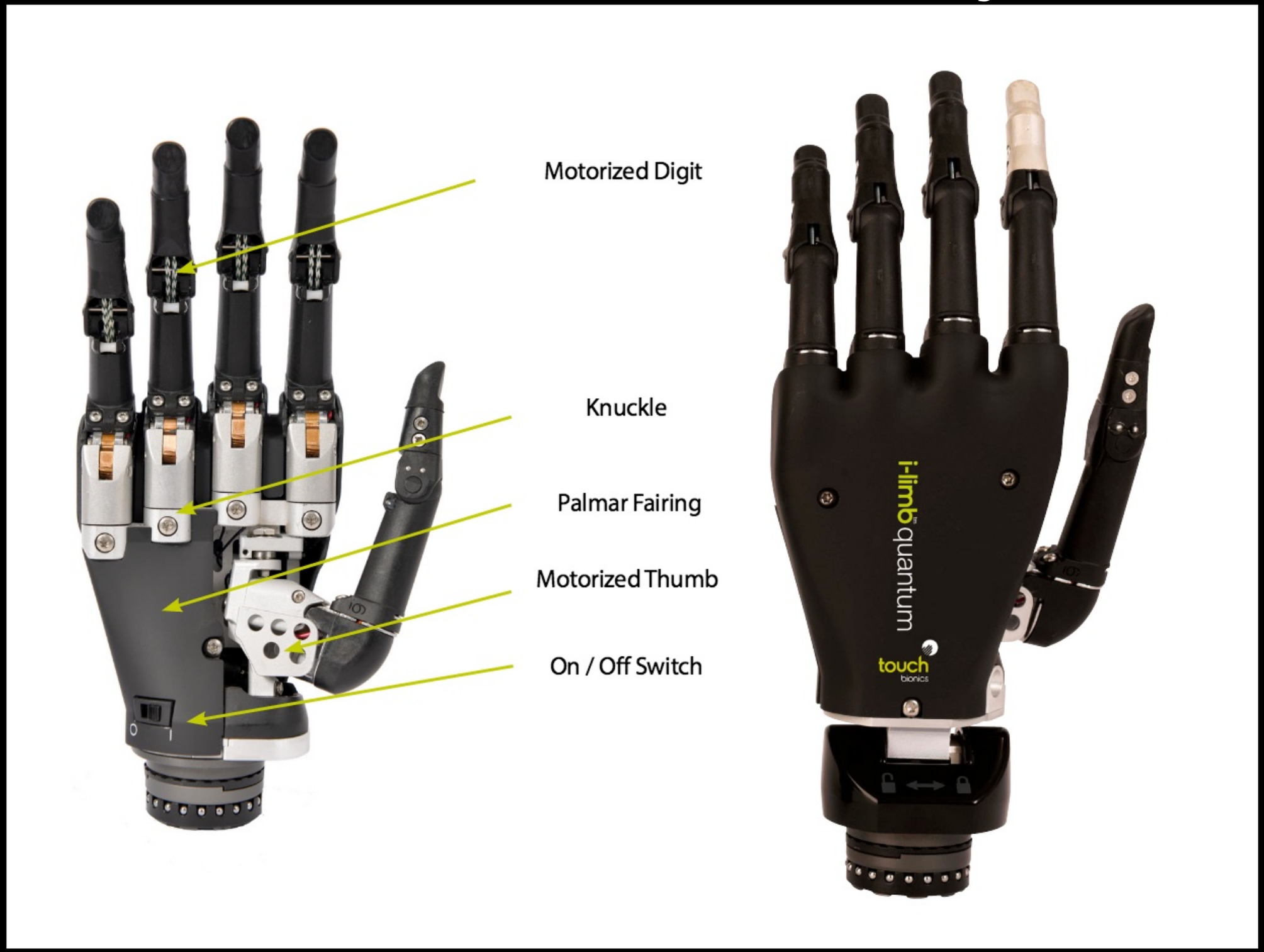
Stretching



Trigger

https://mpatkin.org/ergonomics/handle_checklist.htm

I-Limb Taxonomy



https://www.youtube.com/watch?v=doWAtRT00T0

I-Limb Taxonomy: 1 of 2

Precision Pinch Grip Options

Standard Precision Pinch Opened

middle, ring and little finger remain fully opened and switch off. Index finger and thumb provide grip.

Standard Precision Pinch Closed

middle, ring and little finger automatically close and switch off. Index finger and thumb provide grip.

Thumb Precision Pinch Opened

middle, ring and little finger remain fully opened and switch off. Thumb automatically moves to a partially closed position. Index finger will move to provide grip against a fixed thumb.

Thumb Precision Pinch Closed

middle, ring and little finger automatically close and switch off. Thumb automatically moves to a partially closed position. Index finger will move to provide grip against a fixed thumb.

Tripod Grip Options

Standard 3 Jaw Chuck (Tripod) Opened

ring and little finger remain fully opened and switch off. Thumb, index and middle fingers move to provide grip.

Standard 3 Jaw Chuck (Tripod) Closed

ring and little finger move to terminal close. Thumb, index and middle fingers move to provide grip.

Thumb 3 Jaw Chuck (Tripod) Opened

ring and little finger remain fully opened and switch off. Thumb automatically moves to a partially closed position. Index and middle fingers move to provide grip against a fixed thumb.

Thumb 3 Jaw Chuck (Tripod) Closed

ring and little finger move to terminal close. Thumb automatically moves to a partially closed position. Index and middle fingers move to provide grip against a fixed thumb.

I-Limb Taxonomy: 2 of 2

Thumb Park Continuous

all four fingers remain open and switch off, only the thumb will move.

Thumb Park Quick

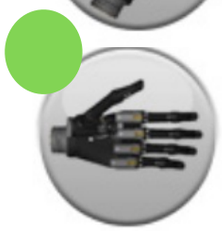
all four fingers remain open and switch off, for 1.5 seconds the thumb will close and then automatically return to an open position.

Grasp

hand forms a shape appropriate for grasping an object. Fingers flex rapidly when any user signal is applied

Cylindrical

hand forms a shape appropriate for grasping a cylinder



Lateral Grip

all four fingers fully close and switch off. only thumb will move.

Rotate Thumb

thumb and all four fingers fully open and switch off. Only thumb will rotate

One Finger Trigger

hand forms a shape appropriate for using a spray bottle with the index finger active

Trigger Two Finger

hand forms a shape appropriate for using a spray bottle with the index and middle finger active

Thumb Trigger

hand forms shape appropriate for using an aerosol spray can with thumb active

Mouse

hand forms shape appropriate for using a computer mouse

Handshake

hand forms a shape appropriate for shaking another persons hand

Index Point

thumb, little, ring and middle fingers close and switch off. Only the index finger will move.

Open Palm

hand forms a shape appropriate with holding plate or saucer

Custom Grip

all fingers automatically move to a user defined position. The user can choose to keep certain digits active and switch others off.

Custom Gesture

all fingers automatically move to a user defined fully opened or fully closed position and switch off.

Don Doff

hand forms the proper shape for donning and doffing a cover

One Object, One Task, 17 Subjects

Lateral

Precision Disk

Palmar Pinch

Parallel Extension Variation?

Ventral Variation?

Palmar Pinch Variation?

Palmar Pinch Variation?

Bimanual Lateral

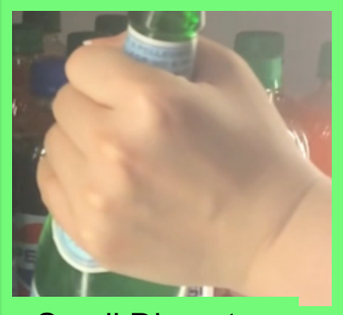
Bimanual Parallel Extension?

Bimanual Cupping

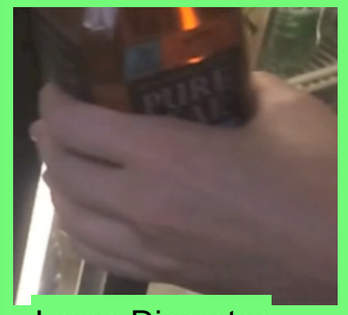
Bimanual Ring

3 Minutes of Shopping, One Subject

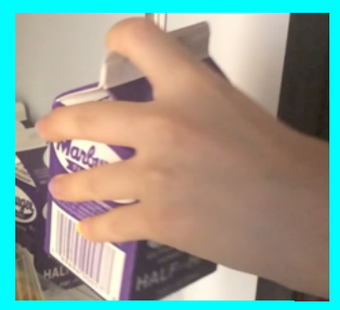
Power Sphere 3



Small Diameter Heavy Wrap 1



Large Diameter Heavy Wrap 8



Large Diameter Heavy Wrap / Index Top 3

Power Parallel with Index Side 2

Power Parallel 1

Power Grip Distal Type 1

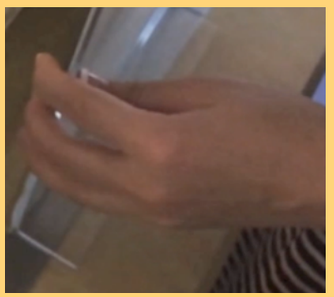
Multi-Item 3

Power Medium Wrap 1

Power Grip Extension Type 3

Power Lateral Pinch 3

Power Lateral Pinch Torque Supported 2

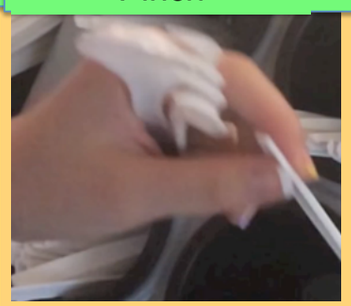


Power Non-Prehensile 1

Two-Hand 1

Thumb Proximal Phalanges Pinch 4

Ulnar 7



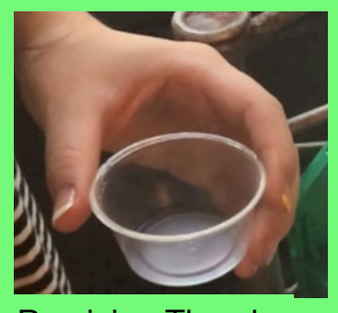
Ulnar Plus Pinch 3

Thumb Index Pad Pinch 8

Power Lateral Pinch, Middle 3

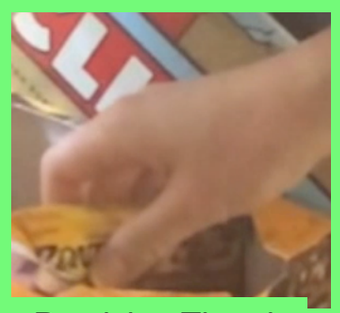
Precision Sphere 1

Precision Disk 4



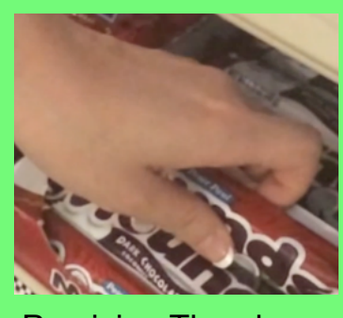
Precision Thumb 2-Finger 1

Precision Tripod 2



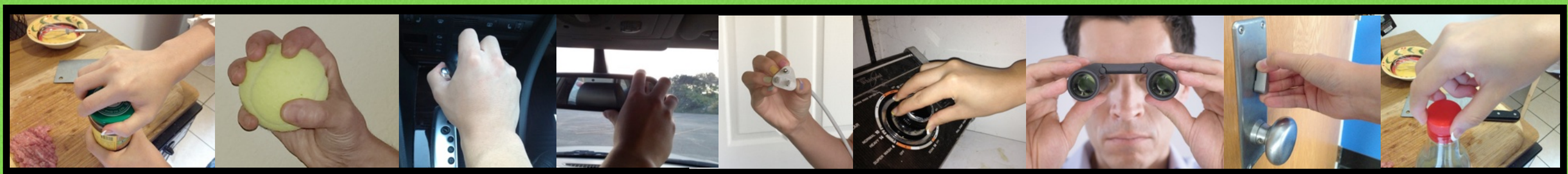
Precision Thumb 4-Finger 4

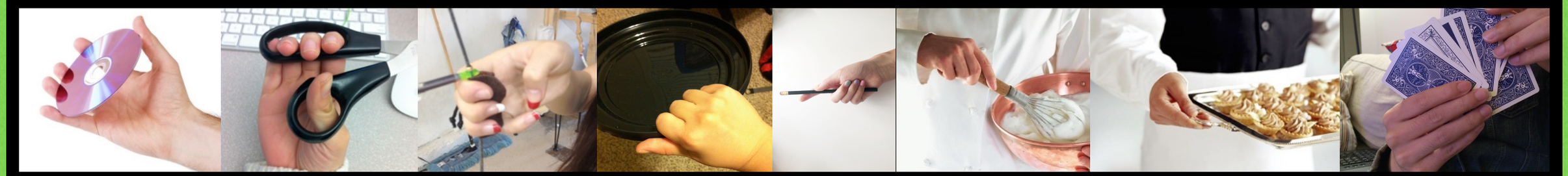
Precision Thumb 3-Finger 3

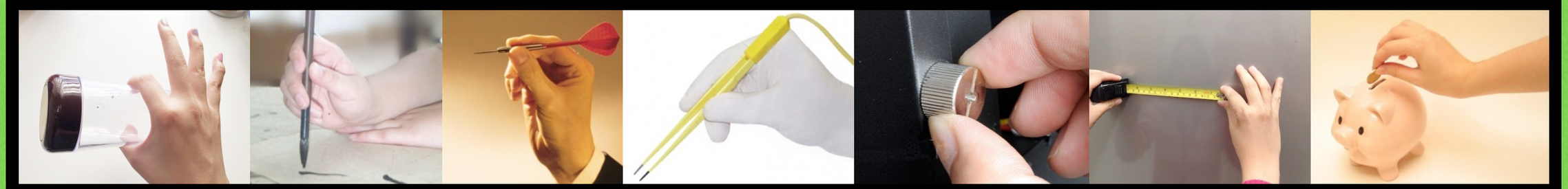


Precision Thumb Index Finger 1

1 Day, Two Subjects, Grasps from Feix et al.

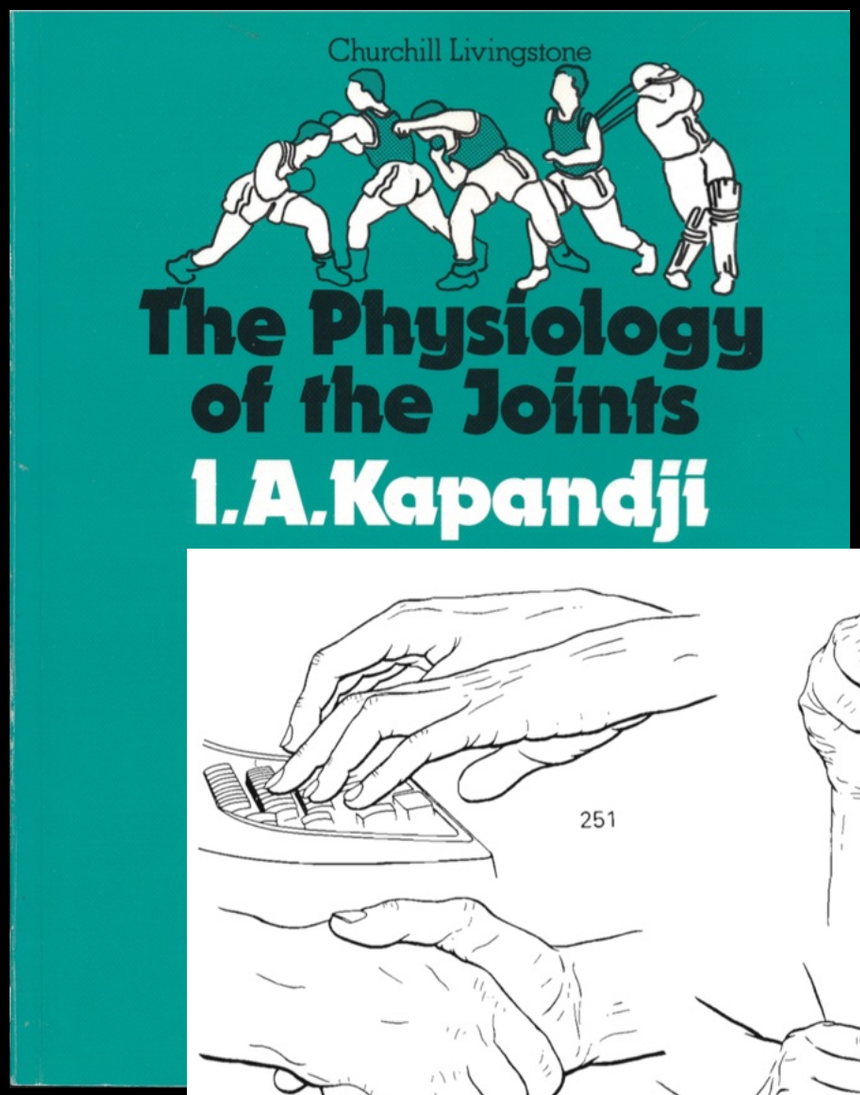


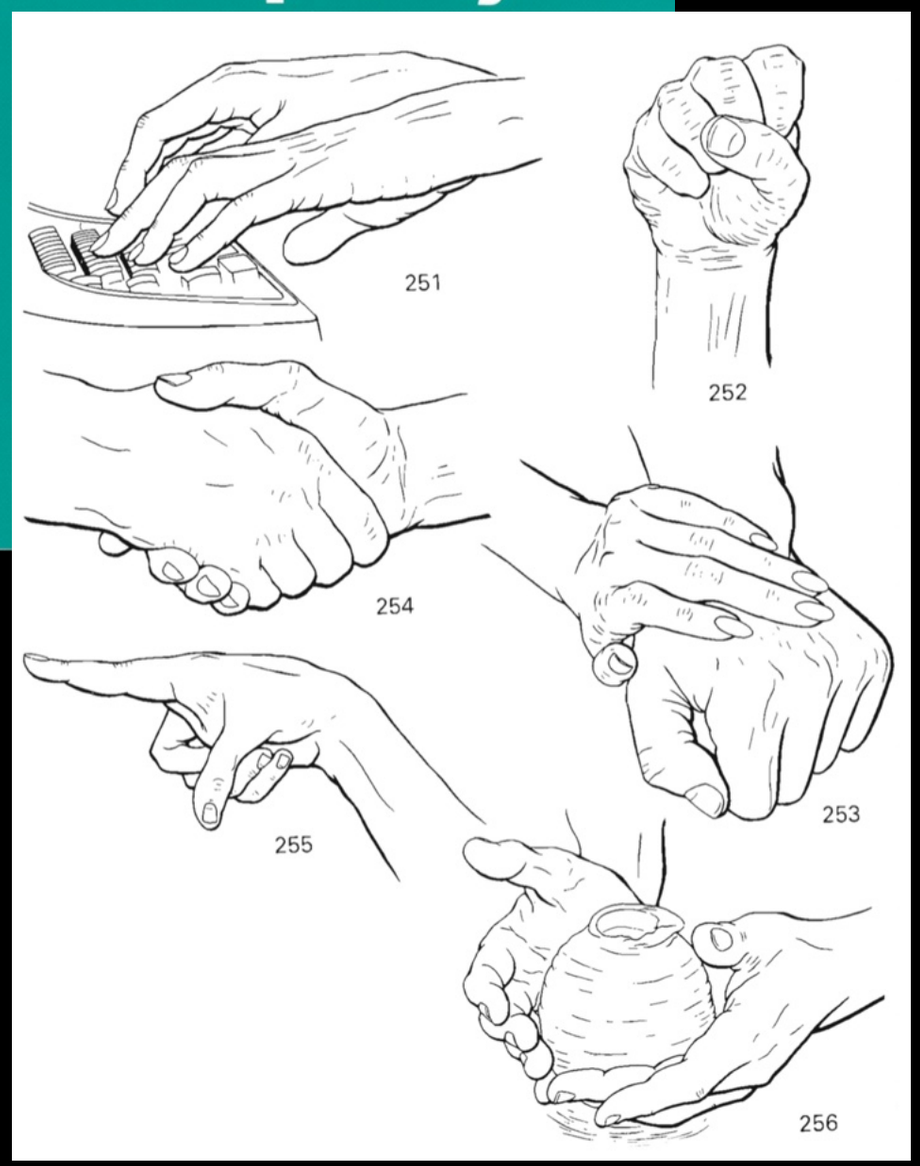


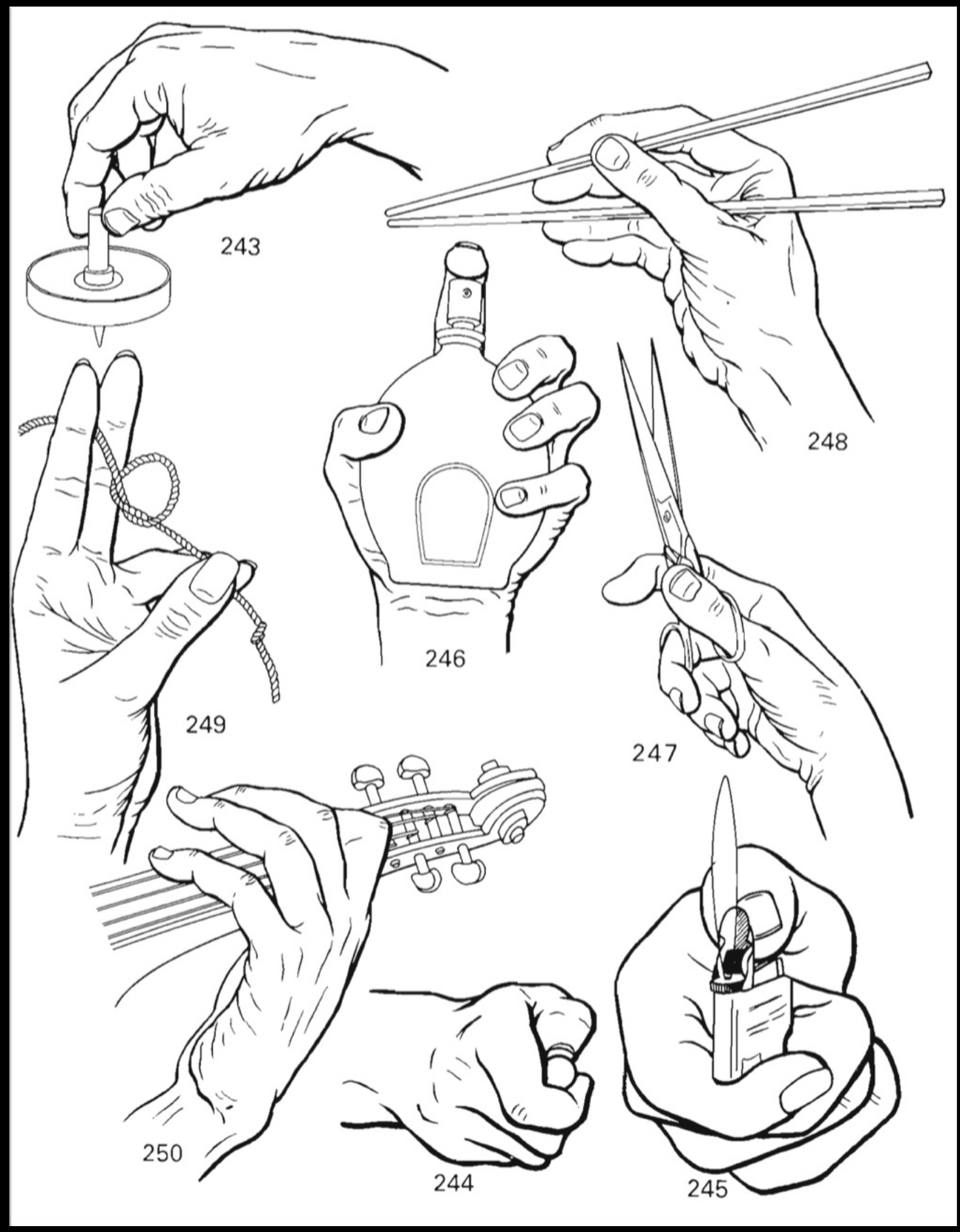


1 Day, Two Subjects, “Grasps” NOT in Feix et al.

Grasps in Action: Two Pages from Kapandji

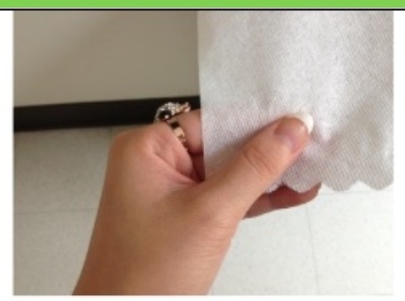
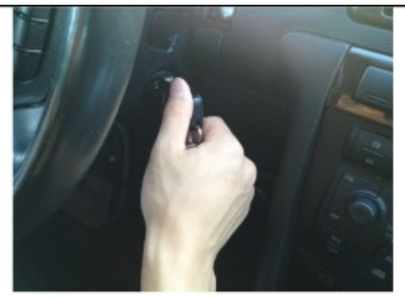


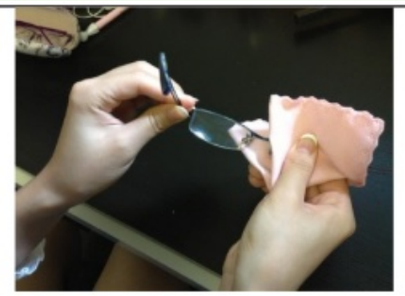




Beyond hand poses

Motion, Force, and Stiffness
Lateral (Pinch) Grasp

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

J. Liu, F. Feng, Y. Nakamura, and N. S. Pollard, 2014. A Taxonomy of Everyday Grasps in Action, IEEE International Conference on Humanoid Robots (Humanoids 2014), Madrid, Spain, November 2014.

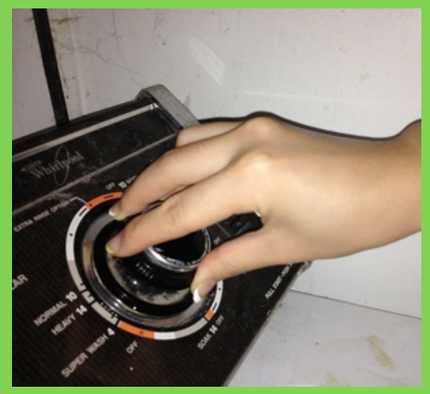
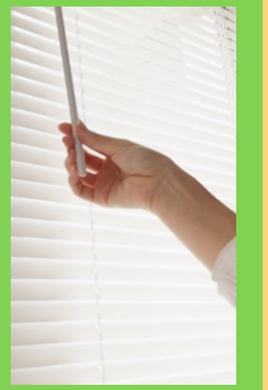
http://www.cs.cmu.edu/~jialiu1/database.html

People prefer expressing forces as verbs
20 Verbs for 173 Observed Grasps

Force Type	**Definition**	**Freq-uency**
Break off	Remove a part of an object	3
Extend	Apply outward forces from within the object	3
Grab	Hold or secure without opposing gravity	32
Hold	Grasp object in a way that resists gravity	41
Lever	Pivot one end of an object around a fixed end	4
Lift	Apply upward force greater than gravity	7
Place	Put something in a specified position	1
Press	Exert force in a direction away from the shoulder	31
Pull	Exert force in a direction towards the shoulder	18
Punch	Press or push with a short, quick movement	1
Put in	Insert one object into another	4
Roll	Cause rotation without prehension	3
Rub/Stroke	Move back and forth while pressing	9
Scratch	Rub with something sharp or rough (with the hand directly or a tool)	2
Squeeze	Apply compressive force around object greater than needed to hold object	4
Take out	Remove one object from another	2
Throw	Propel an object through the air	3
Turn	Flip or rifle through pages	1
Twist	Cause rotation with prehension	13
Swing	Move with a smooth, curving motion like hand waving or arm swinging	6

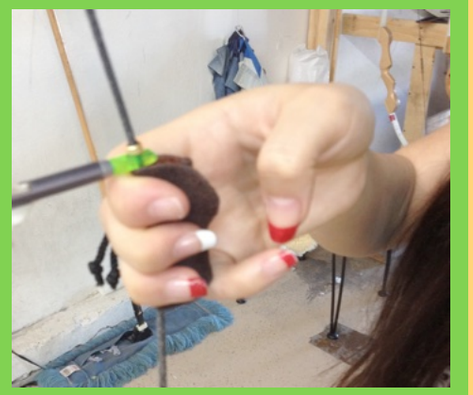
Twist

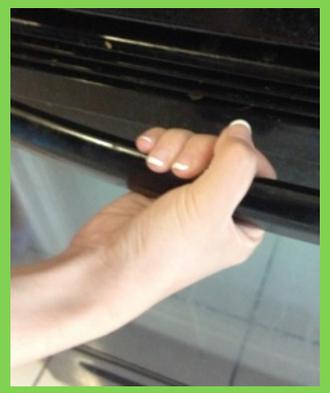


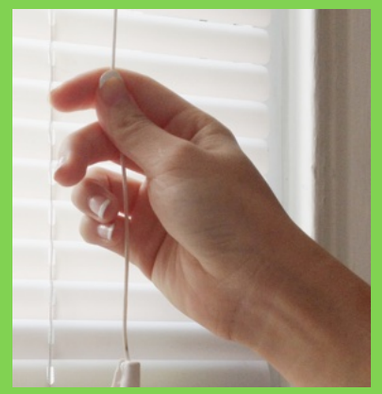


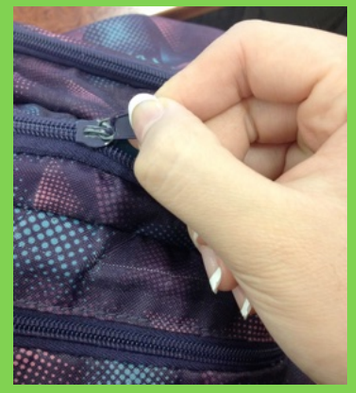

Pull





Pull





Adjust Delicately changing the position of an item in other hand (usually an item held in loose-grip during this), using pinch-grip, knuckle-push, or movements of a single finger or the lips. **M/R**.

Bite-off Use teeth to cut off portion of naturally attached or hand-supported object, either with single bite or repeated biting. **[M]**

Brush-off Using the side of a digit or digits (e.g. 1 and 2 held in "C" shape) to gently brush along stem, midrib or bundle held in hand in order to dislodge debris. **R.**

Combine Carrying out separate functions with fingers 1:2 and 3–5 at same time (in various functions), e.g. pinch-grip with 1:2 to pick while loose-grip of 3–5 in order to accumulate already picked items.

Crossed hands Both hands held flat and palm up, crossed at right angles to support greater force e.g. during scrape-off. **B.**

Dig *Using fingers held flat as blade or curved, to excavate in soft earth or litter (often to get access to roots). Used typically for getting root epithelium, e.g. of* Senecio johnstonii *or* Lobelia wollostoni.

Flat hand Hand held flat and palm up to support plant material e.g. during scrape-off.

Hook Whole hand or only certain fingers or both hands, held rather rigidly in open curve, to pull attached object (often used to heave down mass of vegetation).

Knock-off The knuckle of one or more digits, used with a flick of the wrist, to knock off an item (e.g. flower head) from bundle held in hand. **R.**

Knuckle-push Fist held as in knuckle-walking to apply force to object supported by other hand. **R.**

Knuckles Knuckles held against object, allowing other hand to procure an item. **R.**

Invert Knuckles held against object, allowing other hand to procure an item. **R.**

Leaf-fold A special case of adjust, using finger or lips to pull out leaf-blades from the grip of other hand, then folded over (sometimes using thumb as fulcrum) and gripped again. Used typically for *Laportea alatipes* leaves, only occasionally with thistle. **M/R.**

Lever-apart Object (usually leaves) held in both hands using strong, closed-hand grip, then leverage of rocking the hands or knuckles against each other, used to tear the object. **B.**

Lift-up Power-grip on object to lift from flat surface.

Lip-grip Delicate grip with centre of lips, e.g. when removing debris from bundle.

Loose-grip Loose, part-open whole hand grip, usually applied to detached objects to allow delicate processing with hand or mouth (e.g. pick-out to clean, or leaf-fold) or to accumulate leaves or stems.

Manipulate Rearranging the position or shape of item(s) held in one hand, simply using the fingers and without using other hand.

Mouth-grip Grip using mouth (not usually possible to be sure whether or not teeth-grip), to allow processing with hands, usually to detach from, or adjust bundle.

Mouth-peel Use of lips or teeth to pull off covering while other hand supports the item. **M.**

Peel [-back] One hand (usually with precision grip, e.g. pinch-grip) used to pull off covering, while other hand supports. Often done with a twisting-back action (-back). **R.**

Pencil-grip Closed-hand grip of one hand on cylindrical object (usually stem) but with object caught between pair of fingers and resting on thumb (2:3 or 3:4 or 4:5), usually for support. Presumed to be an accidental variant of power-grip.

Pick Pinch-grip on clearly defined object which is pulled against force of natural attachment, usually to procure the item.

Pick-at Single digit used to damage or loosen item, e.g. to allow peel to begin. **[R]**.

Pick-off Pinch-grip or lip-grip on small item which is pulled off an object held in other hand. **M/R.**

Pick-out Pinch-grip or lip-grip on small item which is taken out from among a mass of items, requiring discrimination of one item from among many (such as in cleaning a food handful). **M/R.**

Pick-up Pinch-grip on object to lift from flat surface.

Pinch-grip Firm precision grip, varying in whether tip-to-tip (1:2 or 1:other) or tip-to-side (1:2 normally); usually either for support or procurement, as if holding in pliers.

Power-grip Potentially strong, closed-hand grip (varying as to whether whole-hand or 1+ fingers only; see Marzke and Wullstein 1995); includes using both hands with thumbs pointing same way,) on cylindrical object (often stem) for support or for procurement, or on a bundle while accumulating items.

Pull-apart Holding an object in the two hands, the hands then pulling apart in a movement at a tangent to body, thus applying force to object to pull it apart. **B**.

Pull-off Holding a naturally attached object with one hand and pulling, thus applying force to detach item; effect as yank.

Reach Various sorts of grip, with one or both hands or fingers or pinch-grip, on attached object which is pulled to bring into range. **[B]**

Retain-nucleus Using the remains of the last handful eaten (bitten off from these remains with a shear-bite) as a basis for starting to accumulate the next (implies combine).

Roll *While holding a loose or untidy bundle, roll against flat support (e.g. of chin or hard palate) to produce roll shape. Used typically for tidying up* Galium ruwenzoriense *bundles.*

Rotate Turn or twist a long object held in strong, closed-hand grip to bring into range or into more convenient position within other hand to allow processing. **R**

Rotate-adjust Rotate item by adjusting position in hand,whilst item is supported with mouth or other hand. **M/R.**

Rotate-push Turn or twist long object held in strong, closed-hand grip and pushed to break, whilst supported by other hand or by substrate. **[R]**.

Sausage-feed Repeated loosening of the grip and re-grasping lower down an approximately sausage-shaped food bundle, in order to feed it into the mouth as a whole, without the bundle coming apart.

Scissor apart Break object by holding it in both hands and moving the hands apart at right angles to axis of object, creating a scissoring motion. **B**

Scissor-grip Part-open or open grip, object is held between the sides of adjacent digits, usually on stem.

Scrape-off Incisor teeth scrape soft layer off harder backing while object supported with flat hand or crossed hands, movement up or down. **M [and B].**

Shear-bite Shearing bites used to detach a slice of a large, compact handful of items, either singly to finish eating a handful (when remains discarded unless retain-nucleus) or repeated in order to eat the entire handful. **M.**

Slice-off Slicing action, with finger(s), or half-open grip, or simply closed fist, to detach unwanted items, against force of substrate or support of other hand e.g. to clean leaves off thistle stem. **[R].**

Slide-adjust Re-locate a firm grip on a different portion of an item by sliding the hand, while supported with mouth, other hand, or both. **M/R.**

Snap-apart Bend object to break it– although not necessarily to fully detach it– supported by both hands on either side of the break. **B.**

Snap-off Holding a naturally attached object in one hand and bending; thus applying force to detach item. **M.**

Snip-case Use incisor teeth to clip off outer casing (an action like that of pincers) in order to discard the casing and expose edible pith. Used typically for removing *Peucedanum linderi* casing, only occasionally for thistle. **M.**

Spaghetti-feed With stem held in mouth without use of the hands, lips used to feed in rest of its length – similar to eating spaghetti.

Squeeze-grip (power) *Potentially strong, closed power grip of one hand on cylindrical object with thumb along the object as support. Used routinely in processing* Peucedanum linderi.

Squeeze-up *Gather together a bundle of items so that they are finally held in some sort of power grip in one hand (often loose-grip becoming power-grip), using closure of first one hand for compression of loose bundle, then the other, alternately. Used typically by immature animals, especially with* Laportea alatipes *leaves.* **R.**

Stem-fold Holding with one hand, used to apply force to central part of long object that is supported at its ends by the other hand and either natural attachment or friction, having the effect of folding it to a manageable size. **R.**

Strip-down Half-open grip (often constricted at 5:palm, but not always) around leafy stem or midrib of leaf, slid down stem to detach leaves or side-shoots, sometimes supported by other hand (thus removing unwanted items during stem processing). **[R].**

Strip-out The exposed section of stem or midrib of large leaf is held in one hand and then pulled, often to the mouth, thus stripping the case away and exposing lower section of object. **R.**

Strip-up [-rev] Half-open grip (often constricted at 1:2, but not always) around leafy stem or midrib of leaf, slid up stem with thumb uppermost to detach bunch of leaves, against force of substrate or other hand's supporting grip (thus accumulating leaves, the bunch protruding between 1:2). Occasionally hand reversed so that thumb away from direction of motion (-rev). **[R]**.

Swap-hand Transfer object or handful from one hand to the other. **R.**

Tooth-pick Pinch-grip or single digit (usually 2) used to remove debris from mouth, either after mouthful has been swallowed and debris lodged between teeth, or from mouthful of food containing unwanted item. **M.**

Tooth-pull Pull with object held in teeth, against bracing of limbs. Typically used to pull up underground shoots of *Arundinaria alpina*, only occasionally used with thistle. **M.**

Tooth-strip Partial closure of incisors around root or stem, pulling against support of hand(s), an action like that of wire-strippers. Typically used for stripping off root epithelium e.g. of *Senecio johnstonii* or *Lobelia wollostoni*. **M.**

Tooth-twist *Holding object in mouth and hand with strong, closed-hand grip (sometimes with other hand duplicating action of upper hand), using a twisting of hand and head to tear the object. Typically used for getting* Arundinaria alpina *shoots from the ground.* **M.**

Teeth-grip Grip with teeth to allow processing with hands, usually to detach from, or adjust bundle. **M.**

Tuck-fold Base of leaf-bunch held by one hand, while the other hand uses digits 1, 4 and 5 to tuck in leaf-blades at the sides, before digits 2 and 3 fold over the top leaves. By definition, the hand holding the bunch is swapped over. **R.**

Twist-apart Object (usually leaves) held in both hands, then twisting of each hand versus the other is used to tear the object. **R.**

Twist-fold A special case of leaf-fold where the leaf-blades are twisted before being folded over. **R.**

Twist-in Handful twisted as it is fed into mouth, in the case of leaves having the effect of keeping the bundle compact. **M.**

Twist-off Holding a naturally attached object in one hand and twisting, thus applying force to detach object.

Two-hand (A) (Asymmetrical) one hand (the "major" hand) uses some sort of strong, closed-hand grip as support while the other ("minor") hand also supports, but with pinch-grip (or sometimes pencil-grip) to allow processing by mouth (minor hand often alternates between supporting role and strip, peel, etc while grip of other hand remains). **R.**

Two-hand (S) (Symmetrical) strong, closed-hand grip of both hands on cylindrical object, with thumbs pointing towards each other, to allow processing by mouth. **B.**

Two-handed-bend *Loosening and re-grasping by the hand holding a long item, while item is folded into a bundle with the other hand, either once or many times, to form a concertina shape as in zig-zag. Used typically for dealing with* Galium ruwenzoriense *stems.* **R.**

Two-hand cup *Object held between palms of both hands and supported by cupping of hands around it. Occasionally used with large pieces of stem, e.g. Senecio johnstonii.* **B.**

Wrap One hand grips the base of a bunch of leaves and the other comes in at a tangent to one side then slowly contracts the fingers systematically wrapping leaf over leaf. By definition, the hand holding the bunch is swapped over. **R.**

Yank Grip with one hand (or teeth) used to apply force on object which is pulled against natural attachment (often to detach the object), or to part of object supported by other hand or mouth (often to detach the part).

Zig-zag Repeated loosening and re-grasping, by the hand holding a plant strand, with a rocking motion of this hand, to enfold the strand into a concertina shape. (Thus combine two grips in same hand.) Has the effect of allowing it to fit into neat bundle using gravity or the strand's natural attachment to bend the strand, or (if specified) bent against an object. Used typically with *Galium ruwenzoriense* stems, only occasionally with thistle. **R.**

Byrne, Richard W., and Jennifer M. Byrne. "Manual dexterity in the gorilla: bimanual and digit role differentiation in a natural task." Animal Cognition 4, no. 3-4 (2001): 347-361.

Intrinsic hand motions

A CLASSIFICATION OF MANIPULATIVE HAND MOVEMENTS

J. M. Elliott
K. J. Connolly

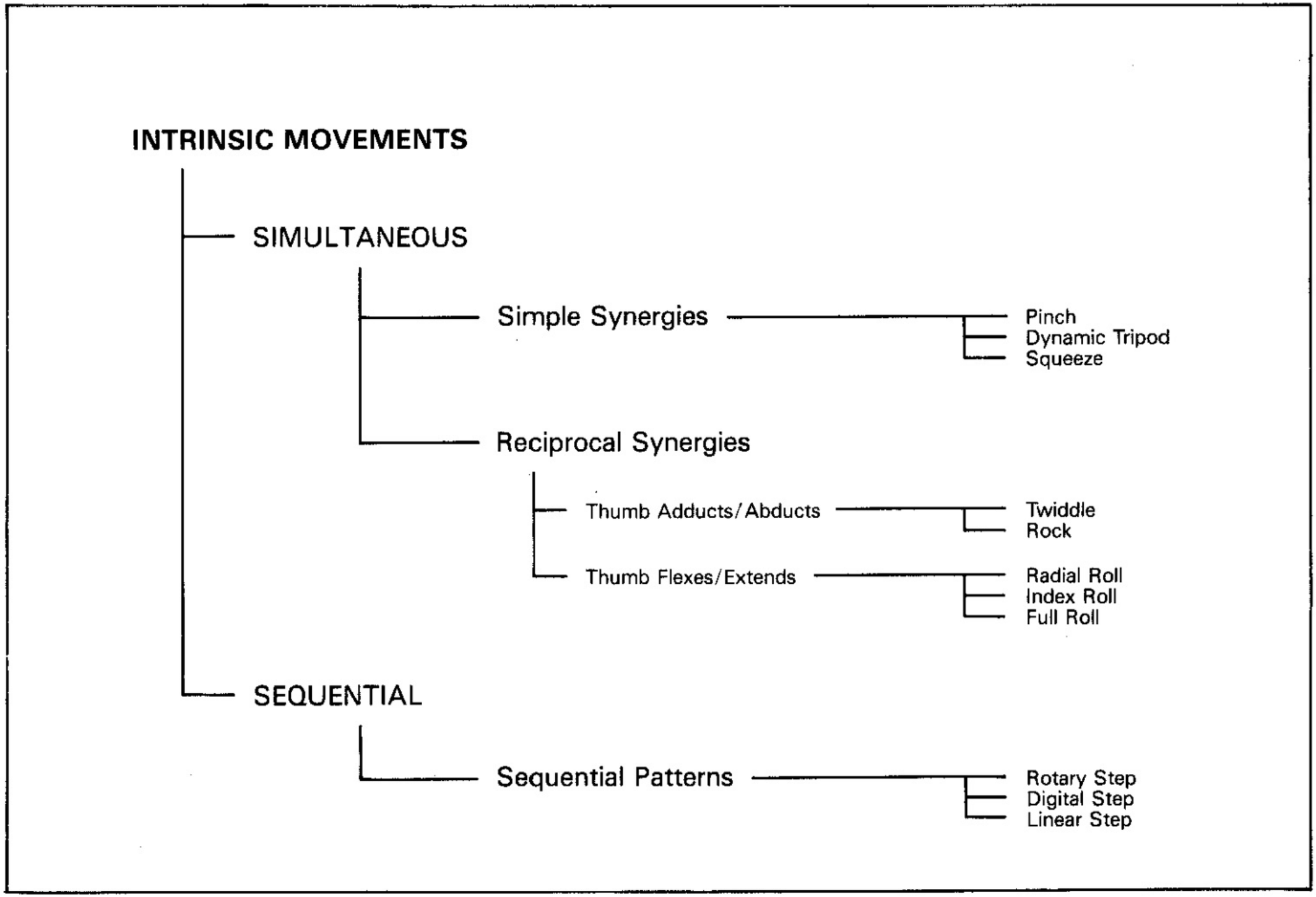


Fig. 1. *Classification of intrinsic hand movements.*

Simple Synergies

Pinch

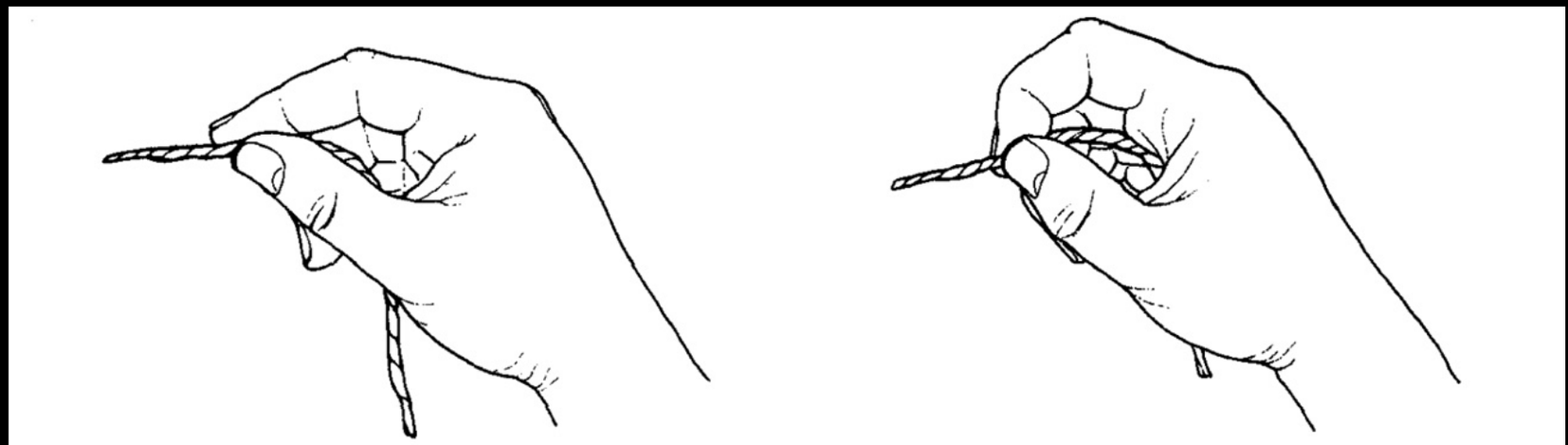


Fig. 4. *Pinch:* (a) *thumb and index extended,* (b) *thumb and index flexed. These represent terminal positions for digits when executing this pattern of movement.*

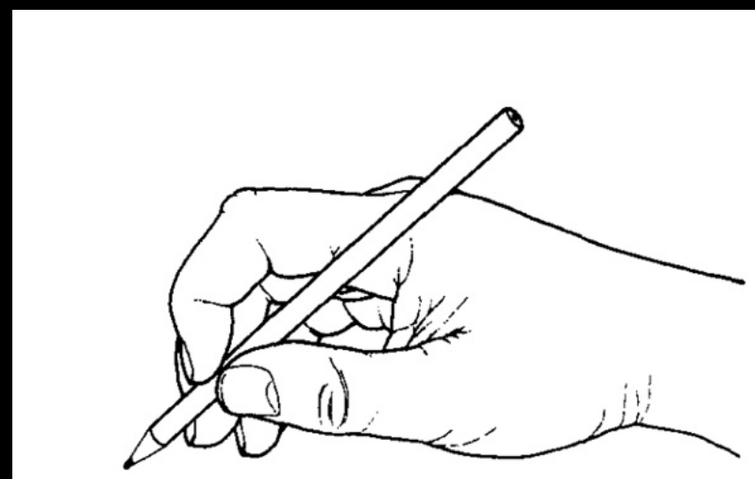


Fig. 5. *Dynamic tripod: small, simultaneous flexion and extension movements of thumb, index and digit 3 manipulate pen.*

Dynamic Tripod

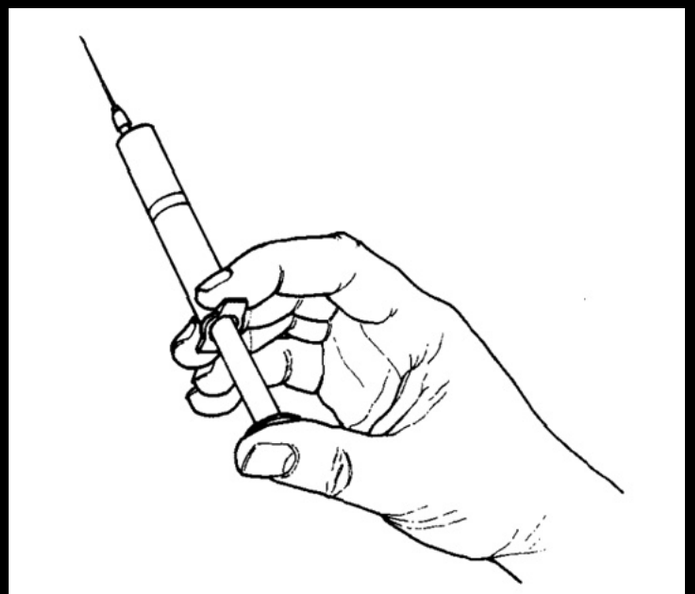


Fig. 6. *Squeeze: precise configuration of fingers is determined by shape of syringe. Simultaneous flexion of thumb, index and digit 3 will drive plunger into barrel.*

Squeeze

Reciprocal Synergies
Thumb Abducts/Adducts

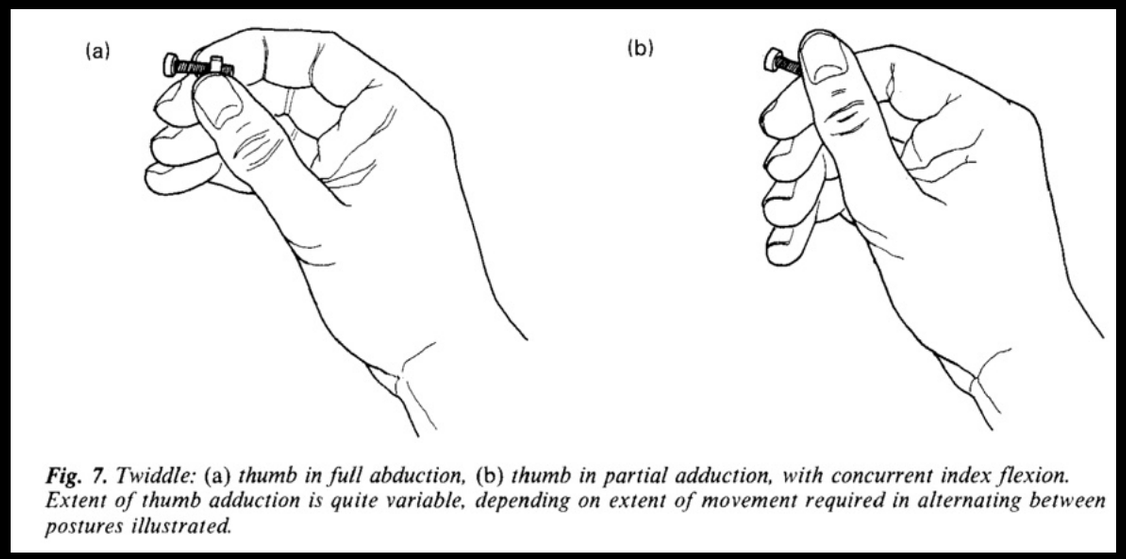


Fig. 7. Twiddle: (a) *thumb in full abduction,* (b) *thumb in partial adduction, with concurrent index flexion. Extent of thumb adduction is quite variable, depending on extent of movement required in alternating between postures illustrated.*

Twiddle

Rock

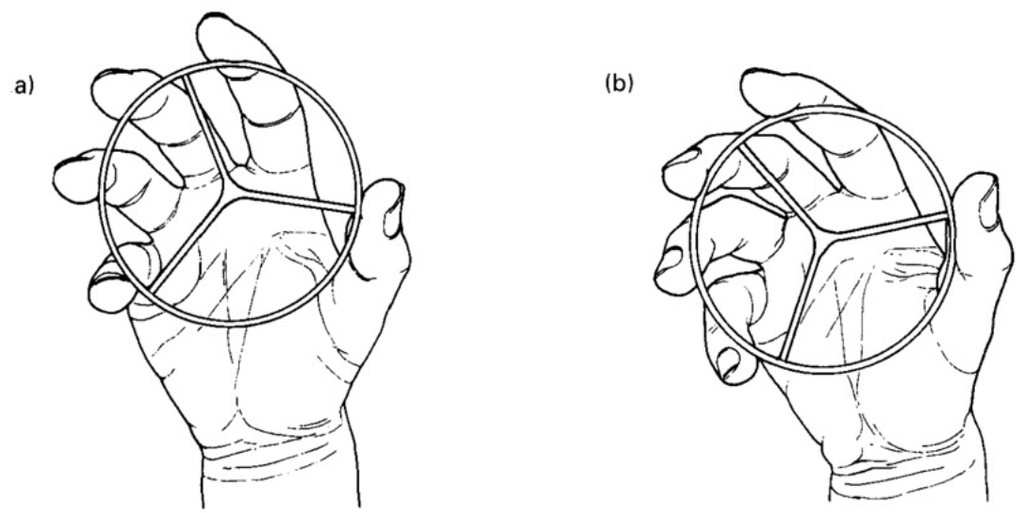


Fig. 8. Rock: illustrated in ventral view with a petri dish. (a) *Thumb in partial abduction,* (b) *thumb in partial adduction.*

Rock

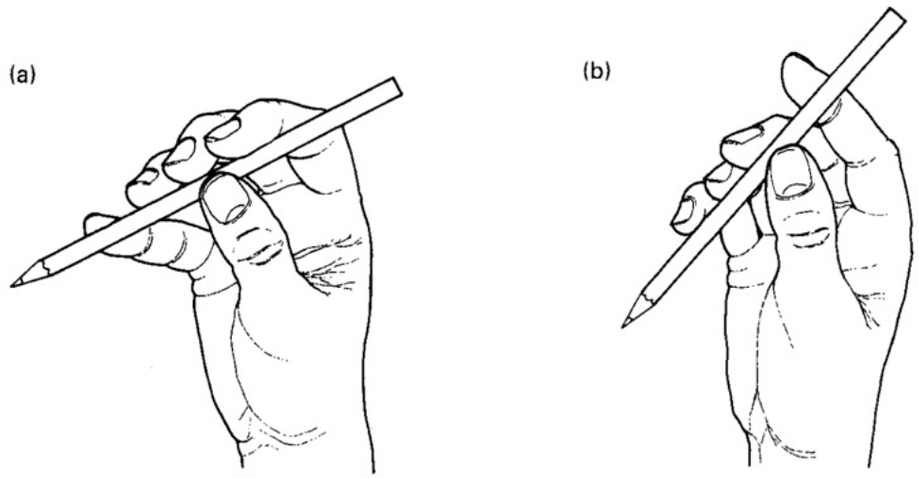


Fig. 9. Rock: illustrated with pencil held transversely, in radio-ulnar axis. Movements of thumb and digit 3 are much reduced compared with movements of other digits. (a) *Ulnar digits relatively extended,* (b) *ulnar digits relatively flexed.*

Reciprocal Synergies
Thumb Flexes/Extends

Radial Roll

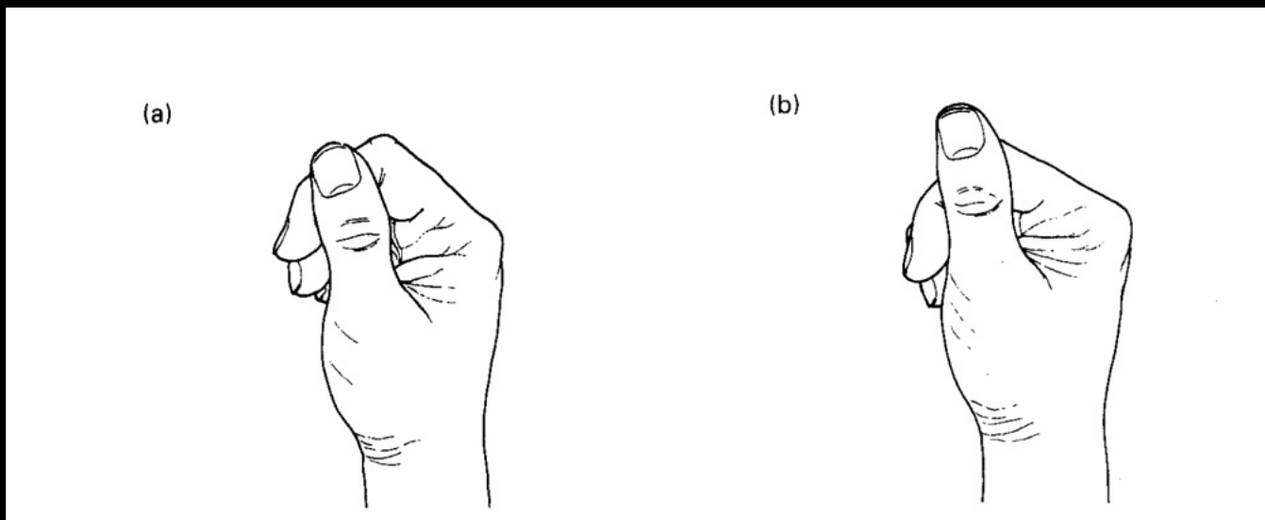


Fig. 10. *Radial Roll. In this example the thumb is adducted throughout; in other instances it may be partially abducted, consequently operating radial index more distally.* (a) *Index less flexed,* (b) *index more flexed.*

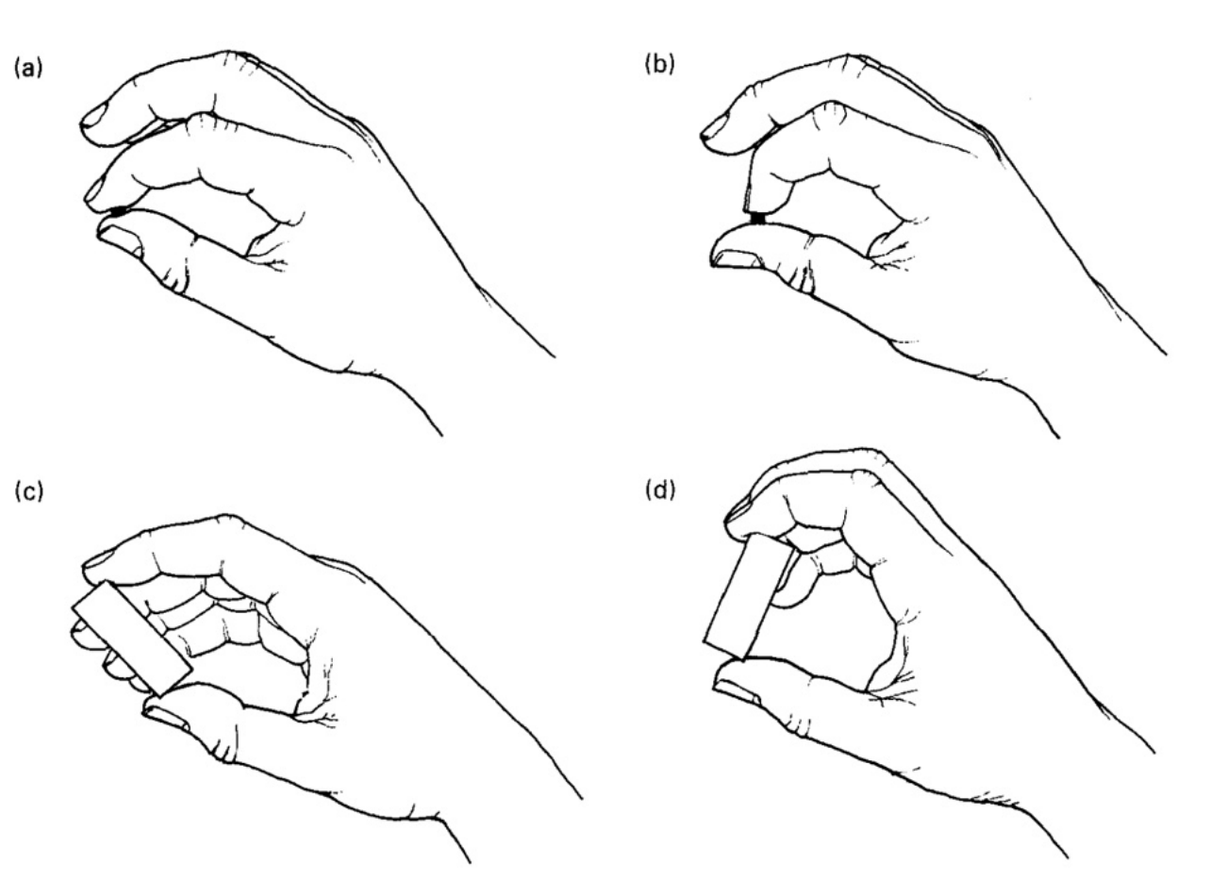


Fig. 11. *Index Roll* (a,b), *showing slight reciprocal flexion of thumb and extension of index* (a), *and the reverse* (b). *Full roll* (c,d), *as for index roll, but with involvement of additional digits. The object rocks about the radio-ulnar axis as result of movement between positions illustrated.*

Index Roll

Full Roll

Sequential Patterns

Rotary Step

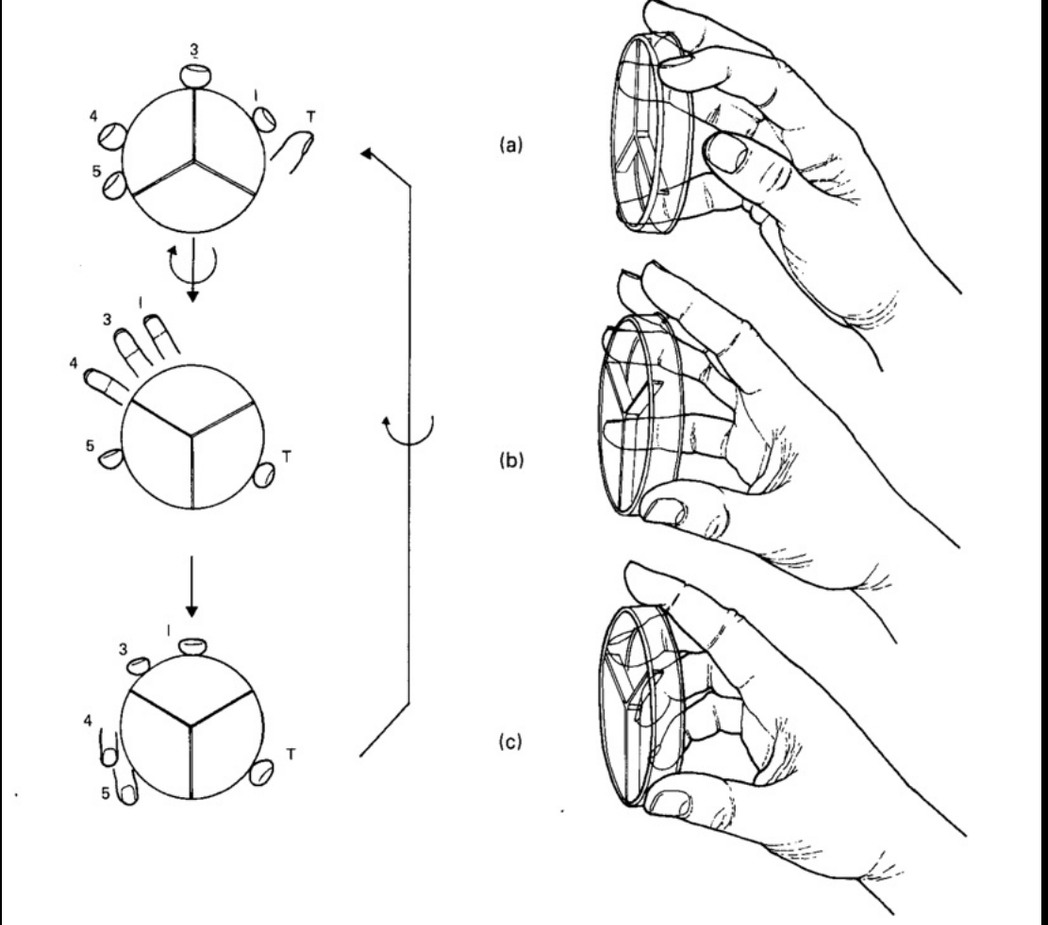


Fig. 12. *Rotary Step. A schematic representation of positions in which the digits are placed* (left), *and successive postures of the hand* (right). *Sequence* (a-b-c-a) *shows successive phases in clockwise rotation totalling approximately 120° of object rotation. This occurs between transitions* a-b *and* c-a, *as indicated by the rotary arrows.*

Digital Step

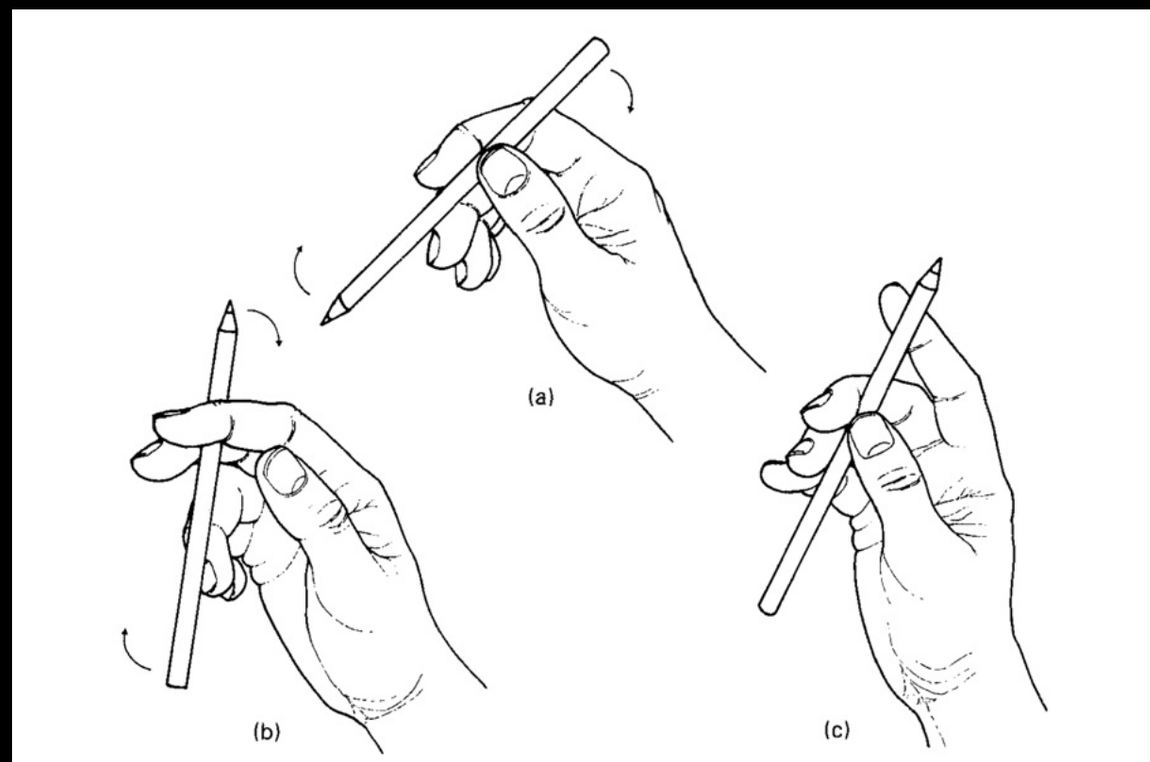


Fig. 13. *Interdigital Step: from* (a) *to* (b) *the object is rotated by extension of ulnar digits, especially digit 3. Flexed thumb passes under rotating object to assume its position at* (b). *From* (b) *to* (c), *thumb and ulnar digits flex to grasp object and index extends and may lose contact with 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.*

Linear Step

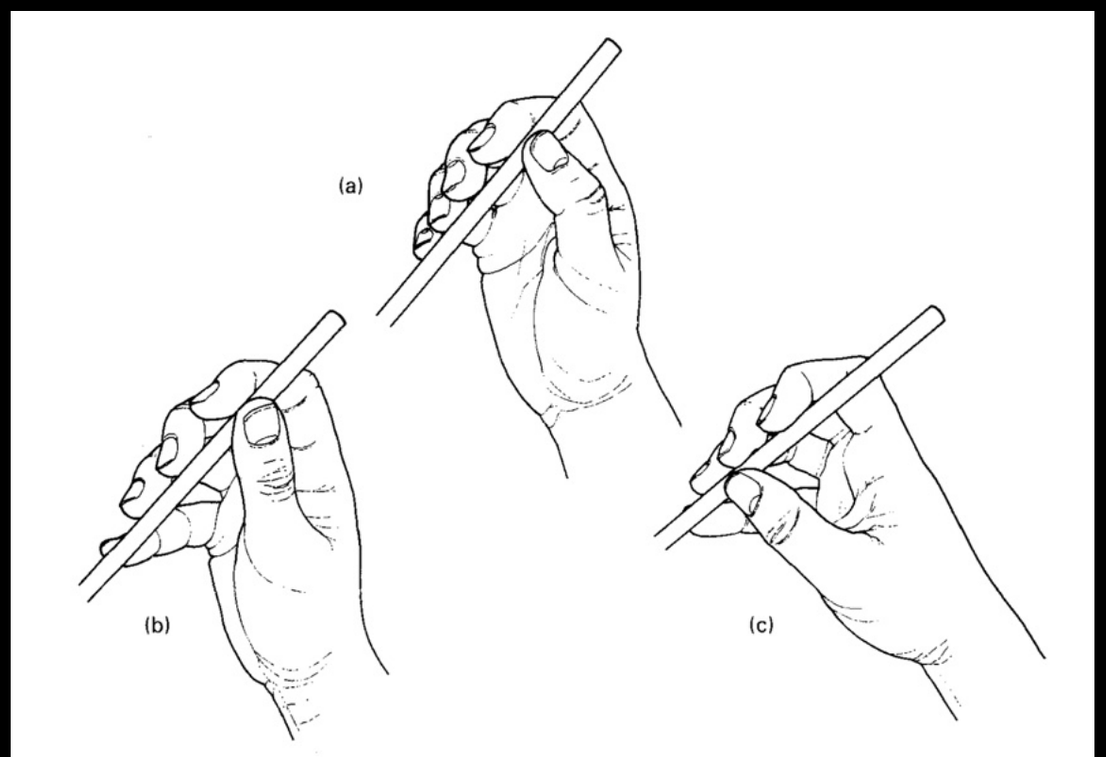


Fig. 14. *Linear Step: from* (a) *to* (b), *ulnar digits extend inter-phalangeally, but flex at carpo-metacarpal joints, sliding along object. From* (b) *to* (c), *thumb abducts to oppose ulnar digits. From* (c) *to* (a), *index flexes to restore initial posture.*

Not Classified

Palmar Slide

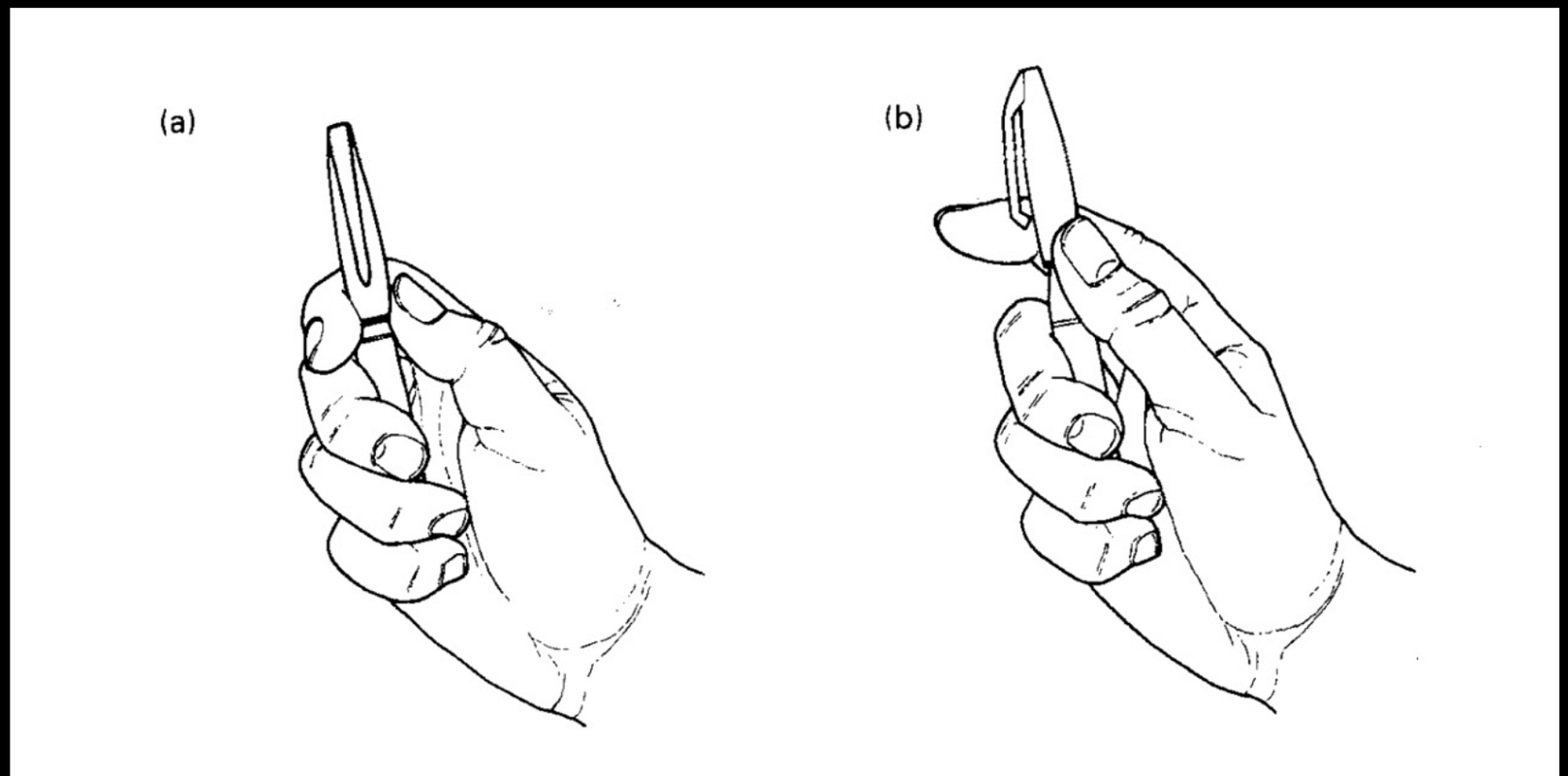


Fig. 15. *Palmar Slide: the movement, illustrated in change from* (a) *to* (b), *involves extension of thumb and radial deviation of index, with some extension.*

Manipulation Taxonomies

A Bimanual Manipulation Taxonomy

Franziska Krebs and Tamim Asfour

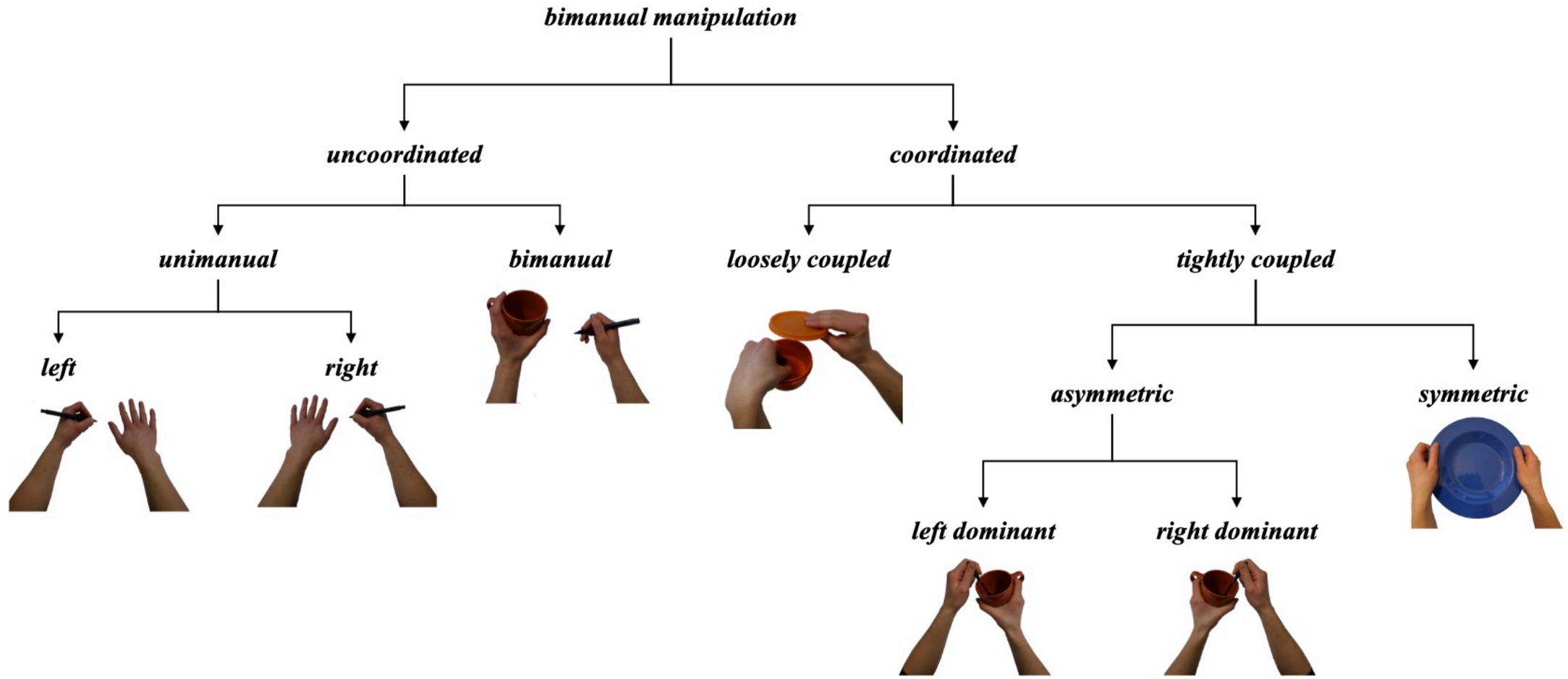


Fig. 2. Bimanual manipulation taxonomy. Tasks are classified based on the aspects *coordination*, *interaction*, *hand role* and *symmetry*.

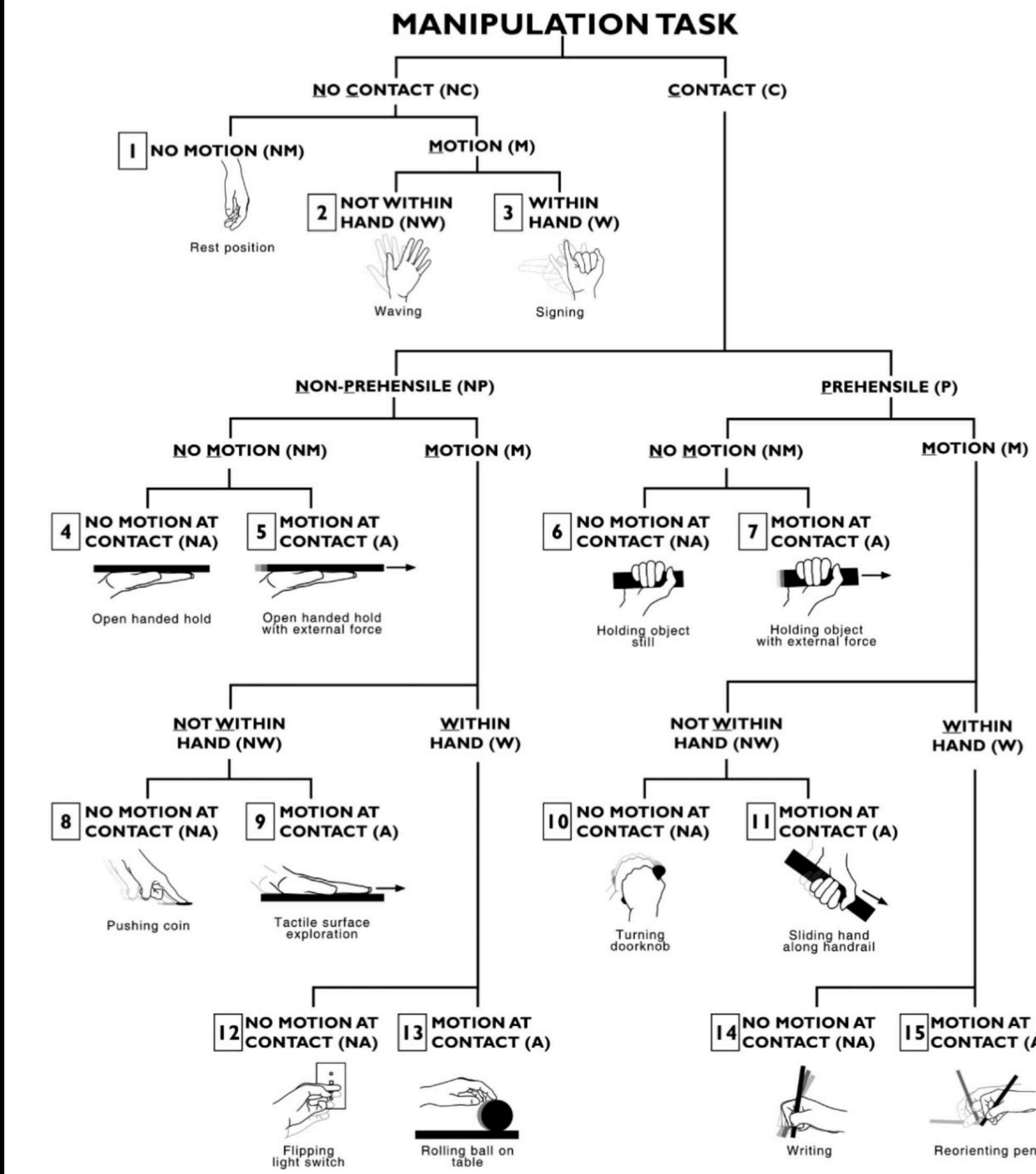
Krebs, Franziska, and Tamim Asfour. "A bimanual manipulation taxonomy." *IEEE Robotics and Automation Letters* 7, no. 4 (2022): 11031-11038.

IEEE TRANSACTIONS ON HAPTICS, VOL. 6, NO. 2, APRIL-JUNE 2013

A Hand-Centric Classification of Human and Robot Dexterous Manipulation

Ian M. Bullock, *Student Member, IEEE*, Raymond R. Ma, *Student Member, IEEE*, and Aaron M. Dollar, *Member, IEEE*

Bullock, Ian M., Raymond R. Ma, and Aaron M. Dollar. "A hand-centric classification of human and robot dexterous manipulation." *IEEE transactions on Haptics* 6, no. 2 (2012): 129-144.

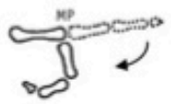
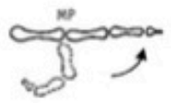
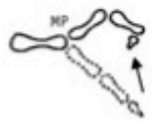
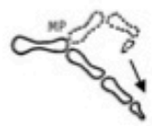
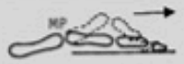


NORIKO KAMAKURA

with a foreword by Catherine Trombly Latham

POSTURES AND MOVEMENT PATTERNS OF THE *Human Hand*

A Framework for Understanding Hand Activity for Clinicians and Engineers

Movement of Ray		Joint Motion Combinations[1]					
		Finger Rays			Thumb Ray		
Movement	Typical Pattern	MP	PIP	DIP	CMC	MP	IP
#1 Bend		Flexion Flexion –	Flexion – Flexion	Flexion – Flexion	← (same as on left) → ← (same as on left) → ← (same as on left) → –	 –	 Flexion
#2 Unbend		Extension Extension –	Extension – Extension	Extension – Extension	← (same as on left) → ← (same as on left) → ← (same as on left) → –	 –	 Extension
#3 Curl up		Extension	Flexion	Flexion	← (same as on left) → Extension Extension – –	 – Hyperextension Extension Hyperextension	 Flexion Flexion Flexion Flexion
#4 Poke outward		Flexion	Extension	Extension	← (same as on left) → Flexion Flexion – –	 – Hyperextension release Flexion Hyperextension release	 Extension Extension Extension Extension
#5 Open		Abduction			Abduction		
#6 Close		Adduction			Adduction		
#7 Press down		Flexion Flexion –	Flexion Hyperextension[2] Flexion	Hyperextension[2] Hyperextension[2] Hyperextension[2]	← (same as on left) →		
#8 Release		Extension Extension –	Extension Hyperextension release[3] Extension	Hyperextension release[3] Hyperextension release[3] Hyperextension release[3]	← (same as on left) →		
#9 Slide in		Extension	Flexion	Hyperextension[2]	← (same as on left) →		
#10 Slide out		Flexion	Extension	Hyperextension release[3]	← (same as on left) →		

Gray zone indicates presence of reaction force.
[1] Motions at the CMC joints of the ring and little fingers are not included (see footnote 2 in text).
[2] Involves reaction force from object.
[3] Involves release from reaction force.

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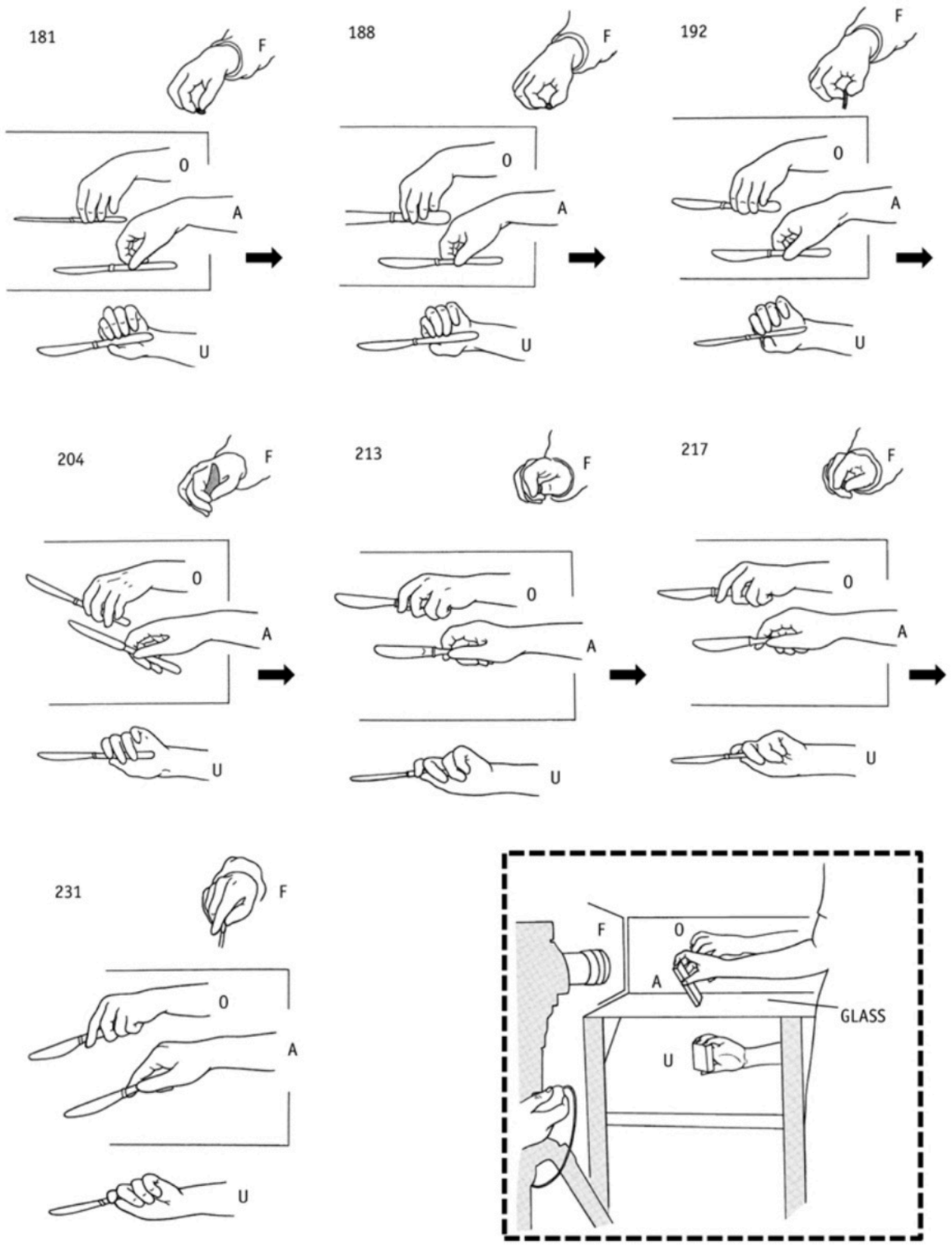

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Asterisks mark frames in Figure 5.1

Frame	Thumb	Index	Middle	Ring	Little	Action	Frame
166–180	no change	no change	no change	no change	no change	Relaxed hand descends toward knife.	166–180
172–180	bend	bend	bend	bend	bend	Surrounds knife handle with fingers.	172–180
*181–187	curl up	curl up	curl up	curl up	curl up	Continuing to surround handle.	*181–187
185–187	curl up	curl up	curl up	curl up	curl up	Getting ready to raise knife.	185–187
*188–189	no change	curl up	no change	no change	no change	Pivots handle from flat to upright.	*188–189
190	bend	bend				Grasps handle with thumb and index.	190
*192–193	poke outward	poke outward				Trivial movement (relaxation).	*192–193
194–198	no change	no change				Keeps holding knife (with *Tip* grip) while lifting hand.	194–198
199–203			poke outward	poke outward	poke outward	As thumb and index hold knife, other fingers begin to change position.	199–203
*204–208	close	unbend	bend	bend	bend	Continuation of above.	*204–208
209	no change	no change	poke outward	poke outward	poke outward	Continuation of above.	209
210–212			bend	bend	bend	Continuation of above.	210–212
*213–216		unbend	unbend	bend	bend	Middle, ring, little fingers join in grip.	*213–216
*217–230		poke outward	bend	bend	bend	Changing type of grip.	*217–230
*231–232	no change	no change	no change	no change	no change	Begins to cut meat (with *PoI* grip).	*231–232

Frame No.*	Pattern	Components	Action
166–172	00000		Relaxed hand descends toward knife.
172–181	XXXXX	X: bend	Surrounds knife handle with fingers.
181–185	XXXXX	X: curl up	Continuing to surround handle.
185–188	XXXXX	X: curl up	Getting ready to raise knife.
188–190	0X000	X: curl up	Pivots handle from flat to upright.
190–192	XX000	X: bend	Grasps handle with thumb & index.
192–194	XX000	X: poke outward	Trivial movement (relaxation).
194–199	00000		Keeps holding knife (with *Tip* grip) while lifting hand.
199–204	00XXX	X: poke outward	As thumb & index hold knife, other fingers begin to change position.
204–209	XYZZZ	X: close; Y: unbend; Z: bend	Continuation of above.
209–211	00XXX	X: poke outward	Continuation of above.
211–213	00XXX	X: bend	Continuation of above.
213–217	0XYYY	X: unbend; Y: bend	Middle, ring, little fingers join in grip.
217–231	0XYYY	X: poke outward; Y: bend	Changing type of grip.
231–	00000		Begins to cut meat (with *PoI* grip).

*These frame numbers correspond to those in Figure 5.1 and Table 5.2.

Table 6.2 Incidences of dissociation patterns of finger movements (modified from Kamakura et al., 1986)

	Tasks (grouped by type of object)					
Pattern of dissociation	I stick-like (n=1,008)	II small, flat (n=704)	III other unitary (n=620)	IV compound (n=2,899)	V soft (n=2,550)	all (n=7,781)
	%	%	%	%	%	%
timrl	5.5	**7.2**	**10.6**	**9.0**	**9.0**	**8.5**
t/imrl	**18.5**	**17.3**	**19.1**	**23.2**	**22.2**	**21.4**
ti/mrl	**11.2**	**17.8**	**7.3**	**9.3**	**9.7**	**10.2**
tim/rl	2.1	5.2	6.9	4.3	5.1	4.7
timr/l	1.8	1.9	4.3	2.1	2.0	2.0
t/i/mrl	**29.7**	**16.8**	**22.2**	**25.7**	**22.8**	**24.1**
t/im/rl	**7.4**	5.6	6.6	6.4	**7.3**	6.7
ti/m/rl	2.1	**7.5**	4.3	3.4	2.8	3.6
ti/mr/l	2.4	3.6	1.5	2.1	1.9	2.2
t/imr/l	4.9	1.9	4.6	1.9	2.5	2.8
others	12.6	11.2	10.1	9.8	10.8	10.7
unclear	1.8	4.0	2.5	2.8	3.9	3.1
Total	100.0	100.0	100.0	100.0	100.0	100.0

t: thumb, i: index finger, m: middle finger, r: ring finger, l: little finger
/: demarcation between types of movement, n: number of film segments

*** Incidence over all groups is 7.0% or greater.
** Incidence reaches at least 7.0% in one of the groups.
* Incidence over all groups is at least 3.0% but less than 7.0%.
n: number of film segments

	Tasks (grouped by type of object)					
In-hand movement pattern	I stick-like (n=1,008)	II small, flat (n=704)	III other unitary (n=620)	IV compound (n=2,899)	V soft (n=2,550)	all (n=7,781)
	%	%	%	%	%	%
XXXXX***	5.5	**7.2**	**10.6**	**9.0**	**9.0**	**8.5**
XYYYY***	**12.1**	**7.8**	**11.0**	**9.0**	**7.5**	**9.0**
X0000***	4.0	6.4	4.2	**10.3**	**11.1**	**8.9**
0XXXX*	2.4	3.1	3.9	3.9	3.6	3.5
XXYYY	3.2	2.3	1.6	1.9	1.5	1.9
XX000**	2.4	**7.1**	1.0	2.8	3.6	3.2
00XXX**	5.6	**8.4**	4.7	4.6	4.6	5.1
000XX	0.2	3.4	4.5	2.8	2.1	2.4
XYZZZ**	**9.3**	2.1	3.2	2.9	2.4	3.5
XY000*	4.2	3.0	2.6	5.3	5.5	4.8
0XYYY	2.8	3.4	3.2	2.8	2.1	2.6
0X000***	**8.6**	5.5	**8.7**	**10.1**	**8.7**	**8.9**
XYY00	3.0	1.4	1.5	1.5	2.1	1.9
00X00	0.9	4.1	1.9	1.9	1.6	1.9
00XX0	1.1	3.3	0.6	1.1	1.1	1.3
XYYY0	3.6	0.1	0.8	0.7	0.6	1.0
Total	68.9	68.5	64.0	70.6	67.1	68.4

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Synergies

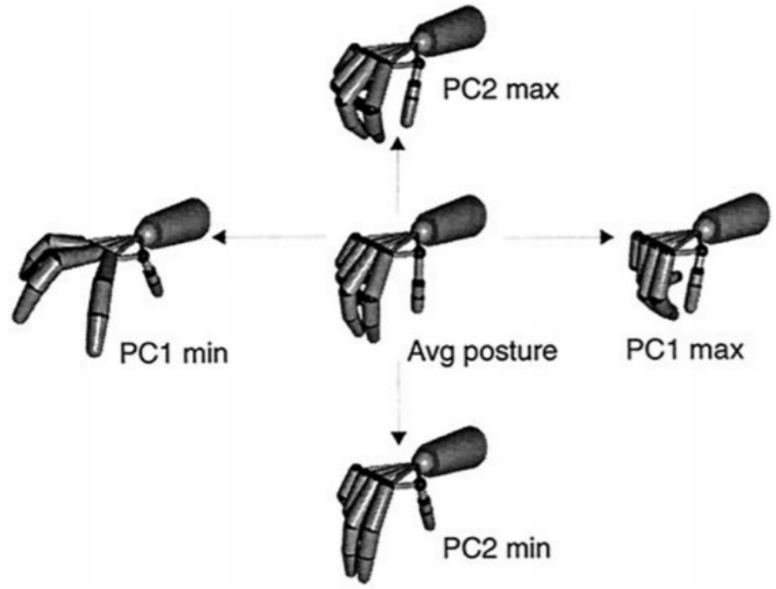
Synergies

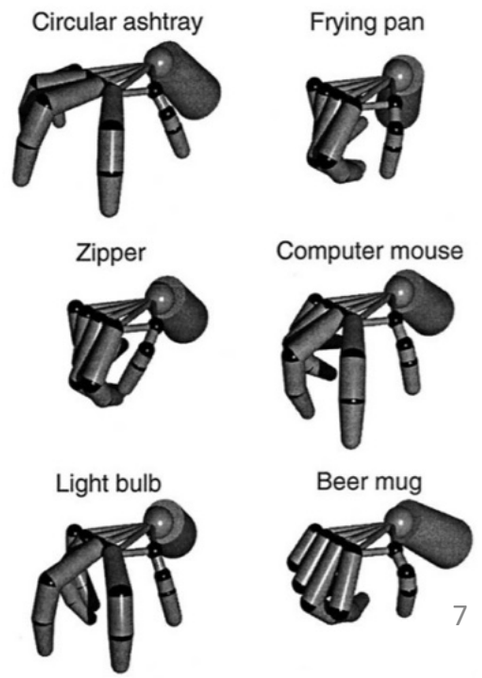
- **Coordinated movements or control signals to accomplish a given task**
- **Motor primitives**
- Arise from physical couplings of tendons and muscles or neuro-muscular patterns
- Analogous to **vector bases**… linearly independent elements that combine to form the set of all movements (postural synergies/eigengrasp space)
- Often analyzed using **Principal Component Analysis**… data suggests that 80% of grasp posture information is explained by the first two synergies/components/bases

slide from Ryan Coulson

Related Work

- ***Postural Hand Synergies for Tool Use*** (1998) by Santello, Flanders, and Soechting
- Subjects asked to grasp and use 57 *imagined* objects
- Found that hand postures were distributed along a continuum (as opposed to a discrete grasp taxonomy)
- PCA: 80% of posture info explained by first two synergies/components



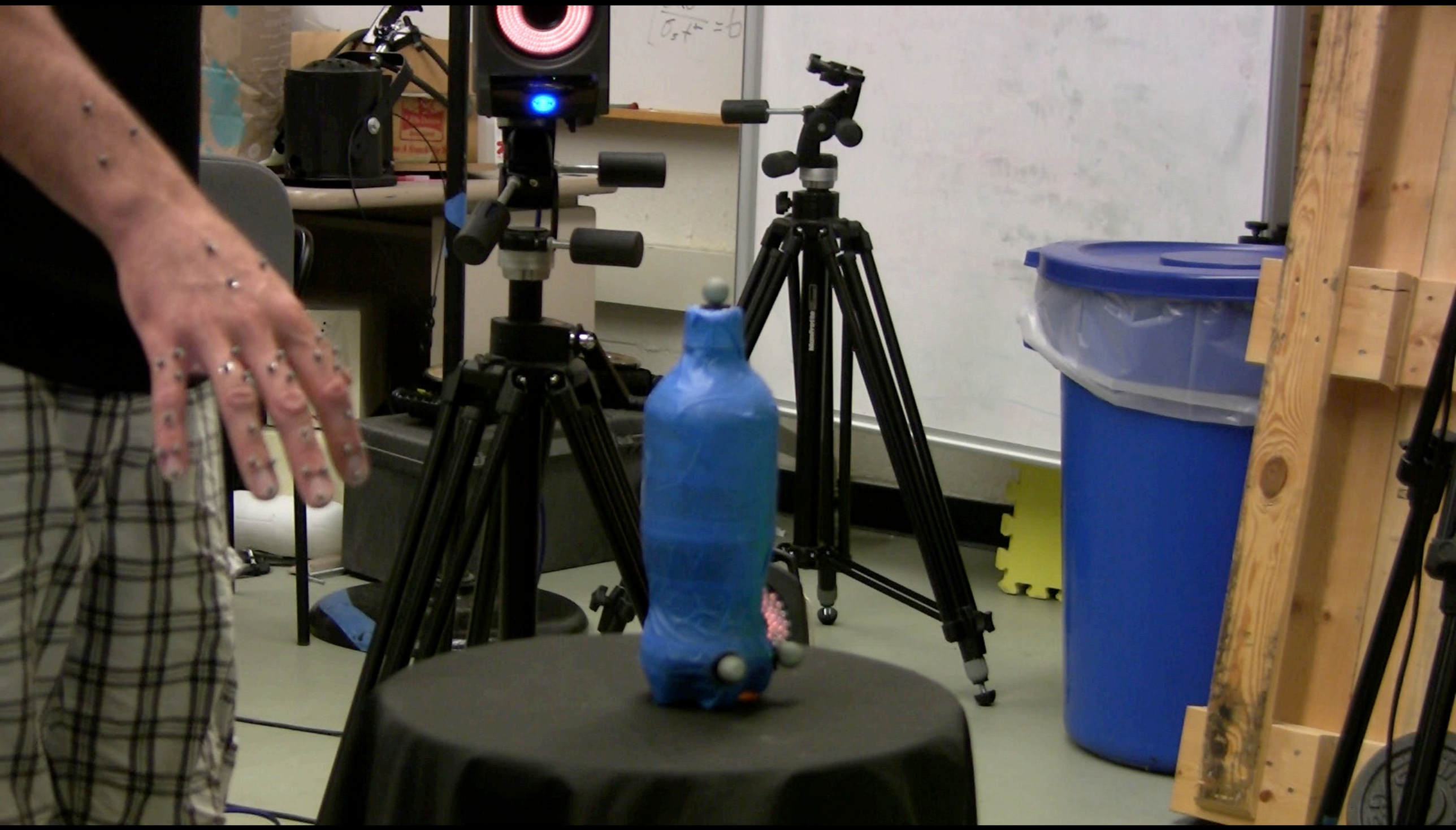


Santello, Marco, Martha Flanders, and John F. Soechting. "Postural hand synergies for tool use." *Journal of neuroscience* 18, no. 23 (1998): 10105-10115.

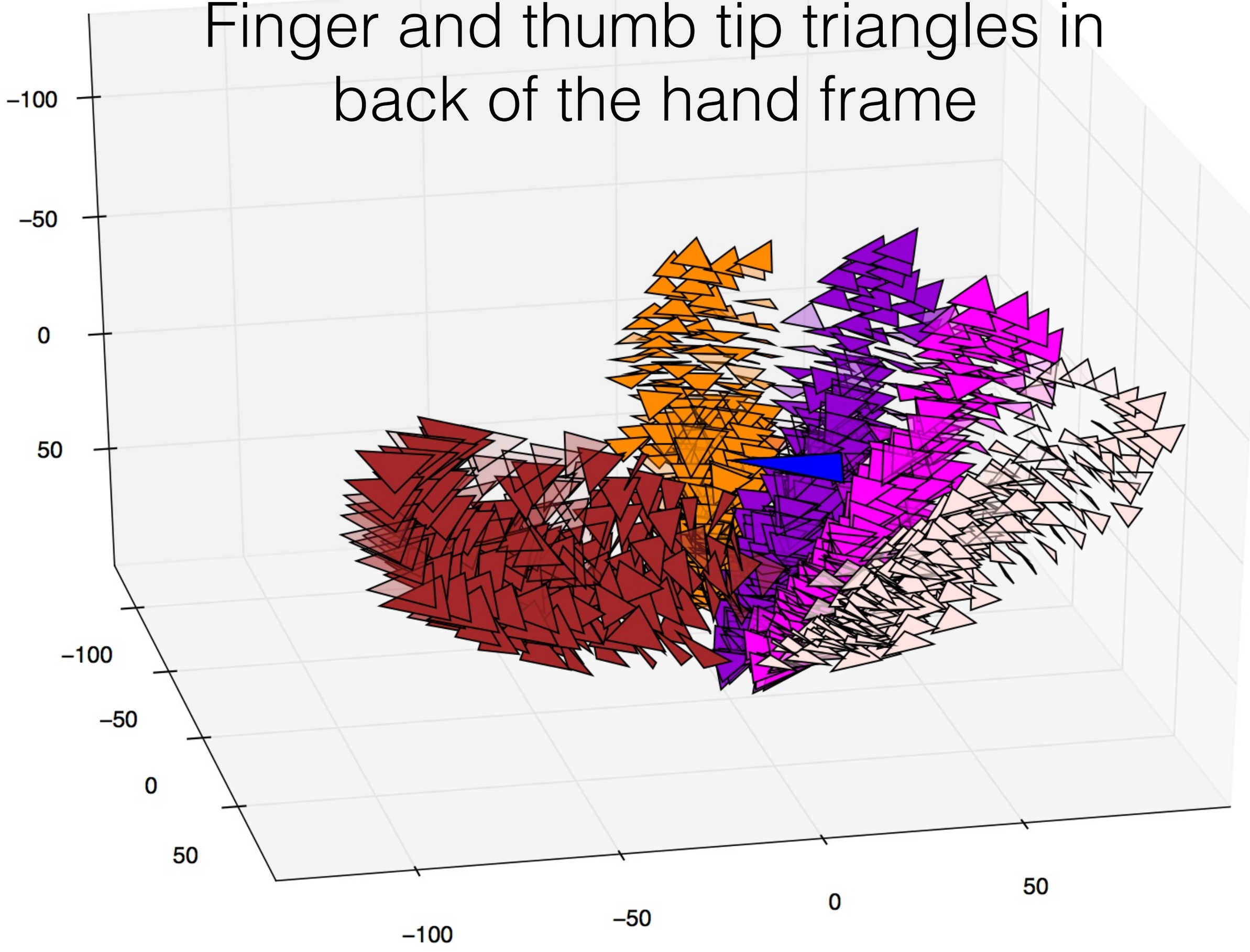
slide from Ryan Coulson

Our data collection effort

Grasps from the 3min shopping video plus Elliott and Connelly



Finger and thumb tip triangles in back of the hand frame



Characteristics of Grasp Transitions from Detailed Motion Capture Data

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***Abstract*— Many benchmarks are available to assess human and robot capabilities. However, when the goal is to design a dexterous robot hand, it is not always clear which benchmarks will best indicate real-world dexterity. In fact, the fine details of human motion during dexterous interactions are not very well understood. These motions have been less studied compared to grasping, in part due to the complexity of capturing interactions with many and changing contacts. We present results from highly detailed capture of human hand motions containing grasp acquisition, grasp transition, and grasp placement. Although our intent was to stress test the hand by examining detailed in-hand manipulations, we found that the resulting hand motions and observed workspace do not appear to exercise the full range of motion and freedoms of the human hand. Our results suggest that it may be possible to design relatively low degree of freedom robot hands that can perform fine manipulations such as grasp acquisition and grasp transitions for a range of objects in a humanlike manner.**

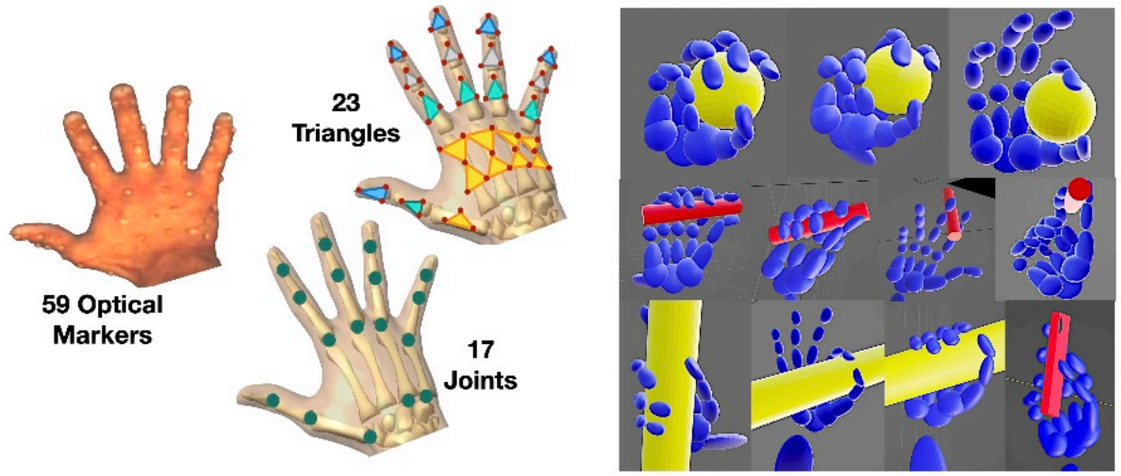


Fig. 1: (Left) Our marker set has 59 markers, enabling major bones in the hand to be located independently. (Right) Samples of grasps between which we have captured transitions.

grasps, or even canonical manipulations, transitions between grasps are much less studied, even though they are very common. We examine grasp pickup, transition, and release motions using a highly detailed motion capture data set to

Methods

MoCap database

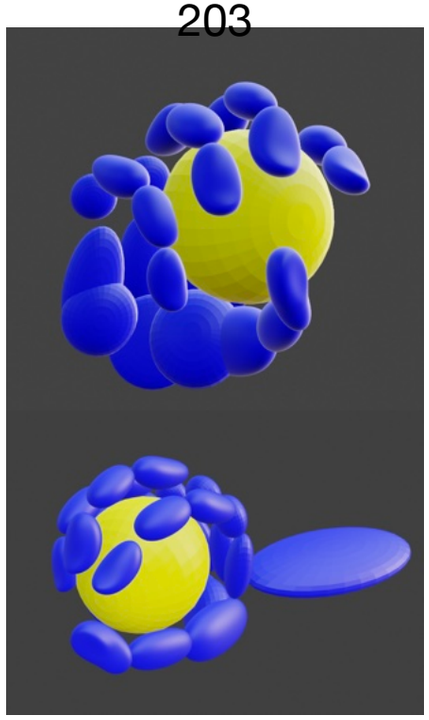
- Optical Motion Capture
- 4 objects
- 11 motions, 13,278 frames
- 28 grasps, 17 grasp transitions, 11 object pickups, 11 object releases

Example Motion

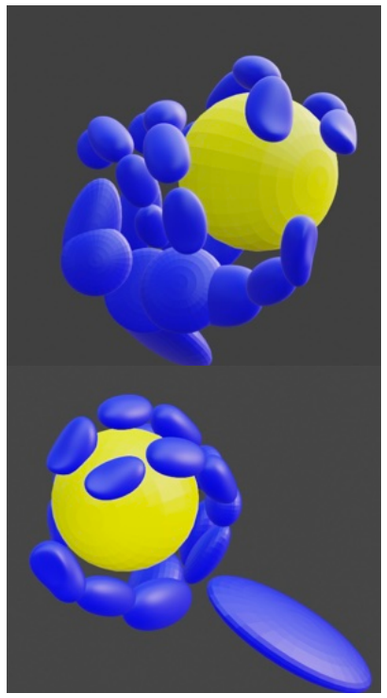
Ball Power Lateral

Ball Power Lateral

Frame 203



Frame



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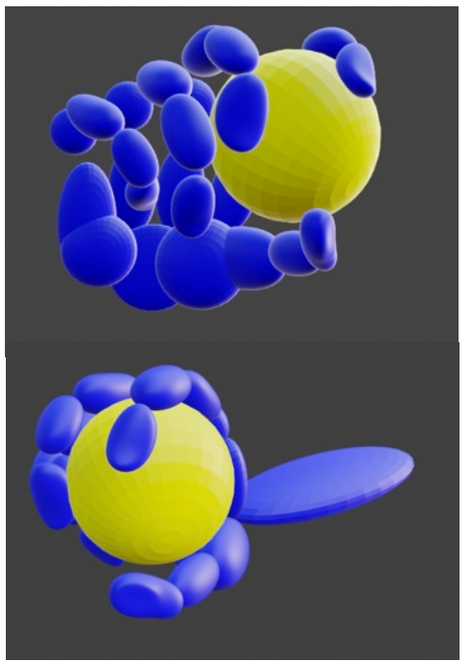
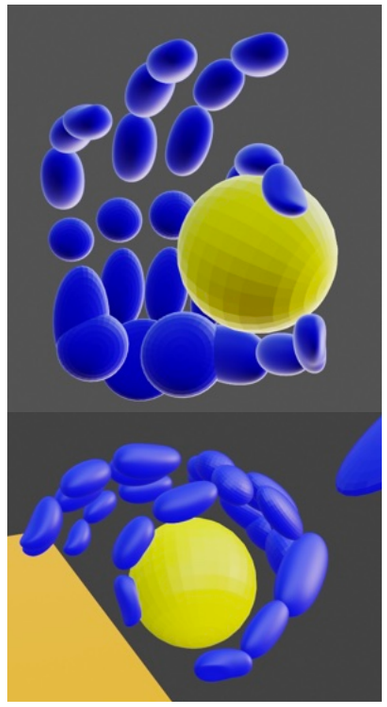
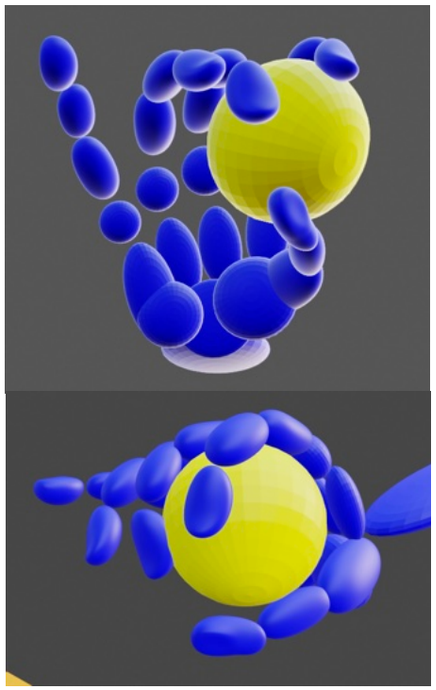


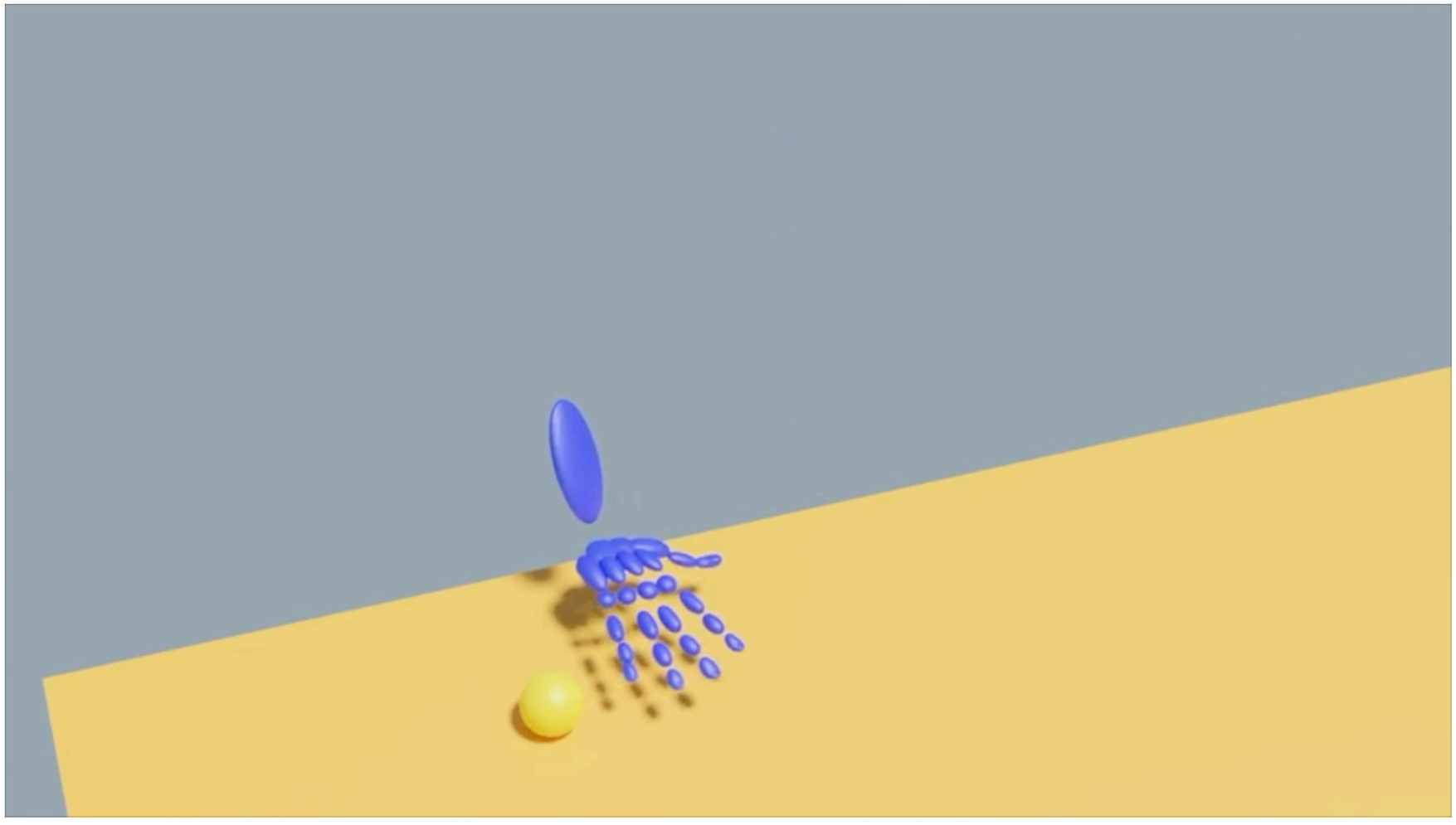
Frame



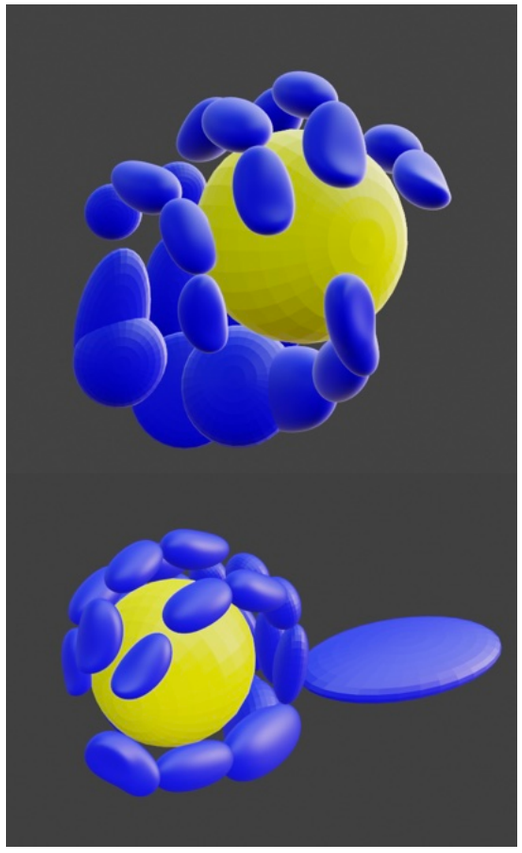
Frame



Ball Power Lateral

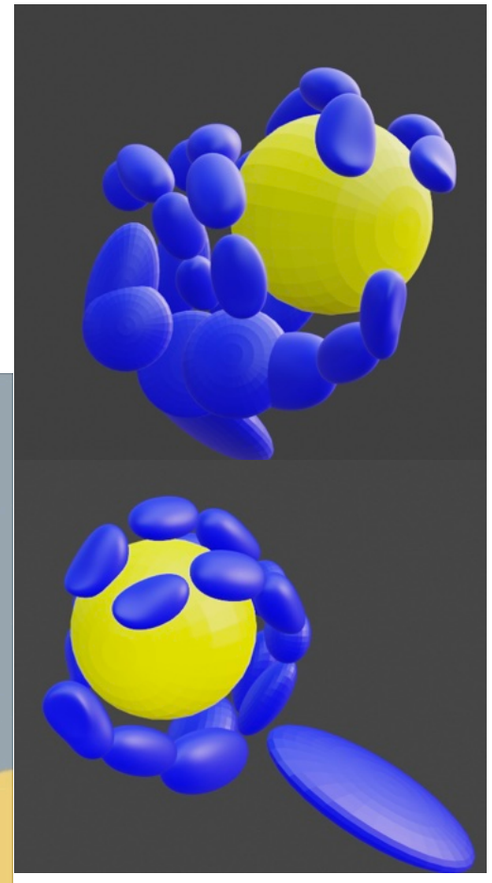


Frame 203

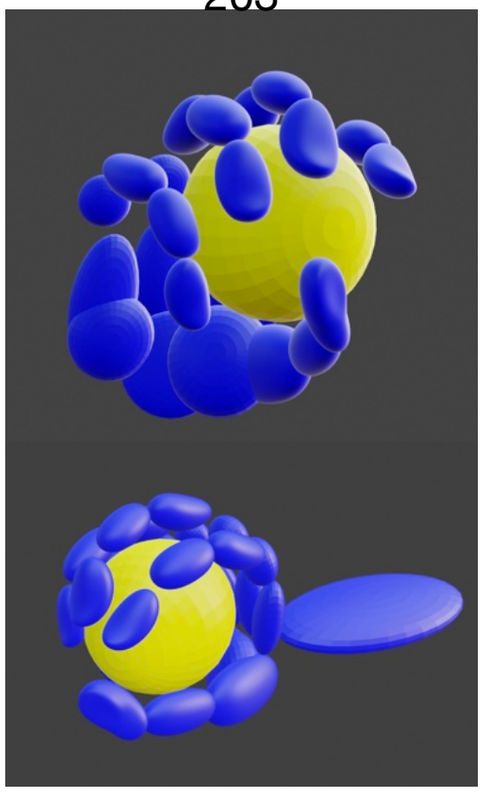


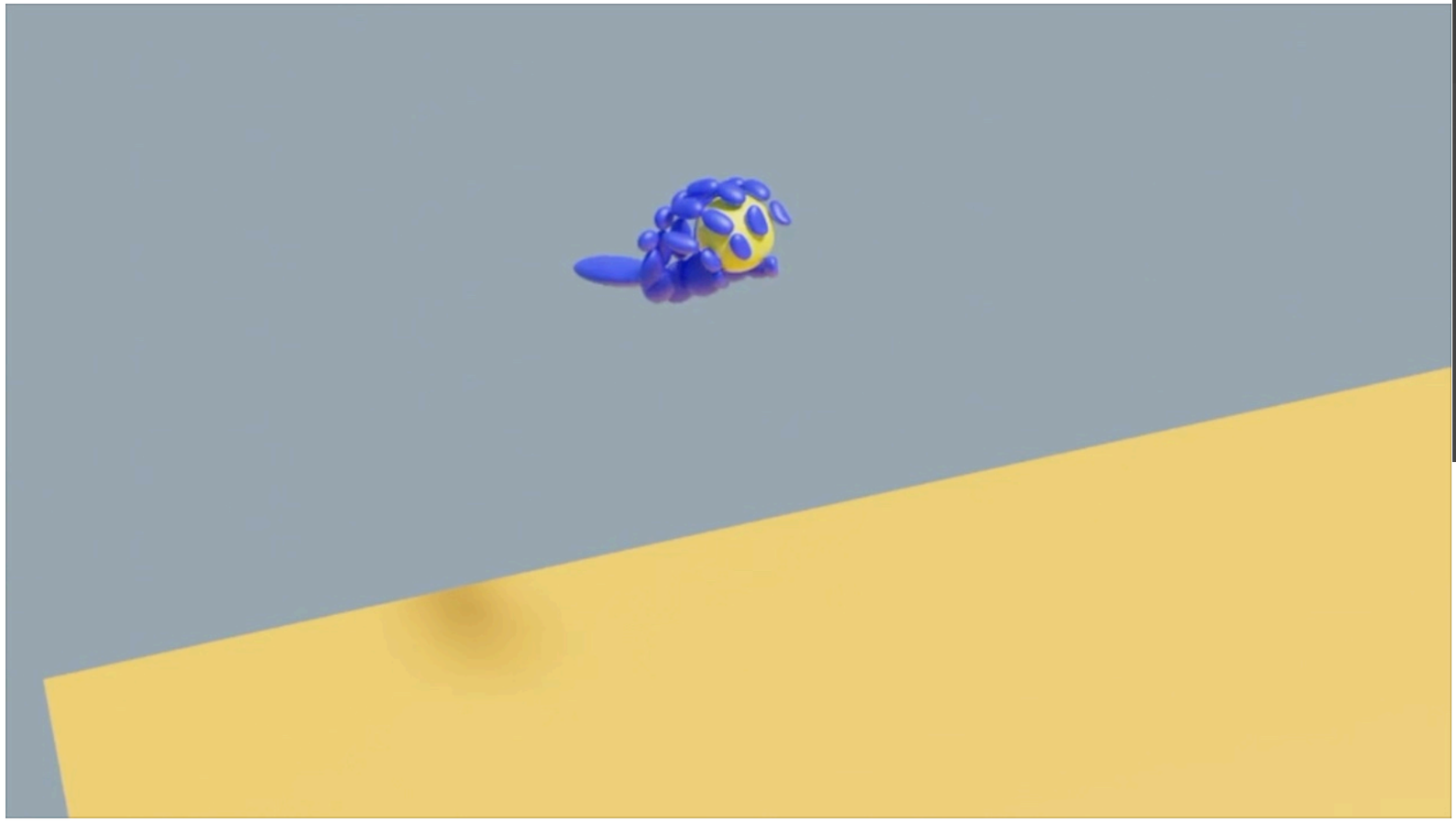
Ball Power Lateral

Frame 452



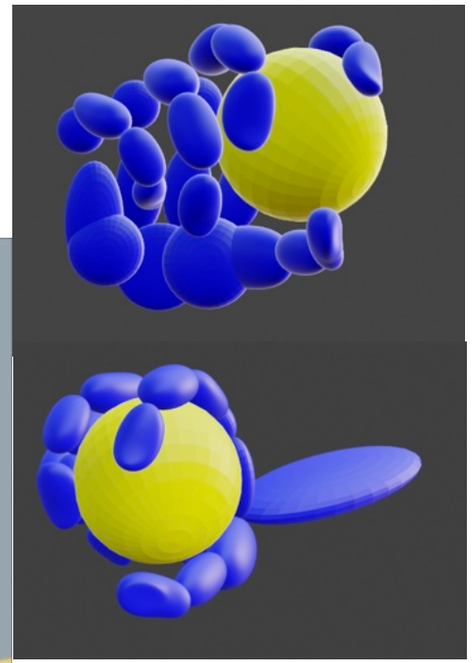
Frame
203



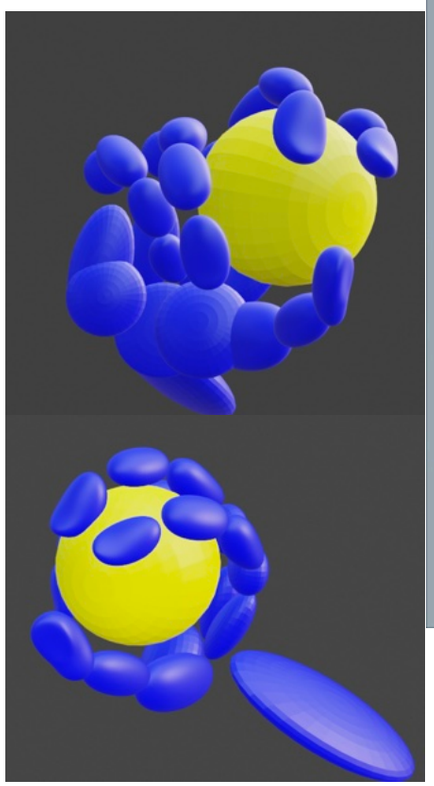


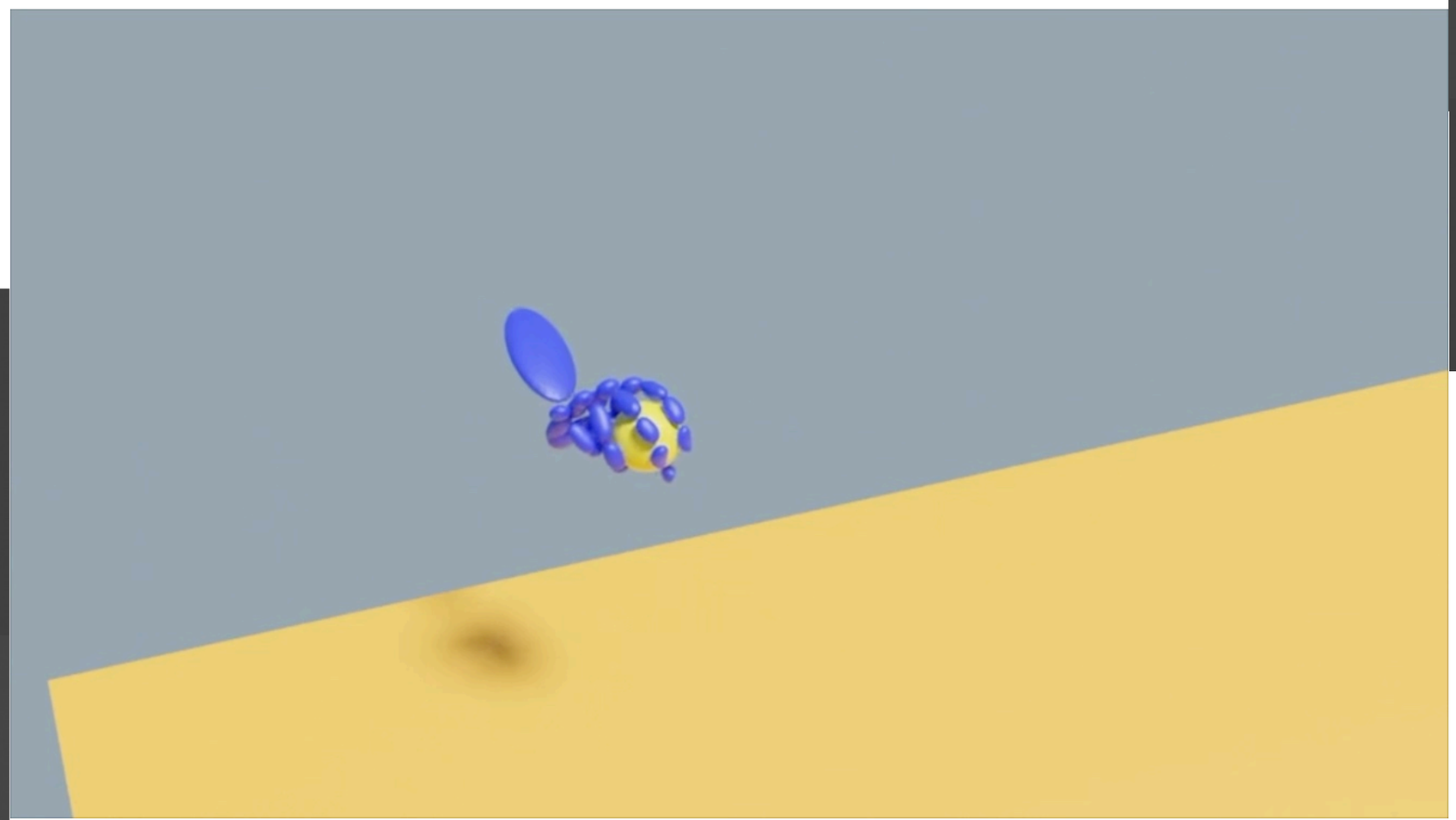
Ball Power Lateral

Frame



Frame 452

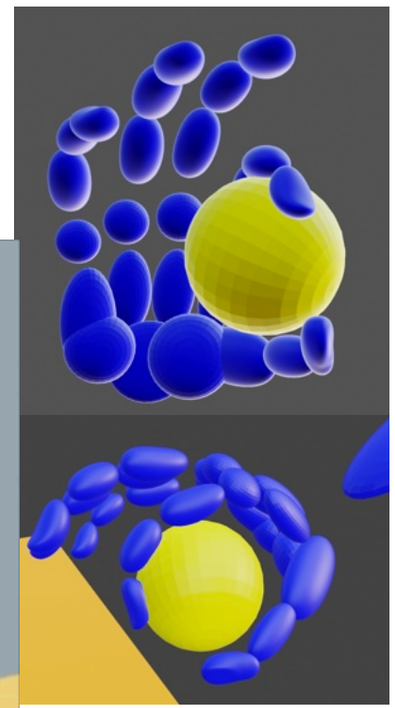


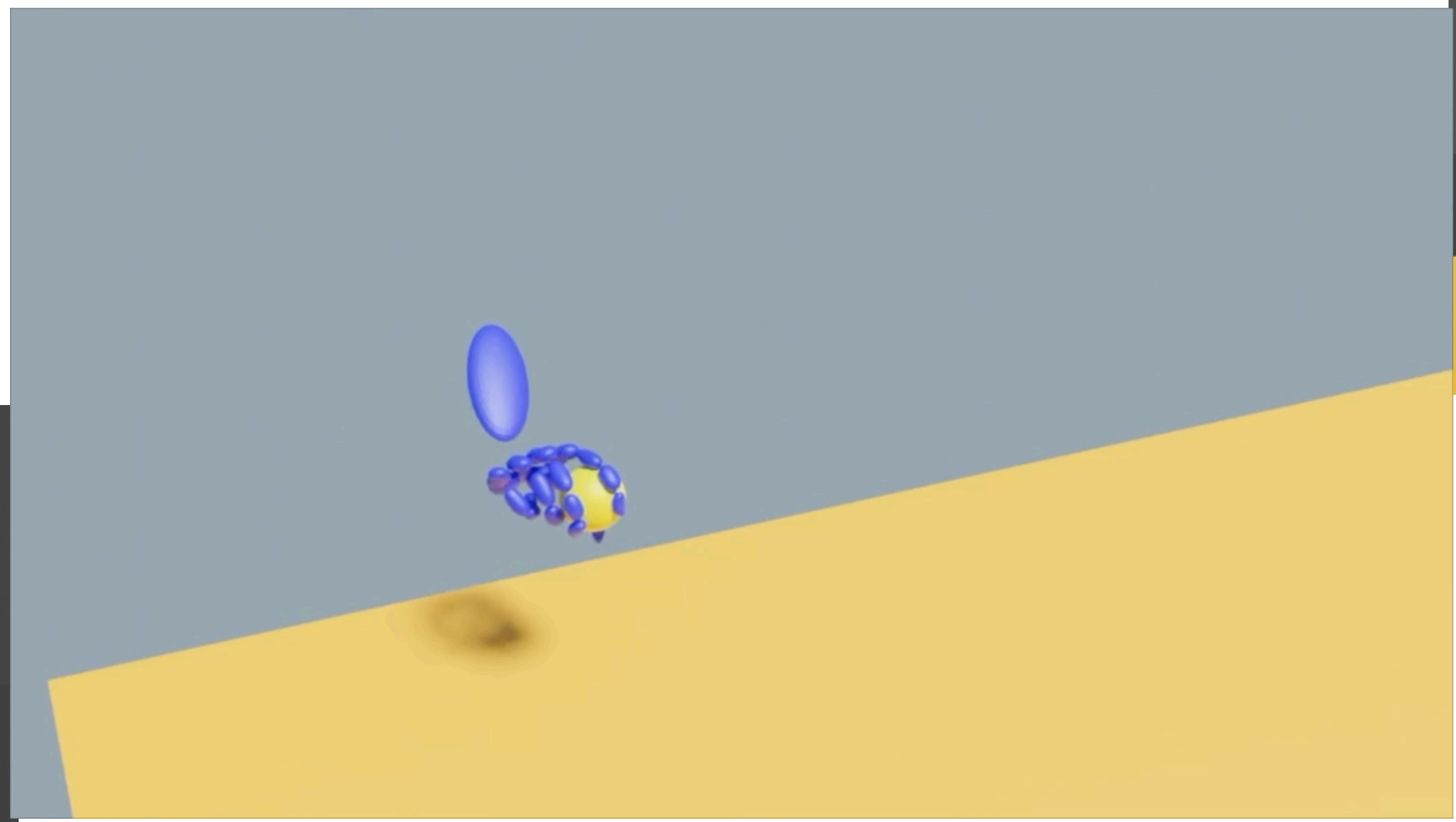


Ball Power Lateral

Frame

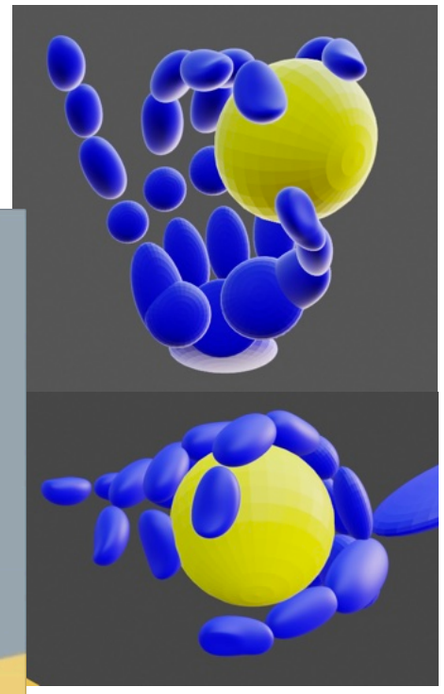
Frame

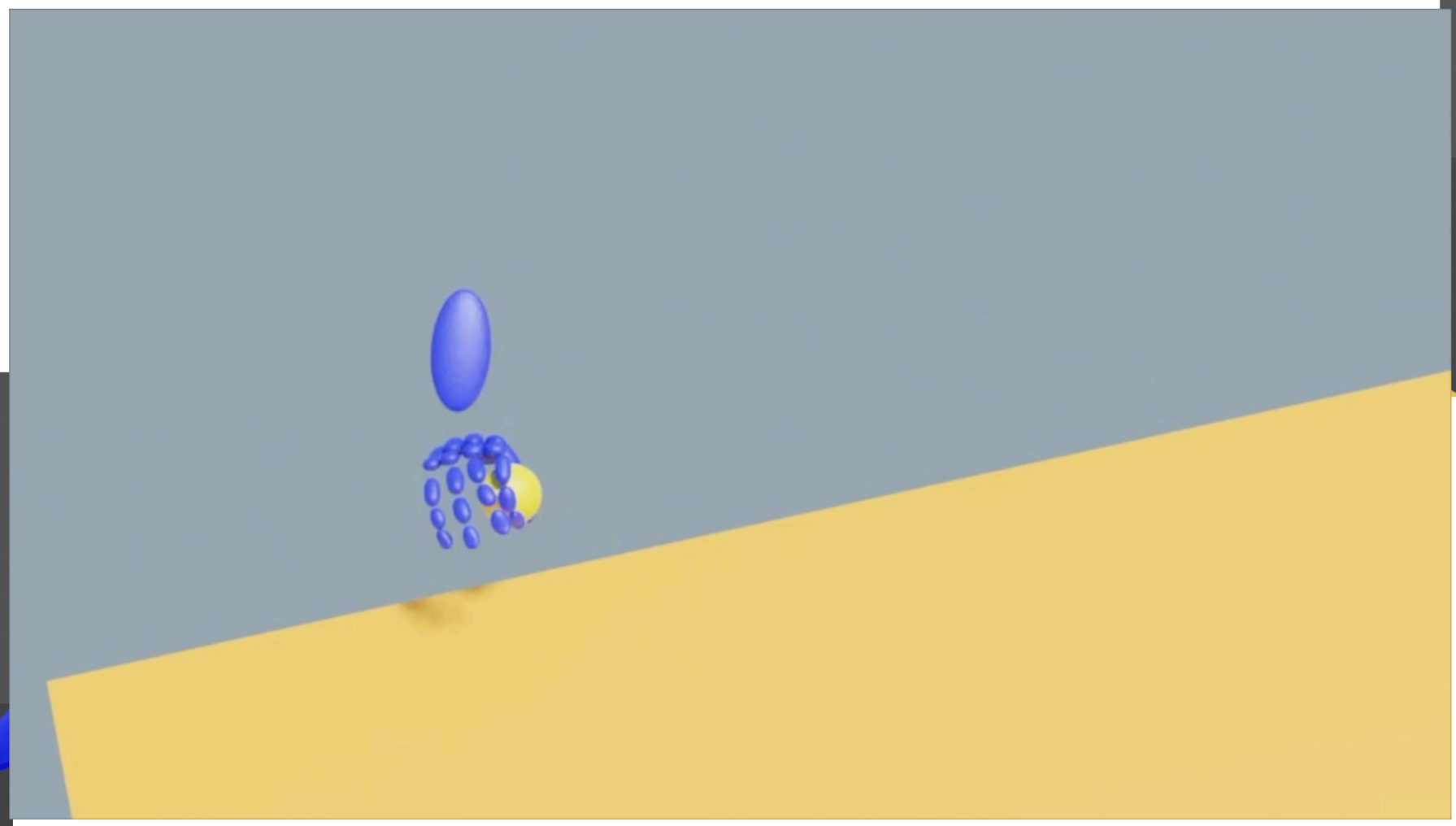




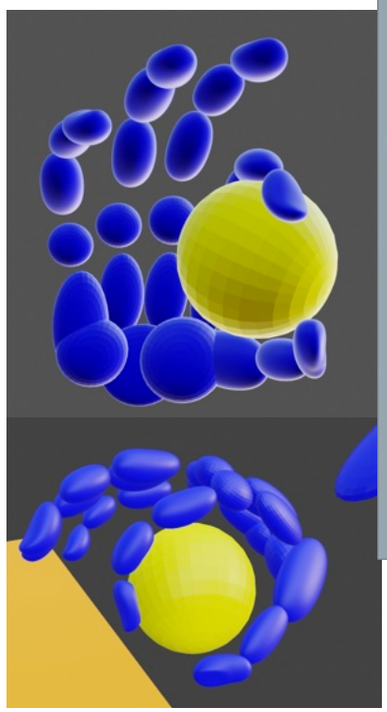
Ball Power Lateral

Frame



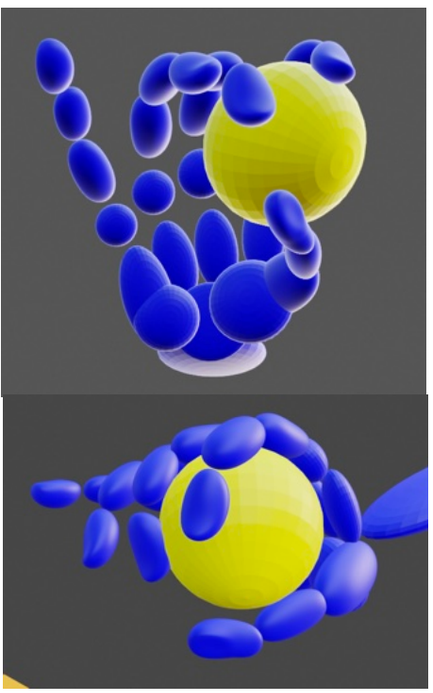


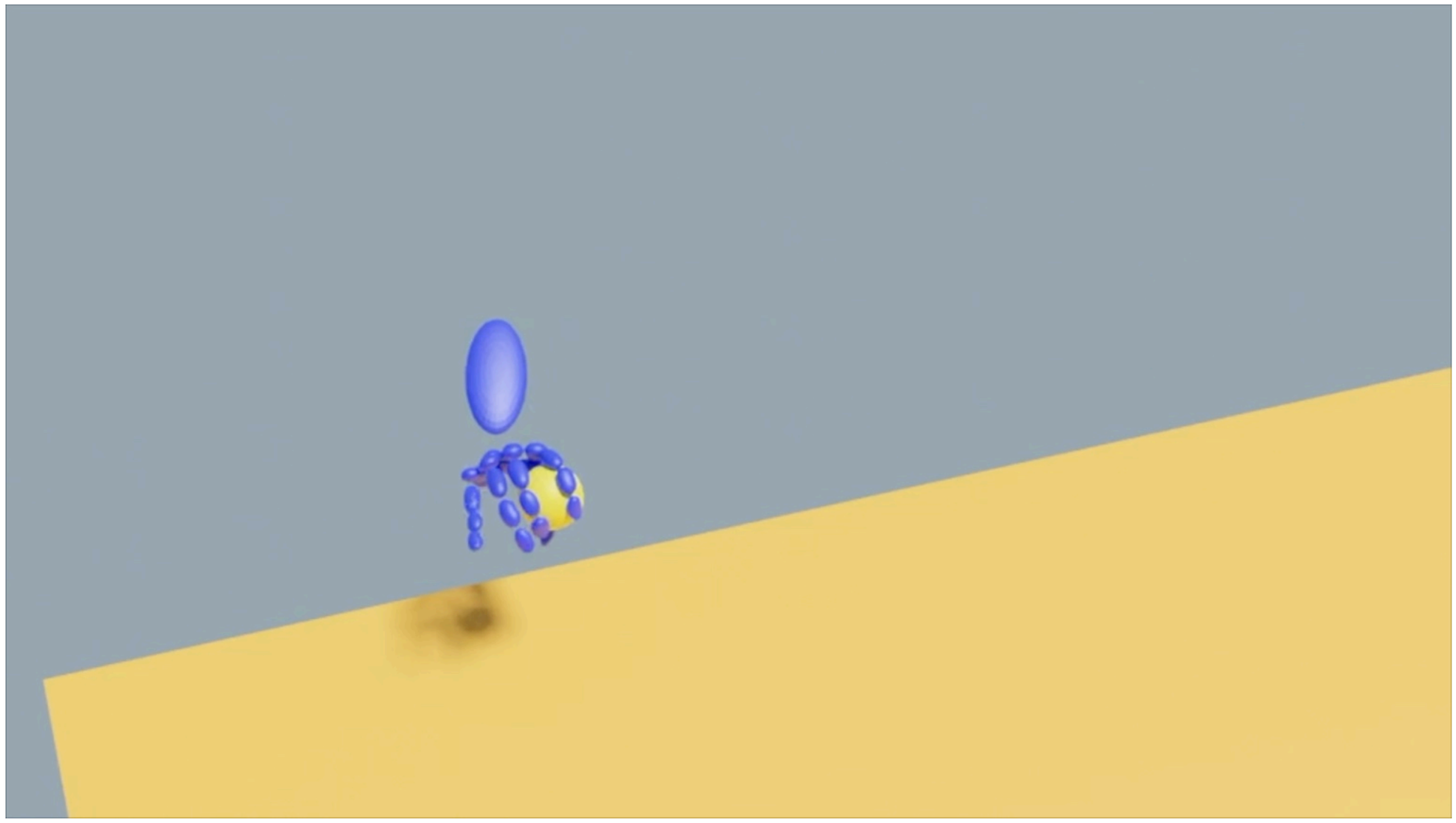
Frame



Ball Power Lateral

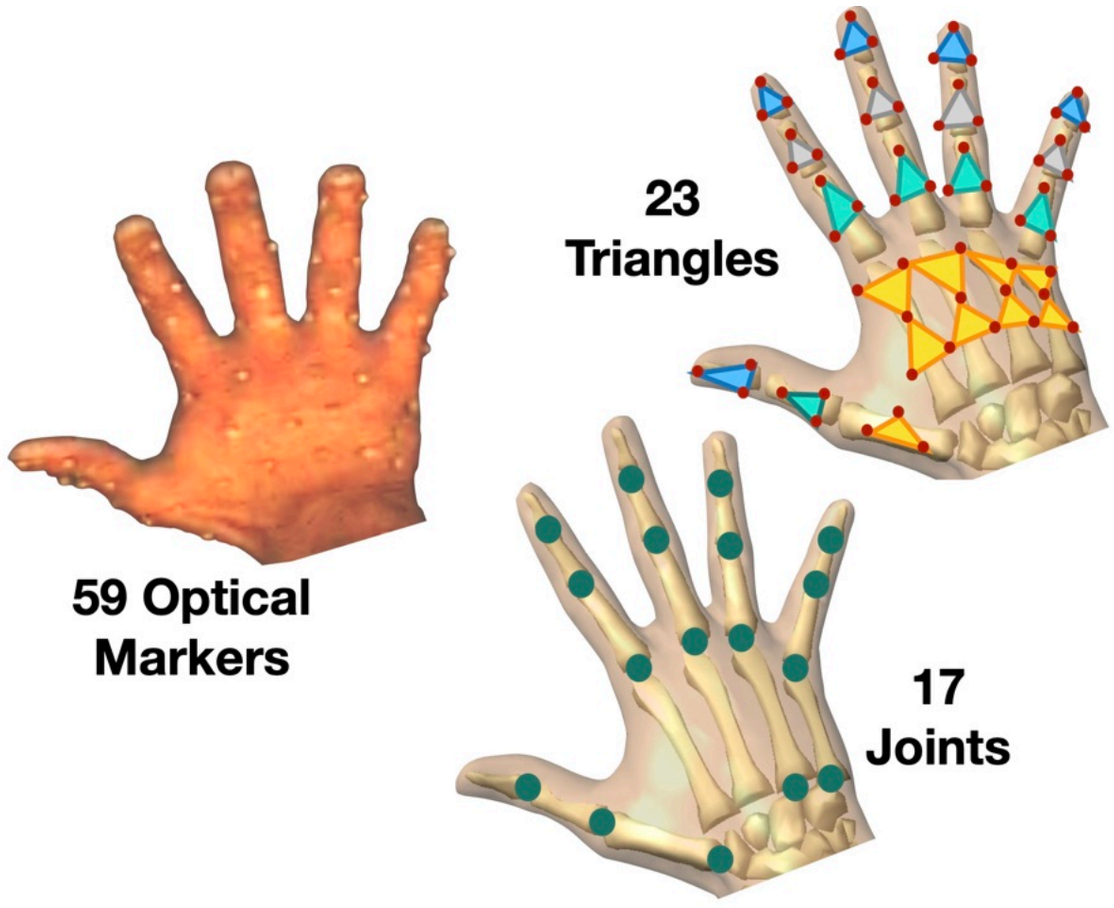
Frame





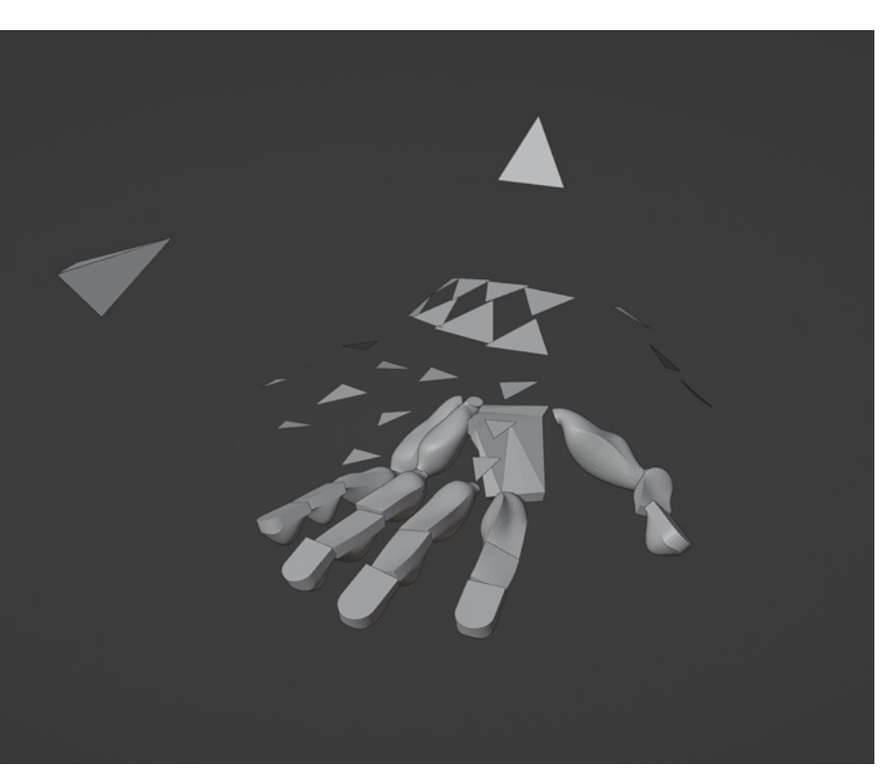
Markers & Joints

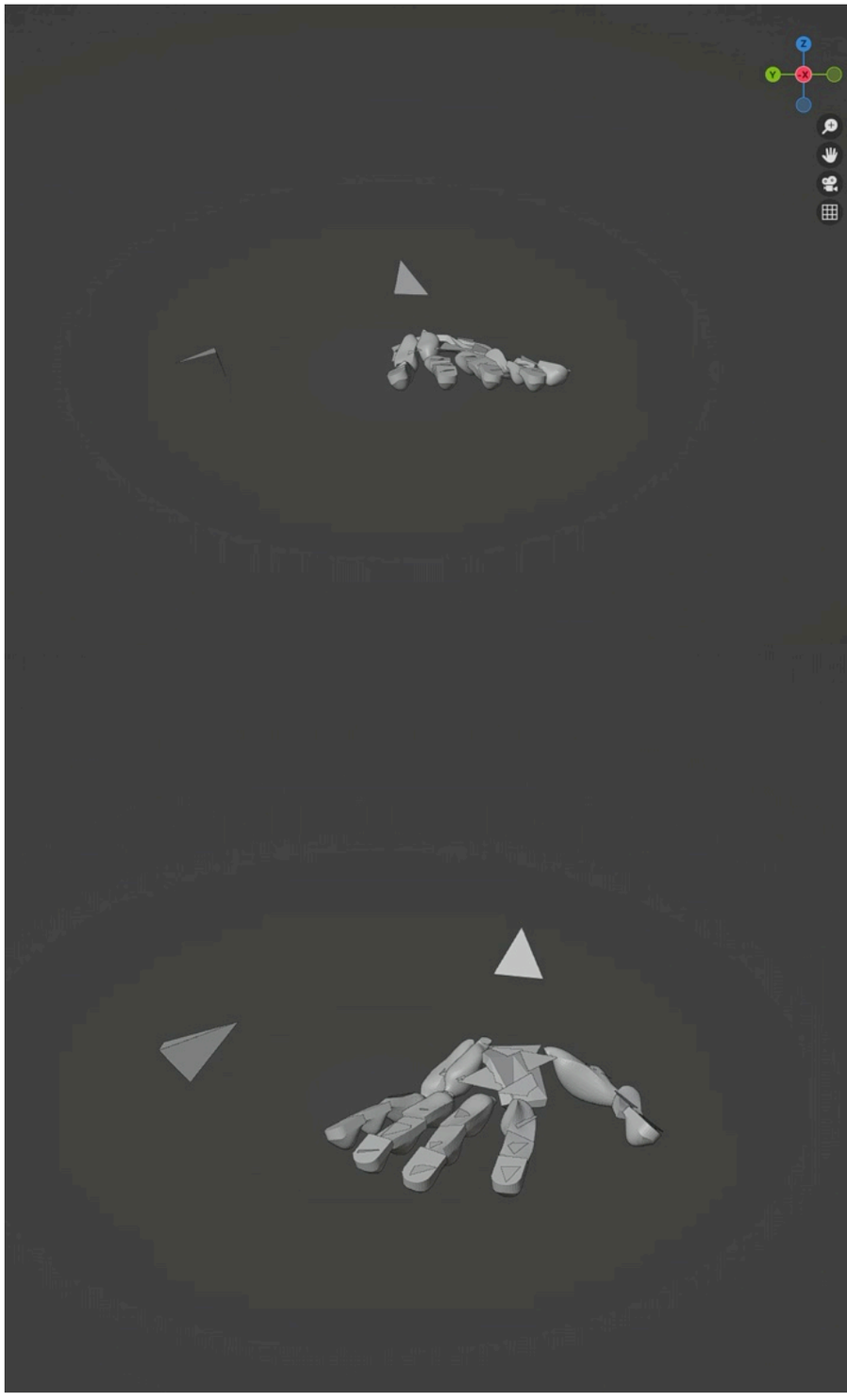
- 59 markers to track 6 degree-of-freedom configuration of each major bone
- Joints represented by quaternions



Methods

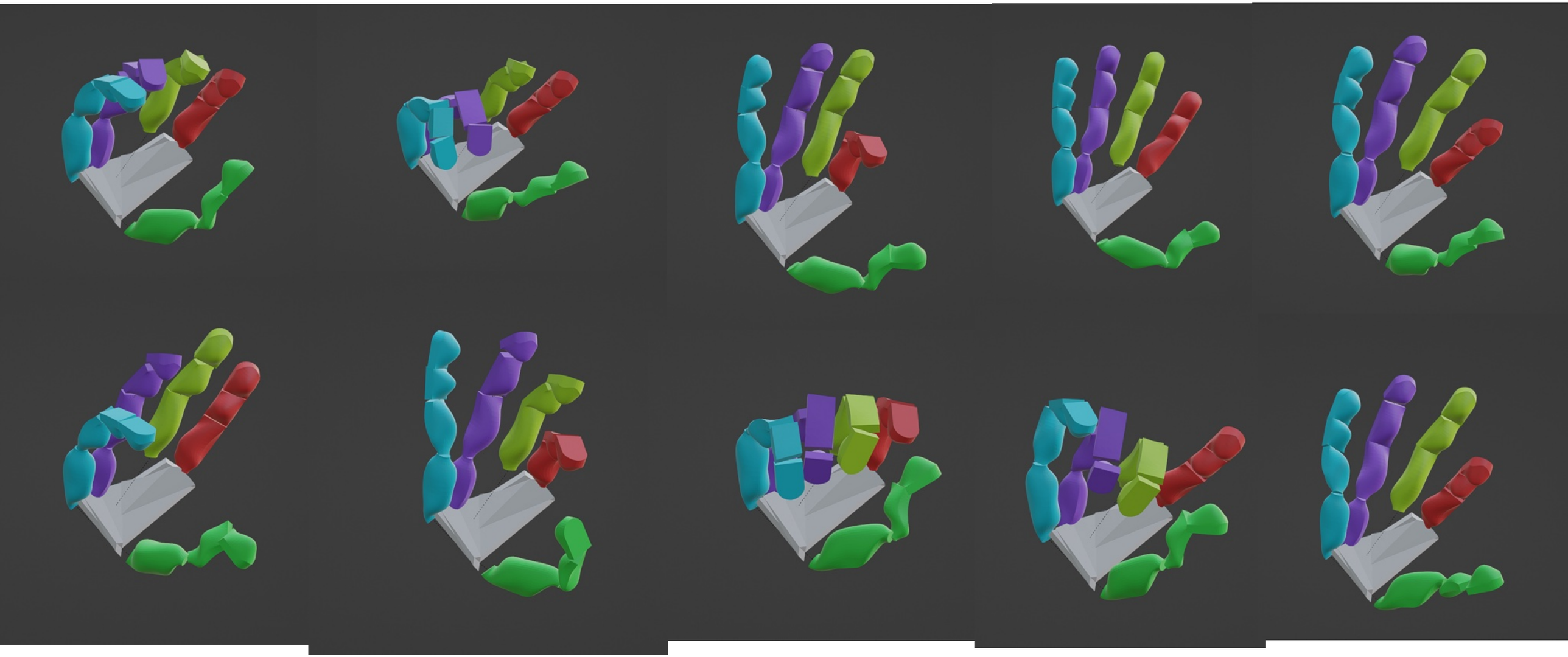
- Gradient based optimization (L-BFGS-B)



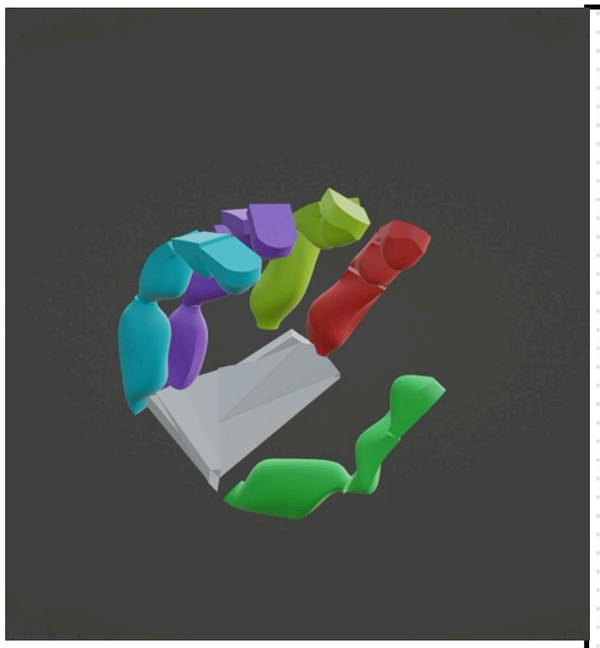


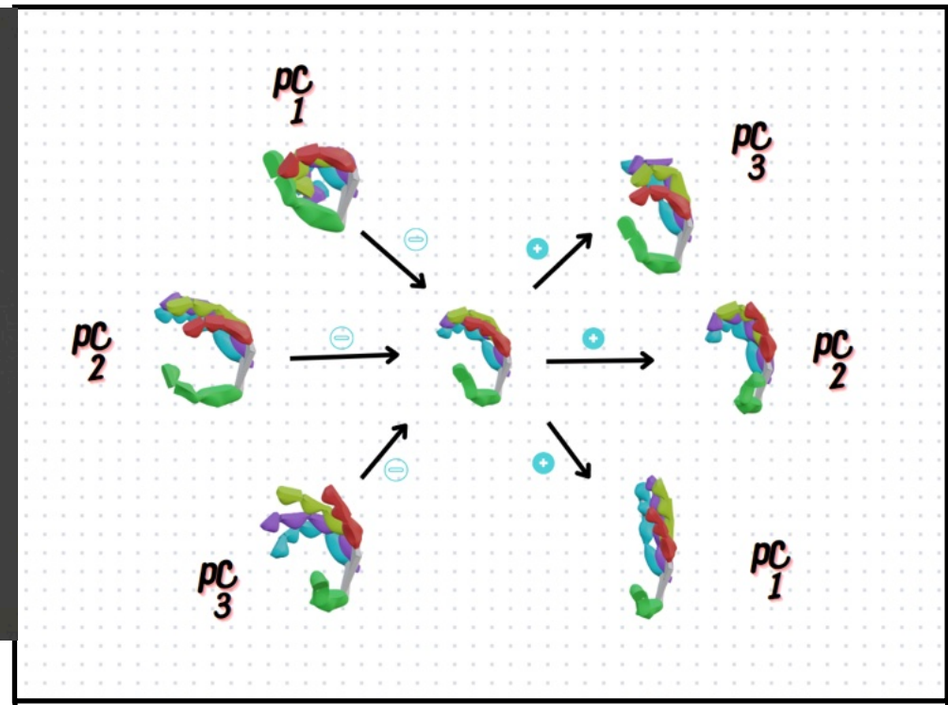
Dataset of most different Poses

- *1000 “nice” poses (here’s 10)*

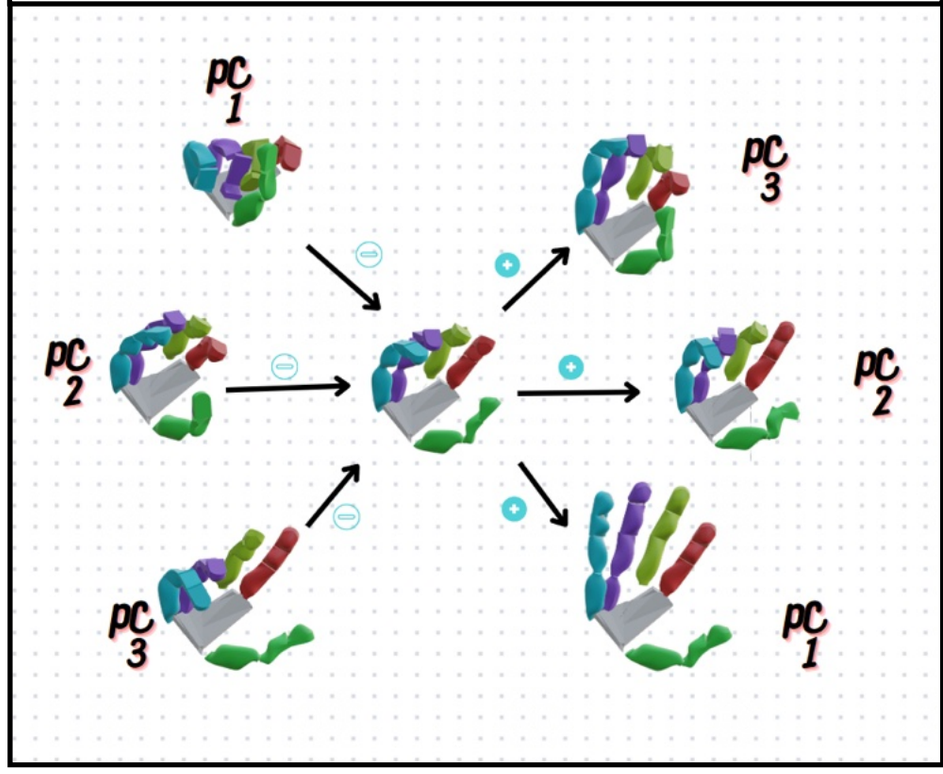


Results
- *Synergies*





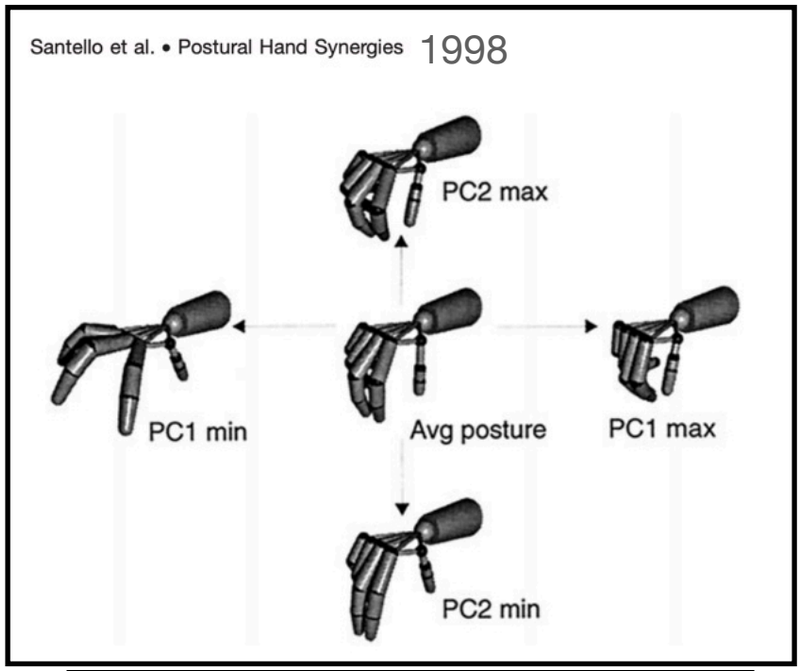
- PC = Principal component
- Computed from dataset, after subtracting the mean
- First synergy (PC1) - standard opening and closing of the hand.
- Second synergy (PC2) - fingers out from and in towards the palm.
- Third synergy (PC3) - twisting motion
- 3 synergies account for 50%, 15%, and 9% of the variance respectively.

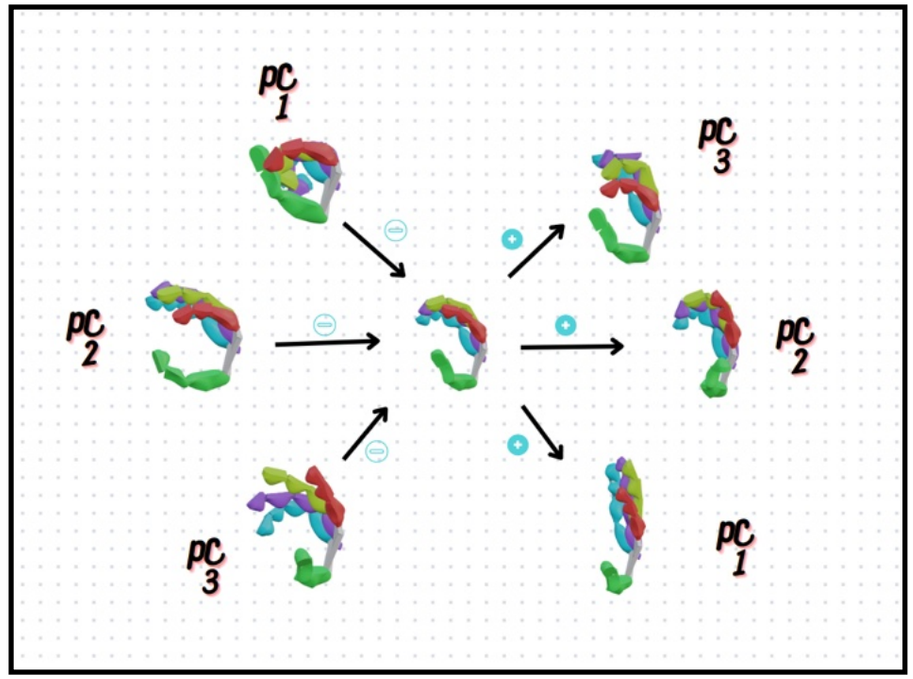


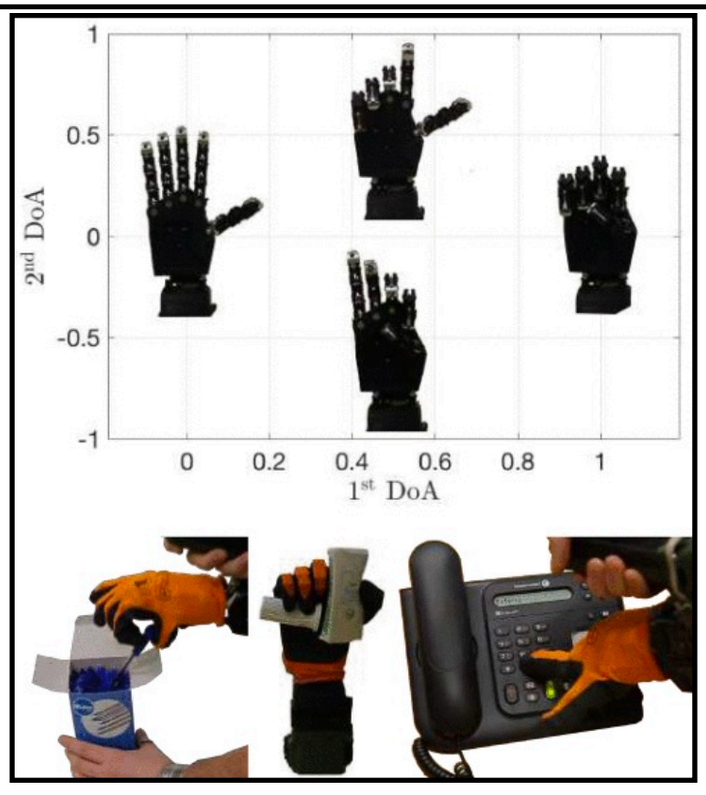
Synergies

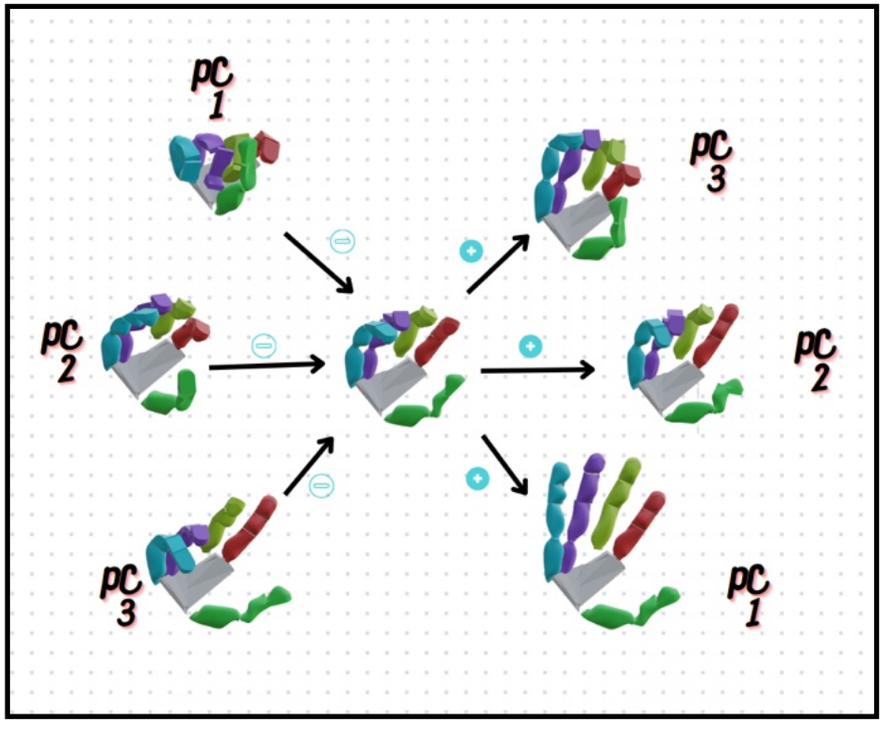
- a comparison

- Synergy 1 - fingers spread + come together
- Synergy 2 - a bit different in each





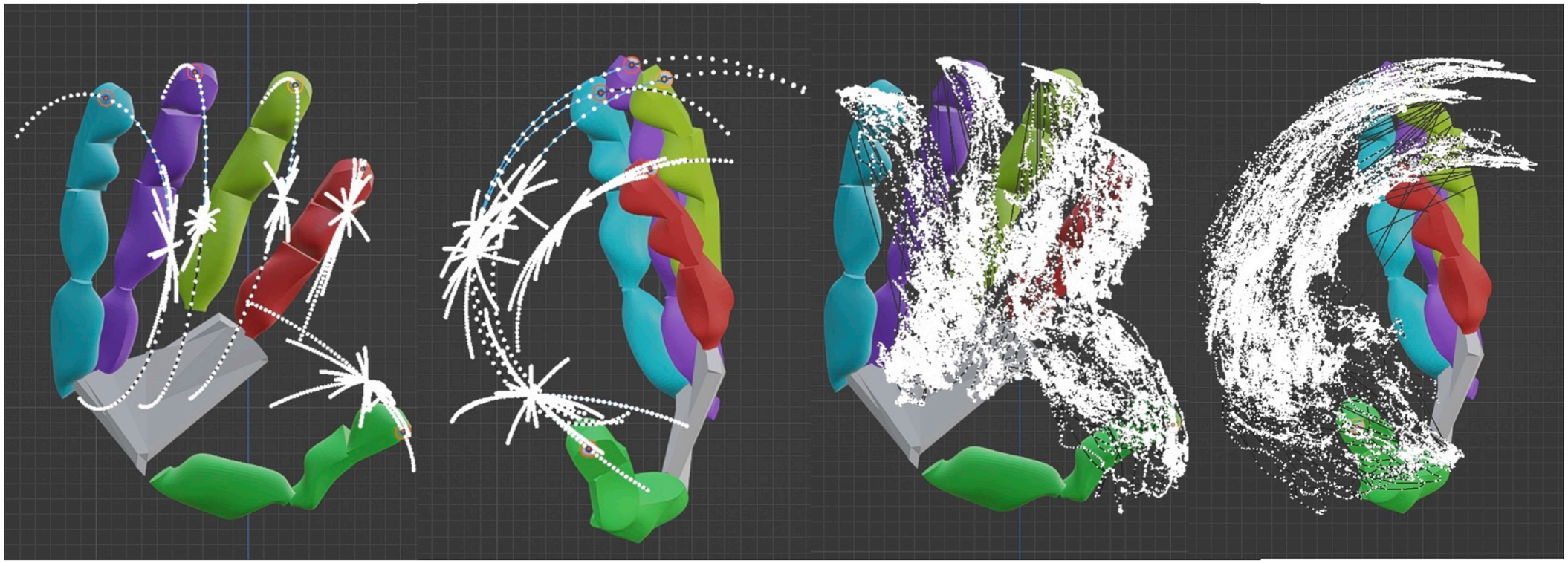




C. Della Santina, et al., “Toward dexterous manipulation with augmented adaptive synergies: The pisa/iit softhand 2,” 2018.

Workspace

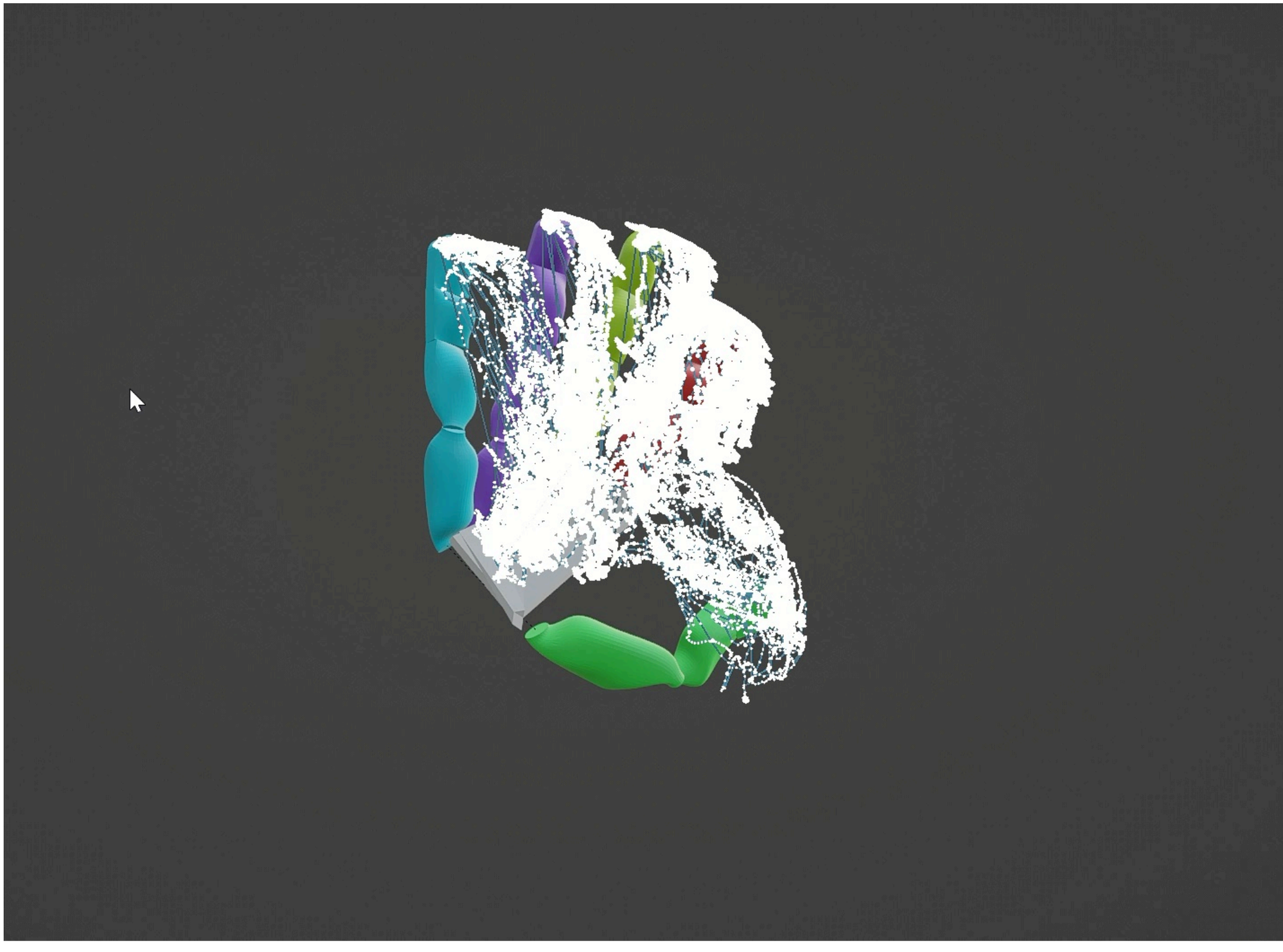
- Dotted lines: motion paths of the distal link on each figure
- Left side = Eigen motions Right Side = all frames



Eigen Motions

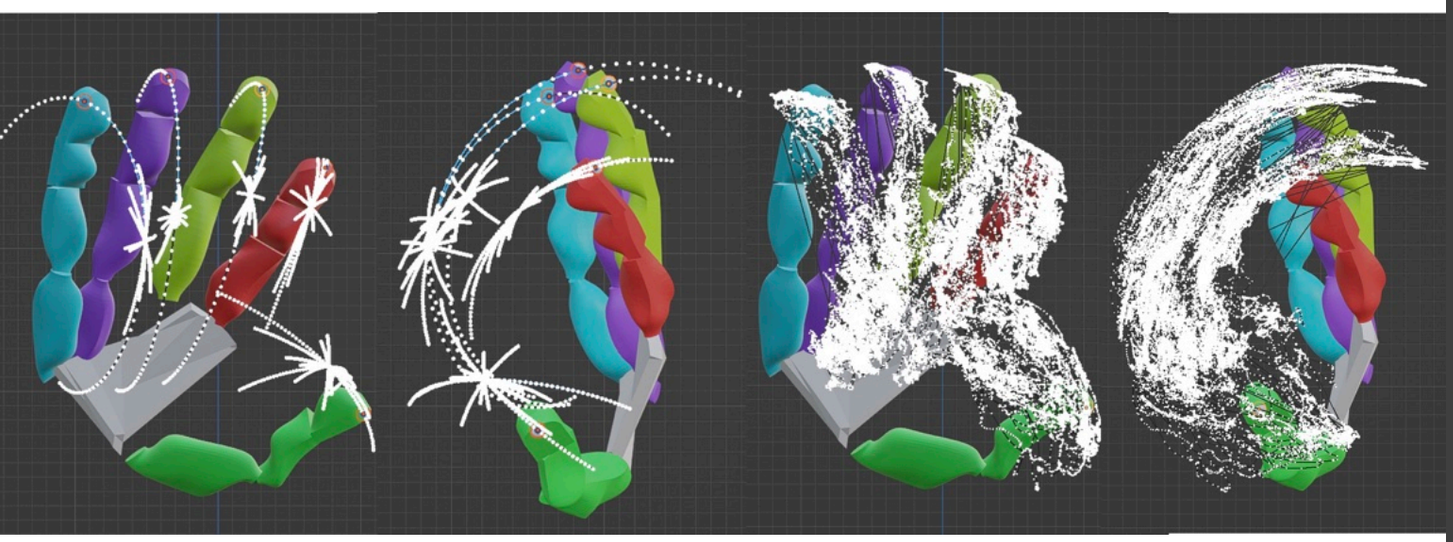
- 6 principal components
- 50%, 15%, 9%, 6%, 4%, 4%, of the variance

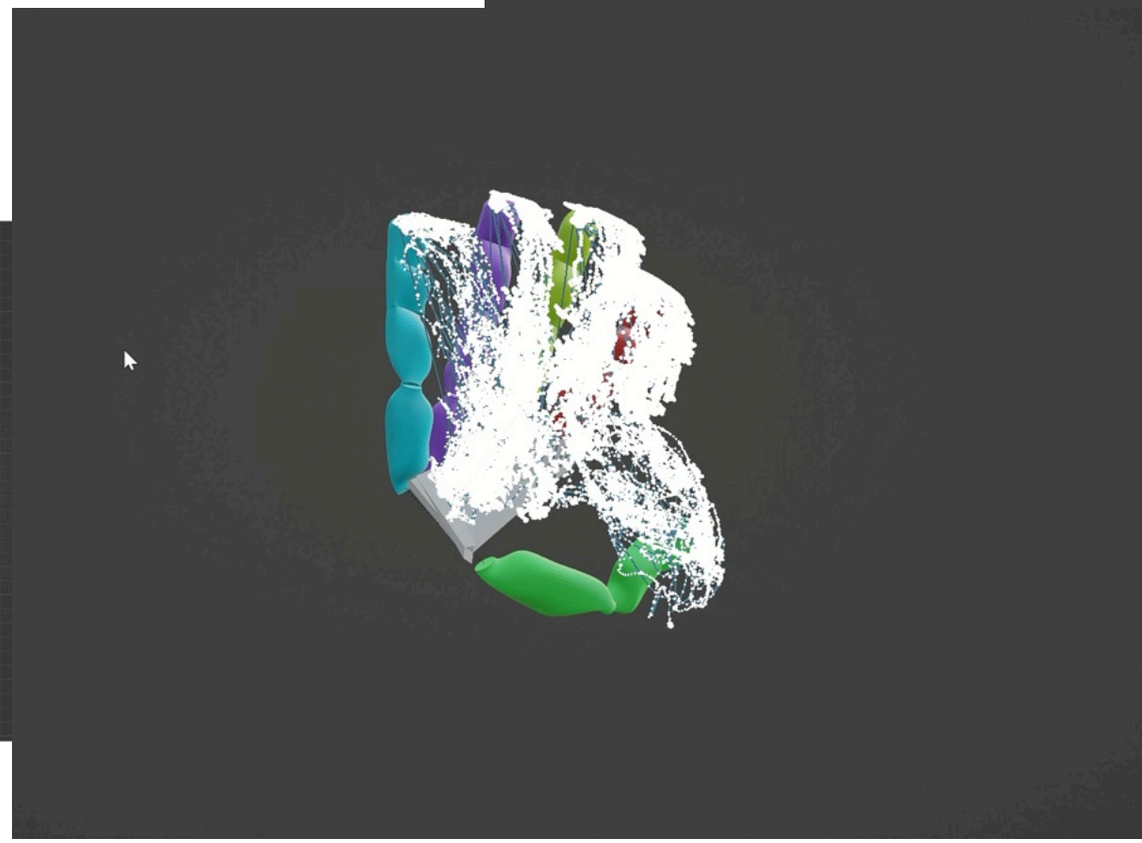
Fingertip Workspace



Workspace
- *takeaways*

- Volume of traced points is small
- Forms a thin shell
- Small range of motion

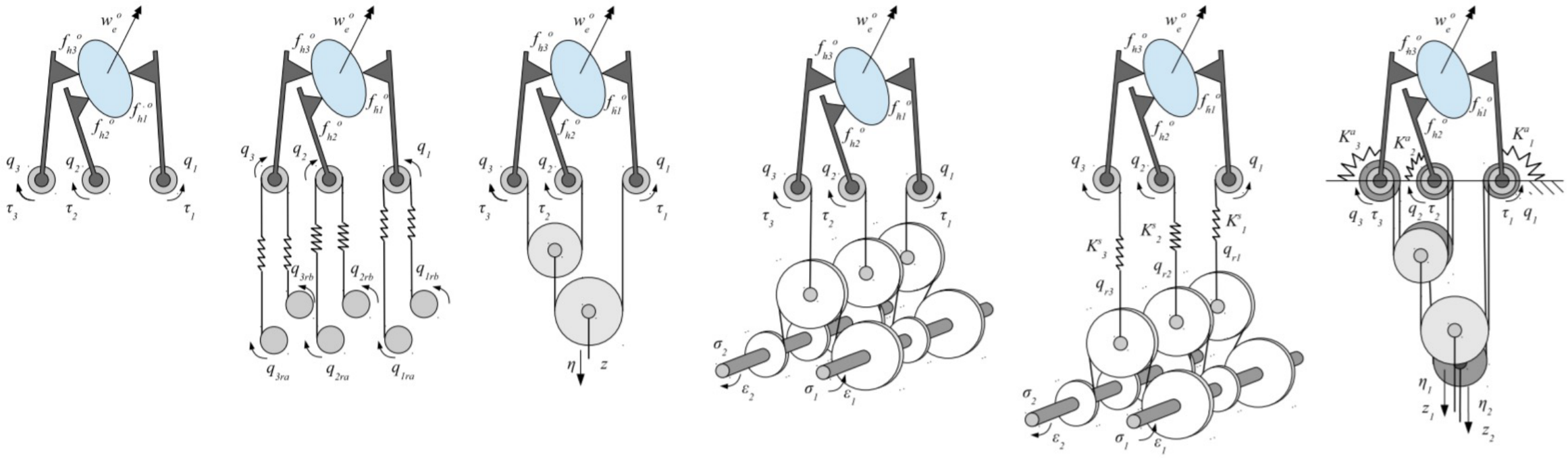




Aside: How can you implement synergies in a robot hand?

Actuation Strategies

(a) full actuation (b) full VSA (c) adaptive UA (d) rigid synergies (e) soft synergies (f) adaptive synergies



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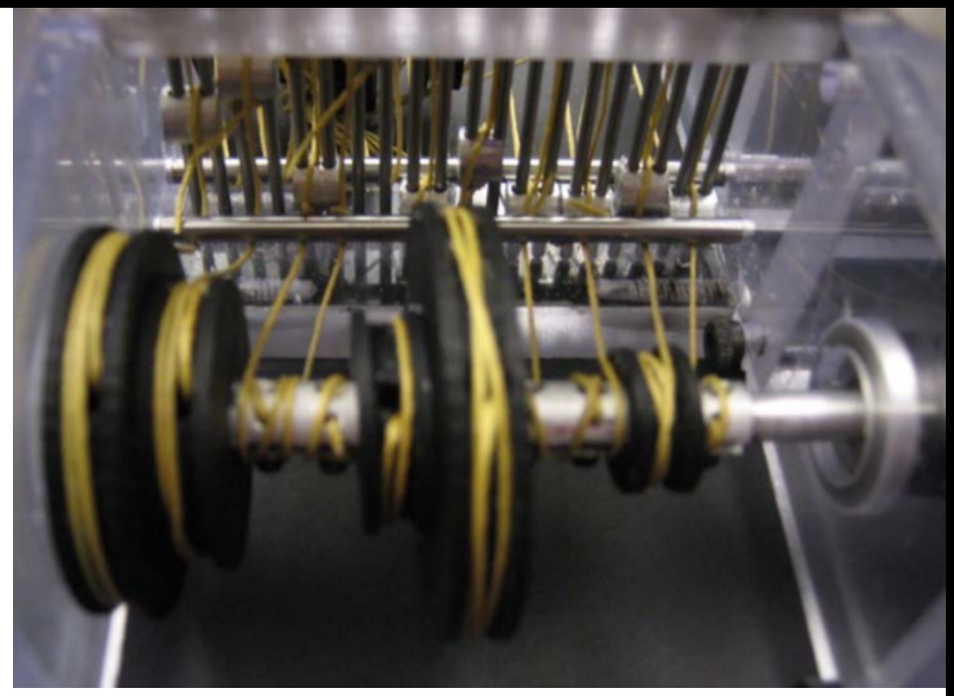
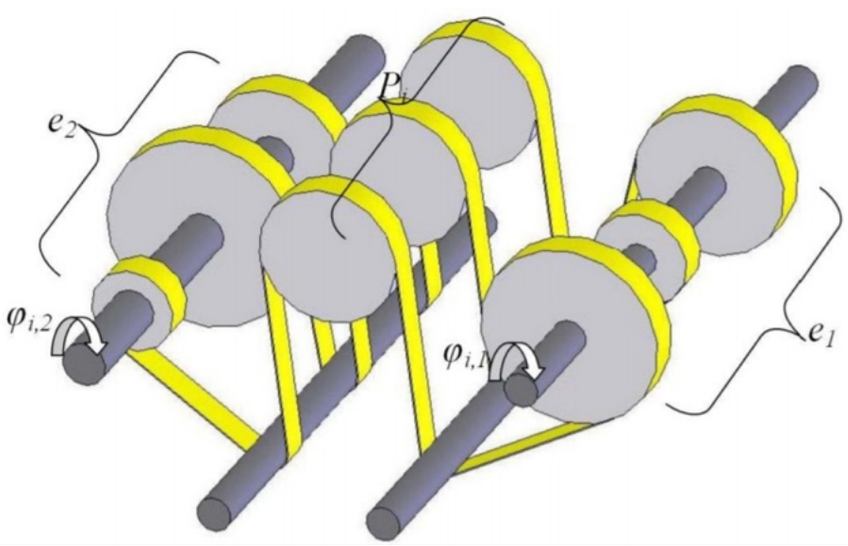
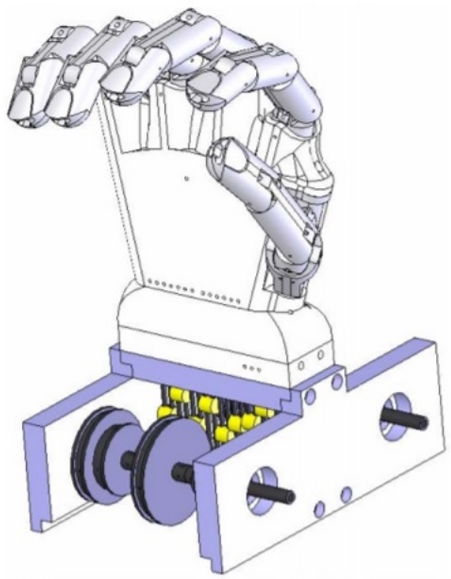
Piazza, C., G. Grioli, M. G. Catalano, and A. J. A. R. O. C. Bicchi. "A century of robotic hands." *Annual Review of Control, Robotics, and Autonomous Systems* 2 (2019): 1-32.

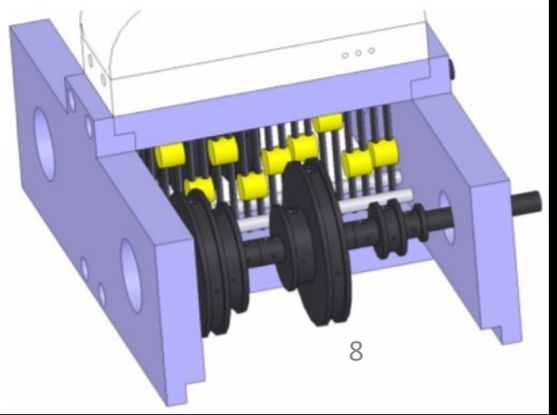
Related Work

- ***Inter-Finger Coordination and Postural Synergies in Robot hands via Mechanical Implementation of Principal Component Analysis*** (2007) by Brown and Asada
- 17 DOF, 2 motors
- Implemented fist two synergies/components via two shafts with pulleys of different diameters









Brown, Christopher Y., and H. Harry Asada. "Inter-finger coordination and postural synergies in robot hands via mechanical implementation of principal components analysis." In *2007 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 2877-2882. IEEE, 2007.

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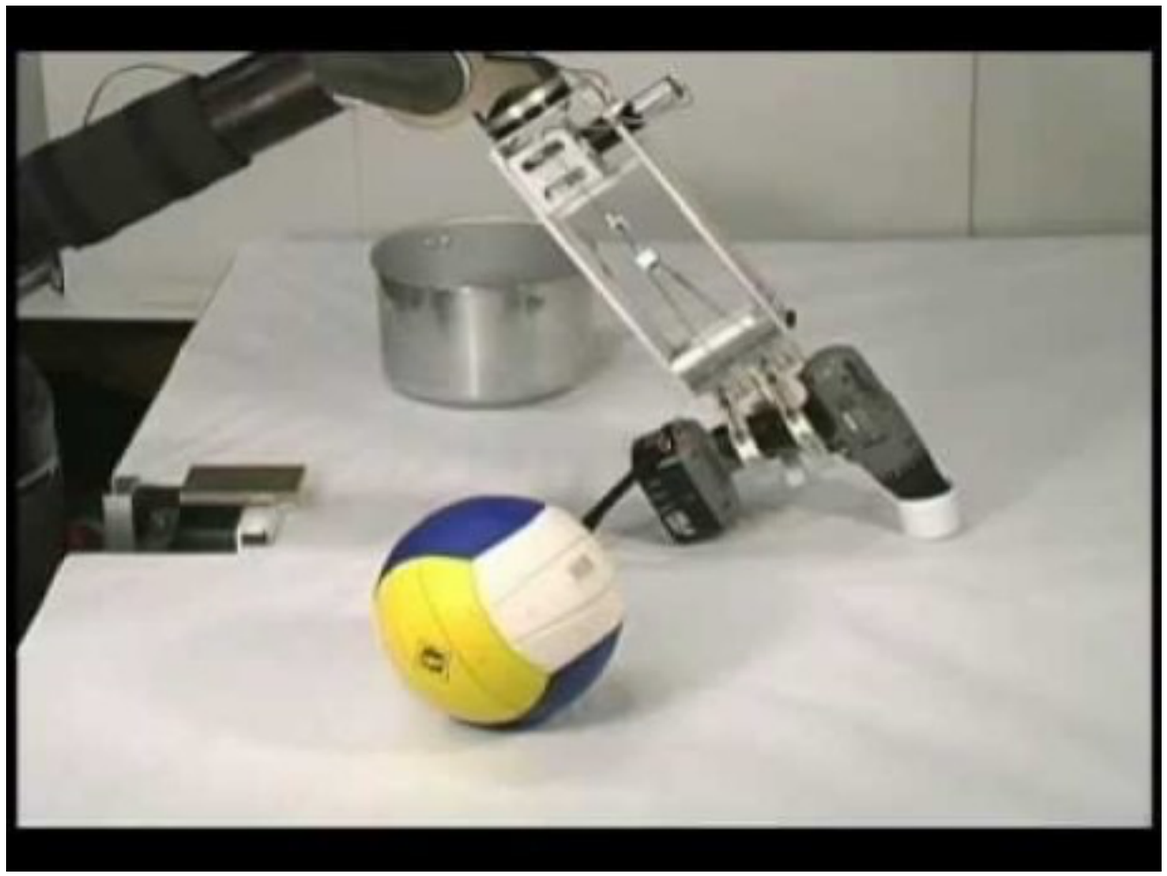
Shape-adaptive Underactuation



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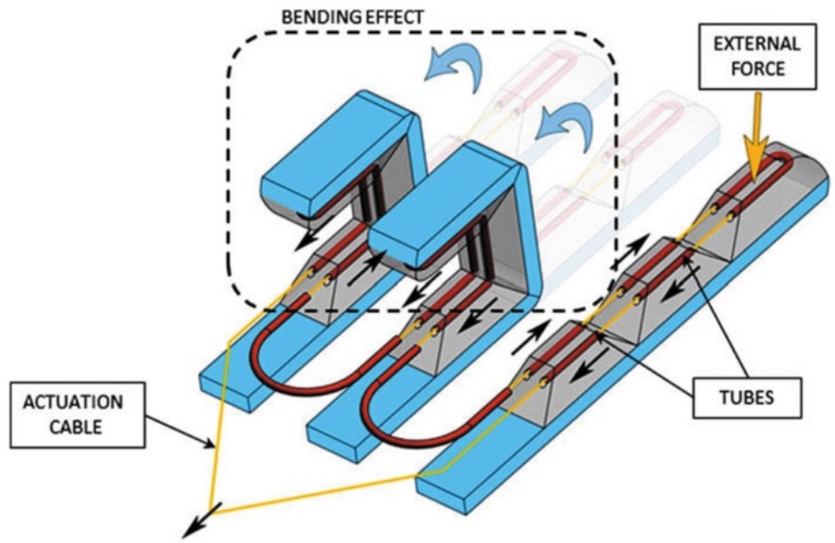

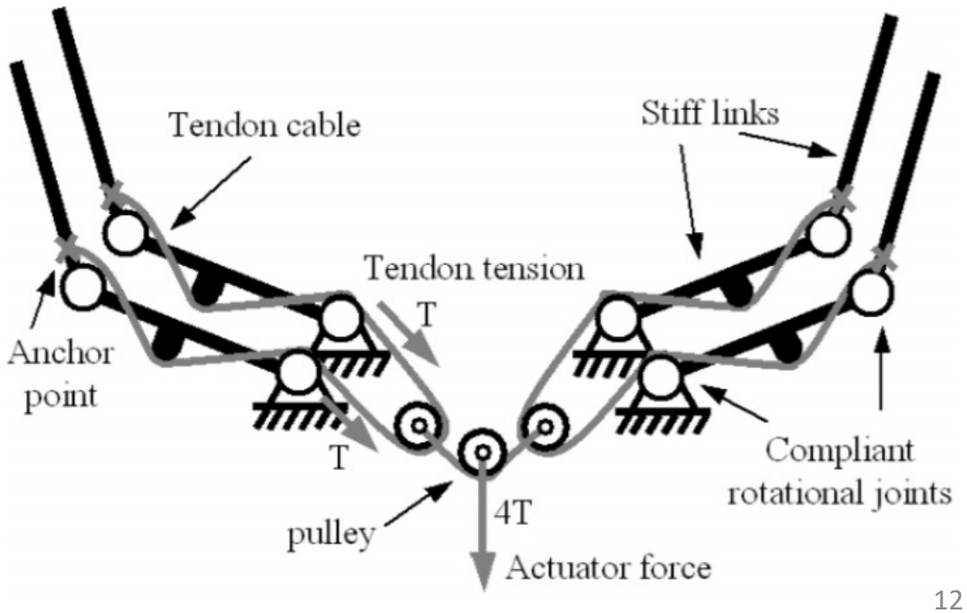

Dollar, Aaron M., and Robert D. Howe. "The highly adaptive SDM hand: Design and performance evaluation." *The international journal of robotics research* 29, no. 5 (2010): 585-597.

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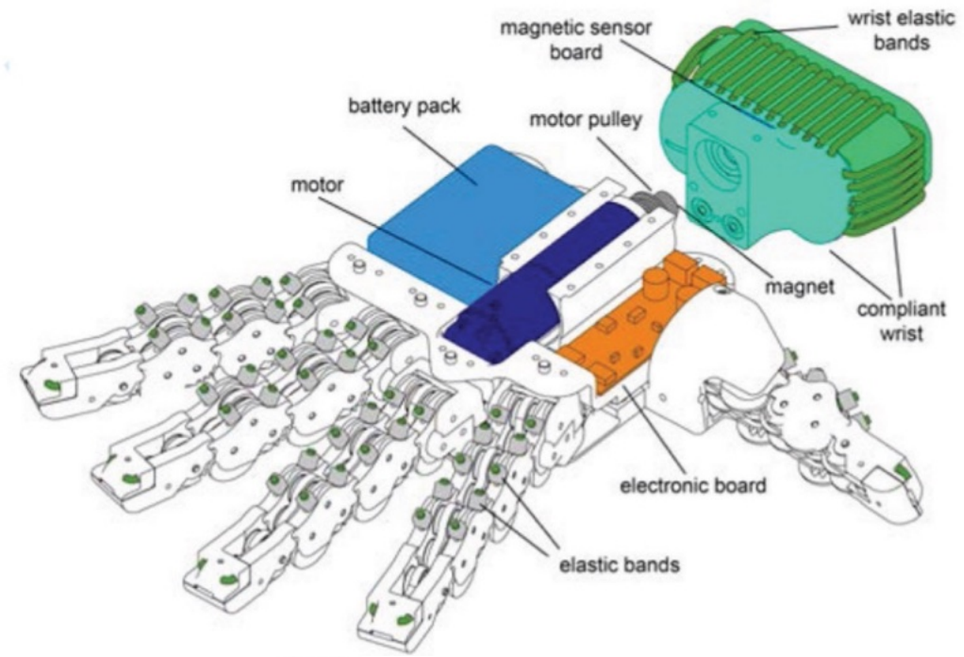
Pisa/IIT SoftHand Design

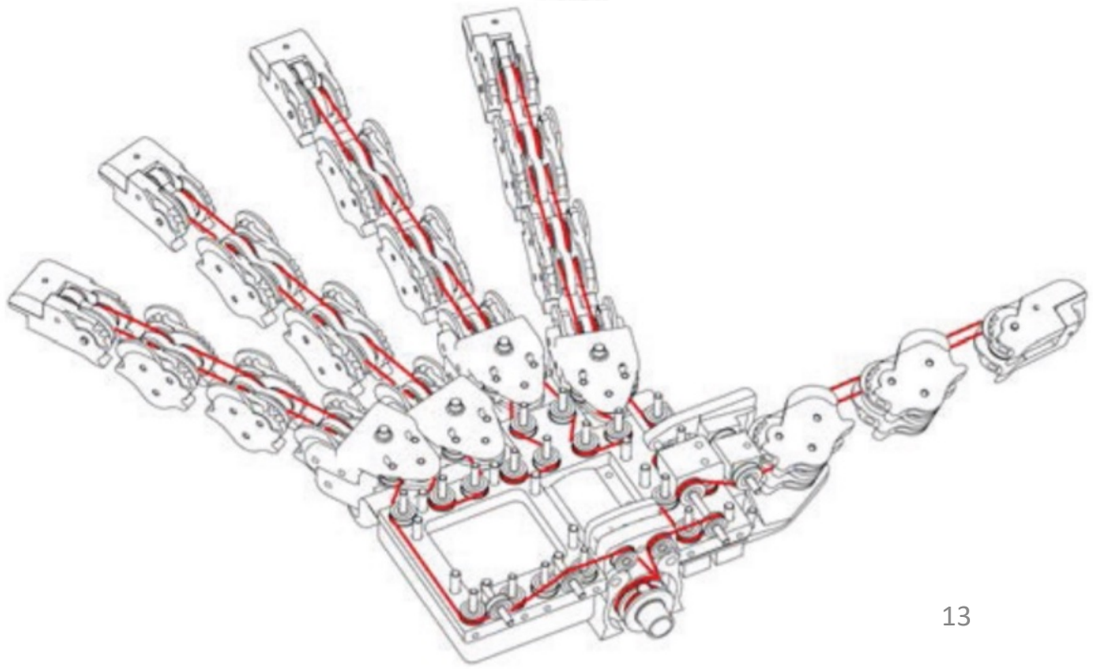
- "Mechanical implementation of soft synergy obtained via numerical evaluation of corresponding transmission matrix *R* and joint stiffness matrix *K*"

$$R\delta q = \delta z$$

$$\delta\tau = R^{\mathrm{T}}\delta\eta - K_q^a\delta q$$

δ: "variation"
q: joint configuration
z: adaptive synergy displacements
τ: joint torque
η: adaptive synergy forces





Della Santina, Cosimo, Cristina Piazza, Giorgio Grioli, Manuel G. Catalano, and Antonio Bicchi. "Toward dexterous manipulation with augmented adaptive synergies: The pisa/iit softhand 2." *IEEE Transactions on Robotics* 34, no. 5 (2018): 1141-1156.

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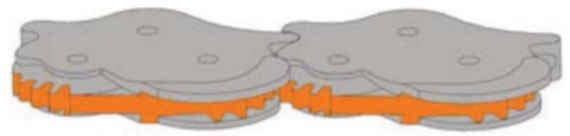
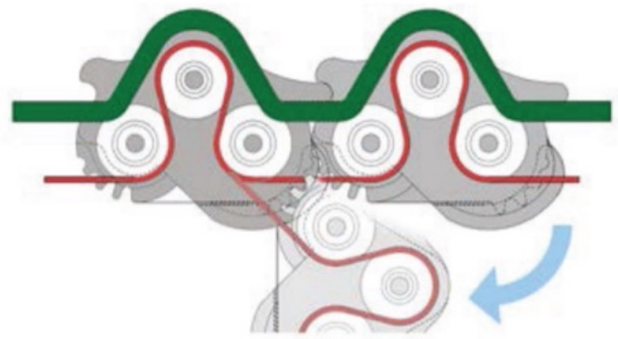
Joint Design

- Compliant Rolling-contact Elements (CORE)
- Held together by elastic ligaments
- Pre-tensioning of ligaments creates attractive equilibrium at rest configuration (fingers stretched)
- No screws/shafts/gears/bearings
- Low friction and wear

(a) Perspective view



(b) Side view and movement



(a) Finger Side bend

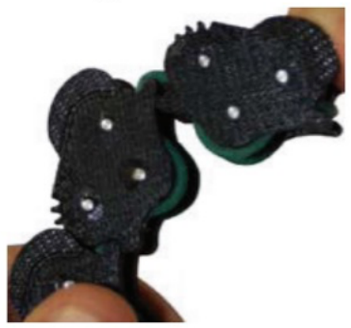
(b) Finger Back bend

(c) Finger Twist

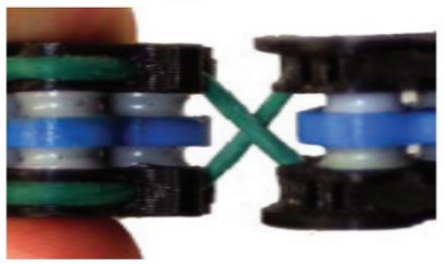
(d) Finger Skew bend

(e) Side bend

(f) Back bend



(g) Twist



(h) Skew bend

Della Santina, Cosimo, Cristina Piazza, Giorgio Grioli, Manuel G. Catalano, and Antonio Bicchi. "Toward dexterous manipulation with augmented adaptive synergies: The pisa/iit softhand 2." *IEEE Transactions on Robotics* 34, no. 5 (2018): 1141-1156.

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Benchmarks

(see references)