Considerations for Assessment and Treatment of the Distal Upper Extremity After Stroke

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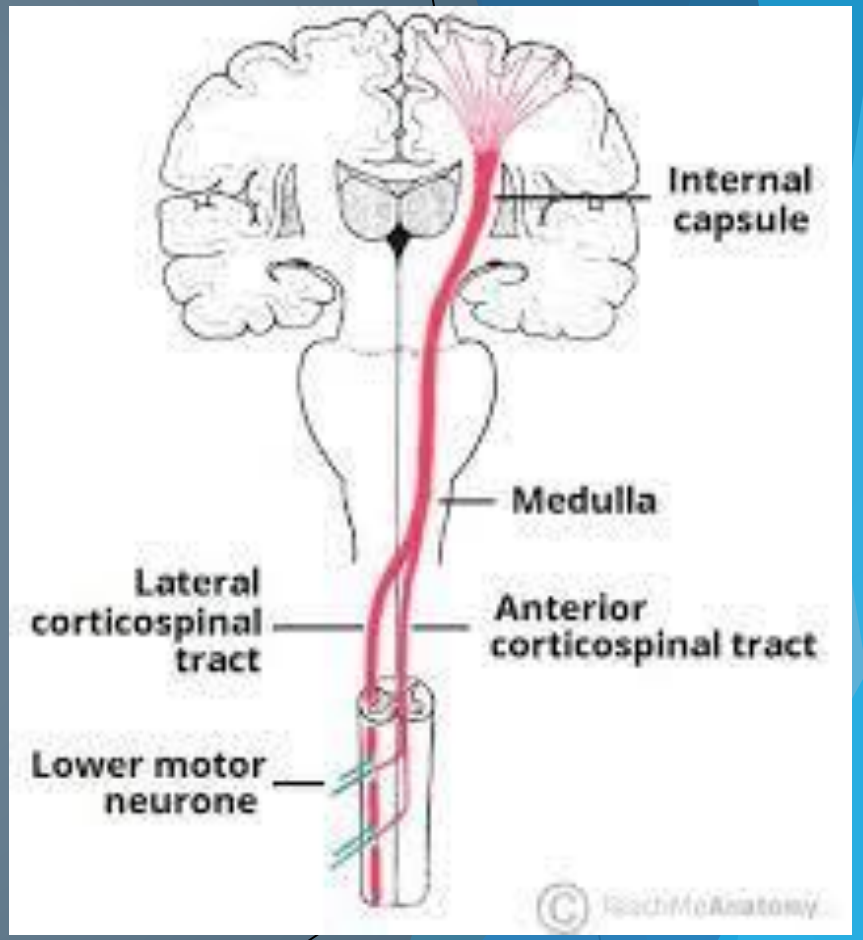
Who needs pockets when you have 5 fingers?

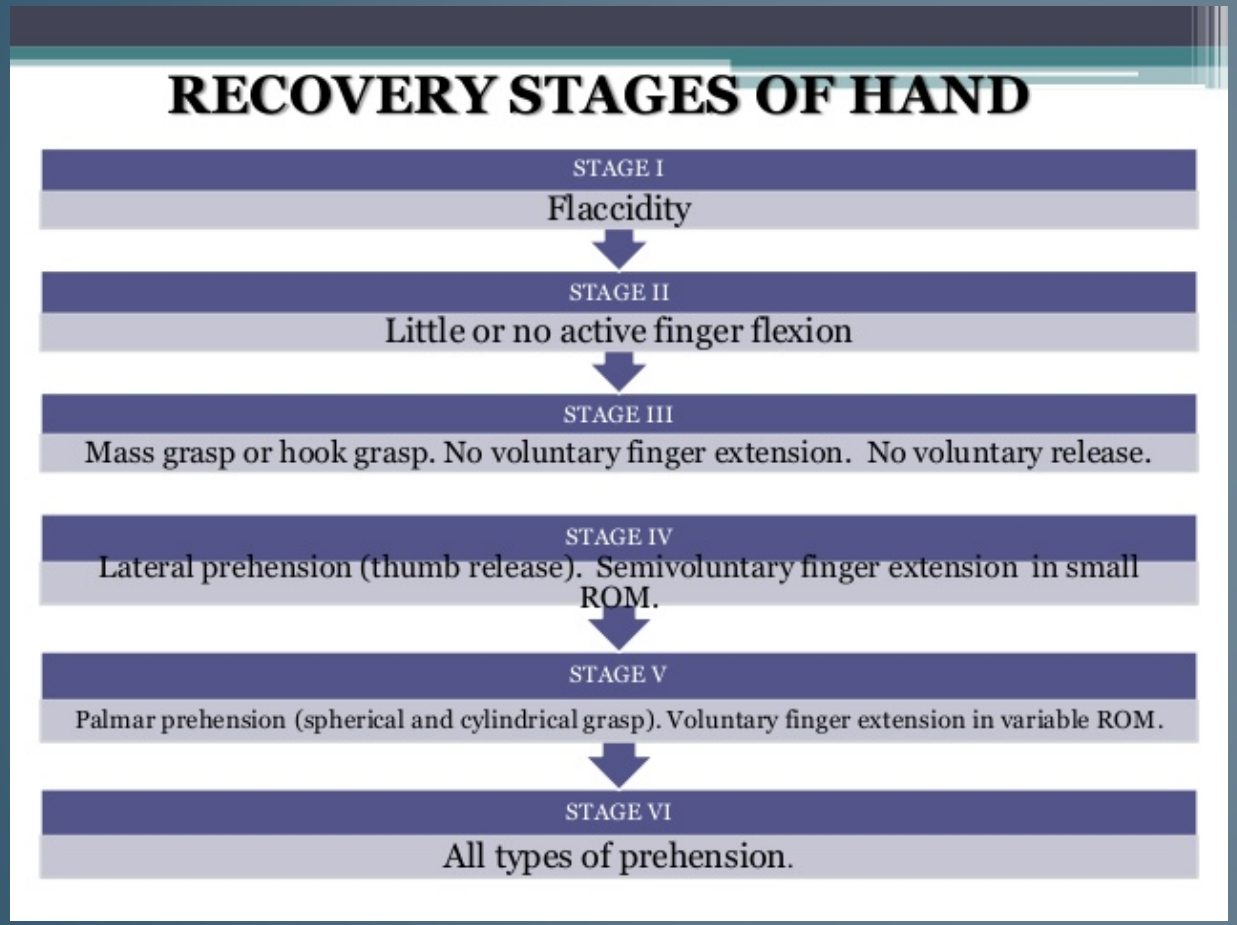
The Corticospinal Tract

- Individualized finger movements require selective activation of muscles.
- Motor cortex via the CST primarily controls these selective movements. -> Pyramidal cells
- In a normal CST system, the human hand is able to selectively move all digits or isolated digits.
  - Requires:
    - Both selective activation of the specific muscles to move the intended finger(s).
    - Selective suppression of the other muscles/digits.

- THUS- The Human hand is really complex!



Brunnstrom's Phases of Hand Recovery



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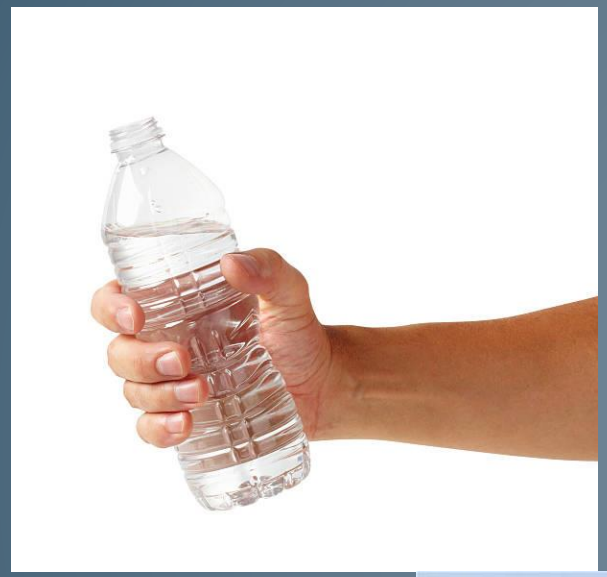
- Lots of work to get from stage 4 to 6.
- Good for Long Term Goal development
  - Short term goals will need to represent the needed criteria that is measurable by progress.

Tiers of Function for the Hemiparetic hand

Steve's Tiers of Hand Function	
Unable to use	Little Volitional movement- especially for active finger extension Unable to use for functional or assistive grasping- too effortful even when using spasticity.
Assistive grasping	Patient can grasp and possibly carry an item by passively placing/wedging it into the palm. Unable to voluntarily release the item.
Limited gross grasp and release	Able crudely carry an object and release it with significant effort.
Proficient grasp and release-	Able to grasp and release without significant effort. May be able to perform a lateral pinch grasp.
Limited prehensile function-	Patient is able to selectively alter grasp and release patterns depending on the size/shape of the object Can achieve pad grasp-- possibly 2-point and 3-point pinches.
Proficient prehensile function-	Able to perform highly sophisticated grasp patterns. Can alter individual digits for various objects.
In hand manipulator	Demonstrates the individualization of the digits to move objects within the hand.

Grasping- why/where do we hold items?



Infinite variations of the Human Hand

Object Dependent Hand Use

- Main Factors that influence hand grip and prehension
  - Object shape
  - Size
  - Purpose of the action (holding or manipulating)
  - Weight
  - Relative position (to the center of the wrist)

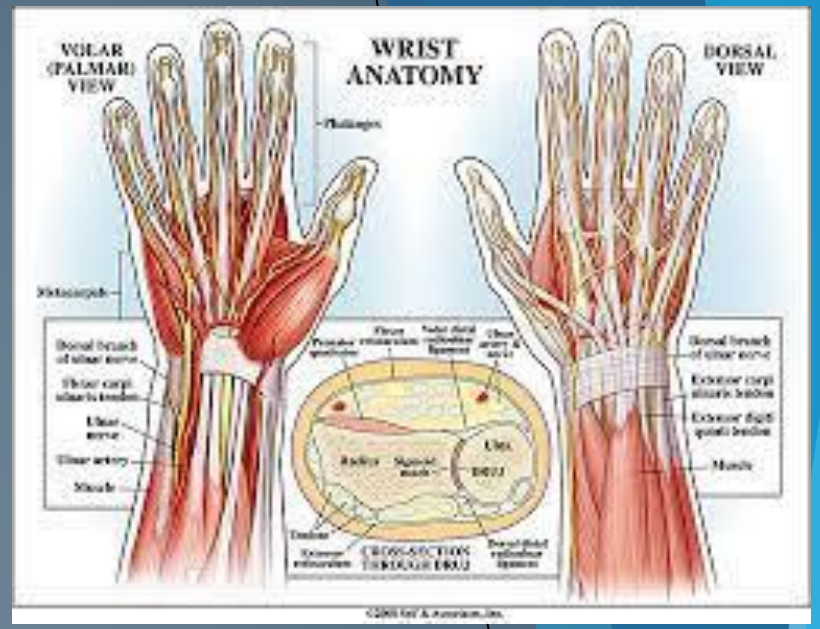
The Wrist

- ***"Without proximal stability, provided by the wrist, the finger flexors are typically rendered ineffective"- Donald Neumann***
  - (Kineseology of the Musculoskeletal System).

- Functions of the wrist in relation to hand function
  - Effective hand placement
  - Load Acceptance
  - Length / tension relationship of the finger flexors and extensors.
    - Extrinsic vs. Intrinsic
  - Assists with kinematics of pronation and supination.

- Is the wrist the primary mover or a stabilizer?

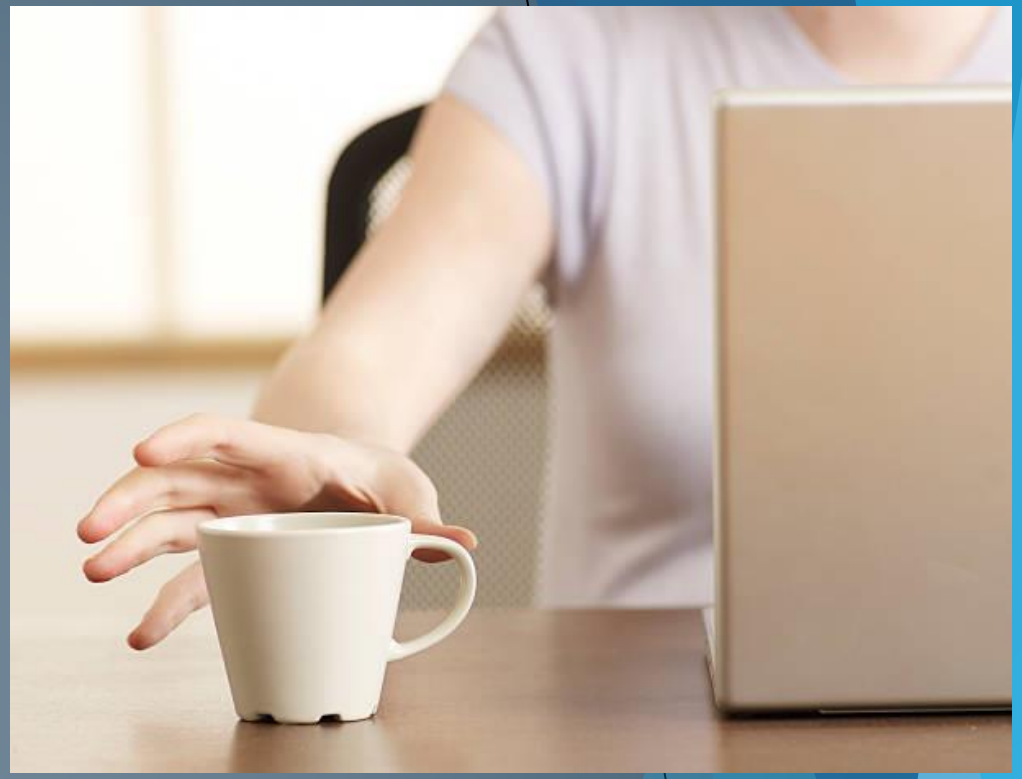
Role of the wrist



- Provides a stable base for functional grasp and release
- Optimal grasp requires active wrist extension
  - Dynamics of the wrist extensors on the finger flexors
  - Finger flexor force increases = Wrist must be able to counter the amount of force to keep a stable wrist
- Object shape and position in space determines the position needed for function.
  - Wrist needs to move in all directions for unlimited hand function
  - Picking up a fork off of a countertop vs. inside a silverware drawer

Role of the wrist

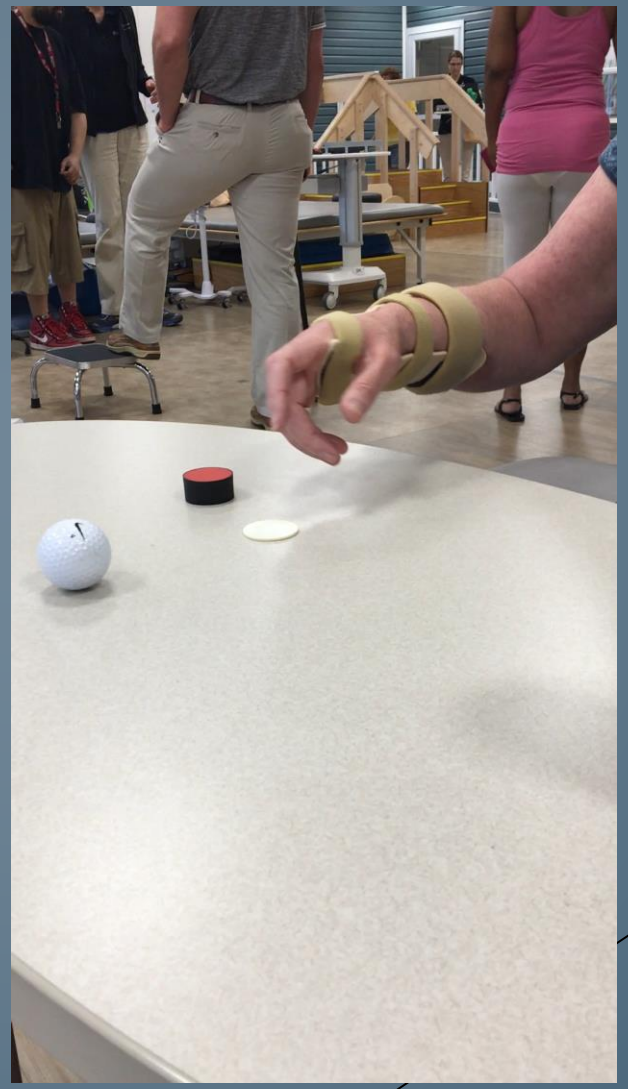
- Active wrist extension is needed
  - Isometric demands
    - Balance of flexors and extensors
      - What occurs during opening of hand?
      - Grasping of object?
      - Release of object?



- Wrist in motion- maintaining “just right” grasp pressure.
  - Finger extrinsic and intrinsic have to adjust their forces as the wrist changes positions
  - Muscle length demands

Wrist Control- Holding, Carrying, Transitions

Wrist Control- Holding, Carrying, Transitions

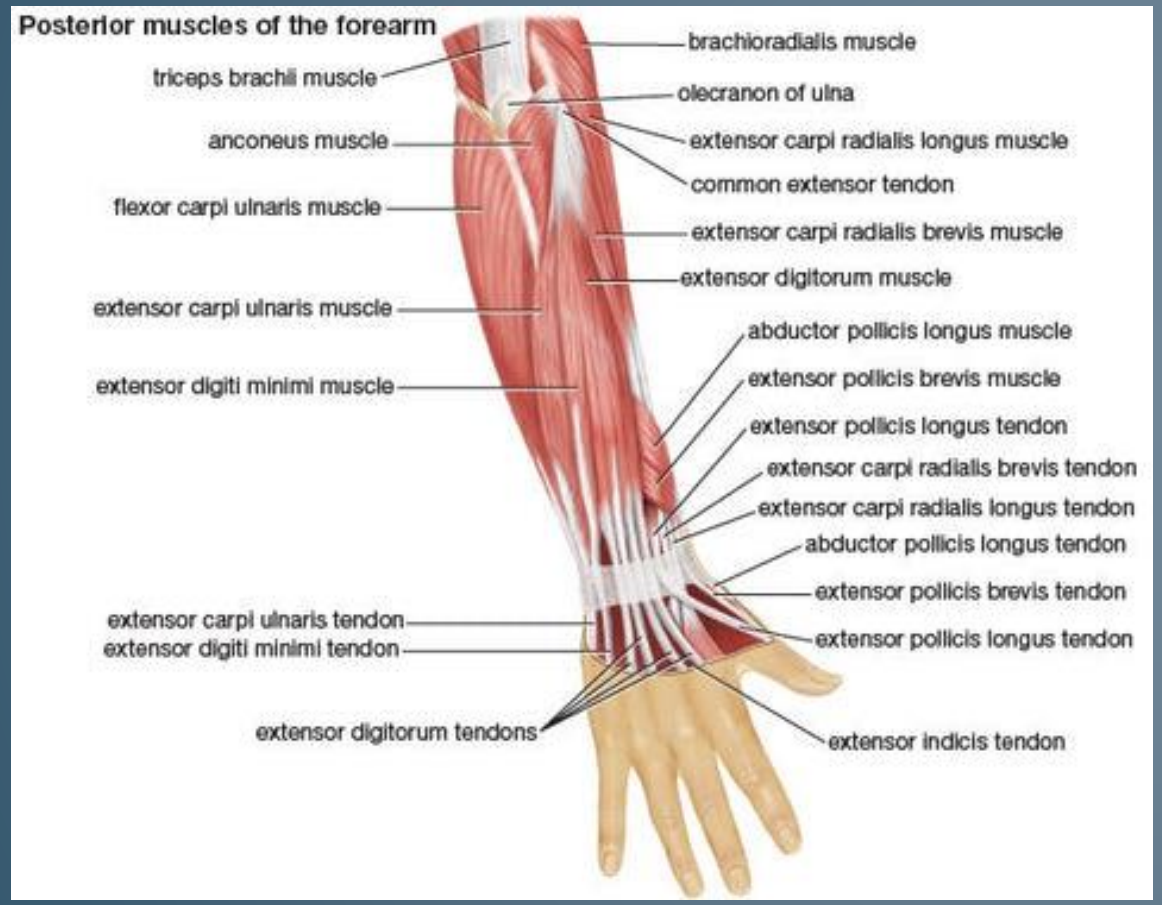


Wrist orthotics to support weakness

Wrist orthotic to support radial weakness. Ulnar gutter style

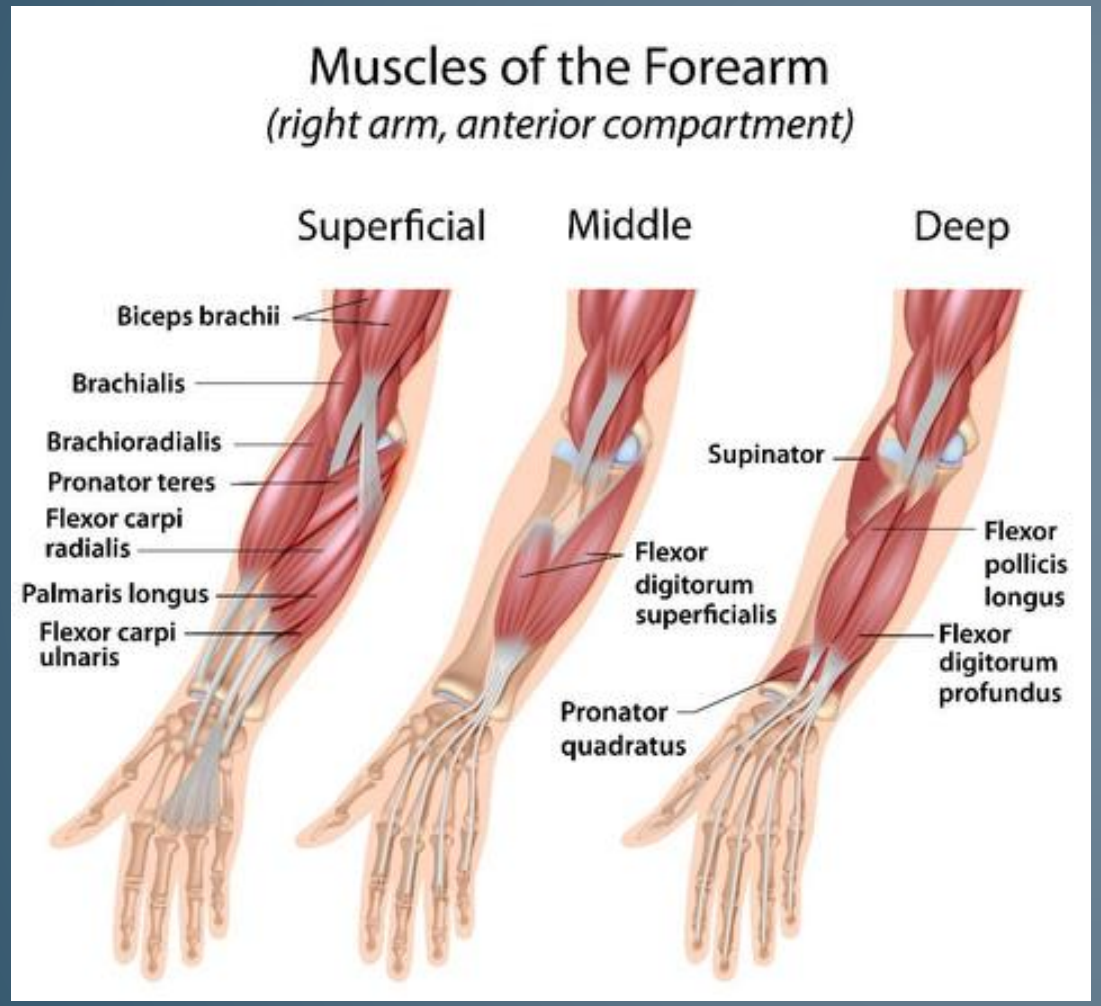
Wrist Control- Holding, Carrying, Transitions

Muscles acting on the wrist



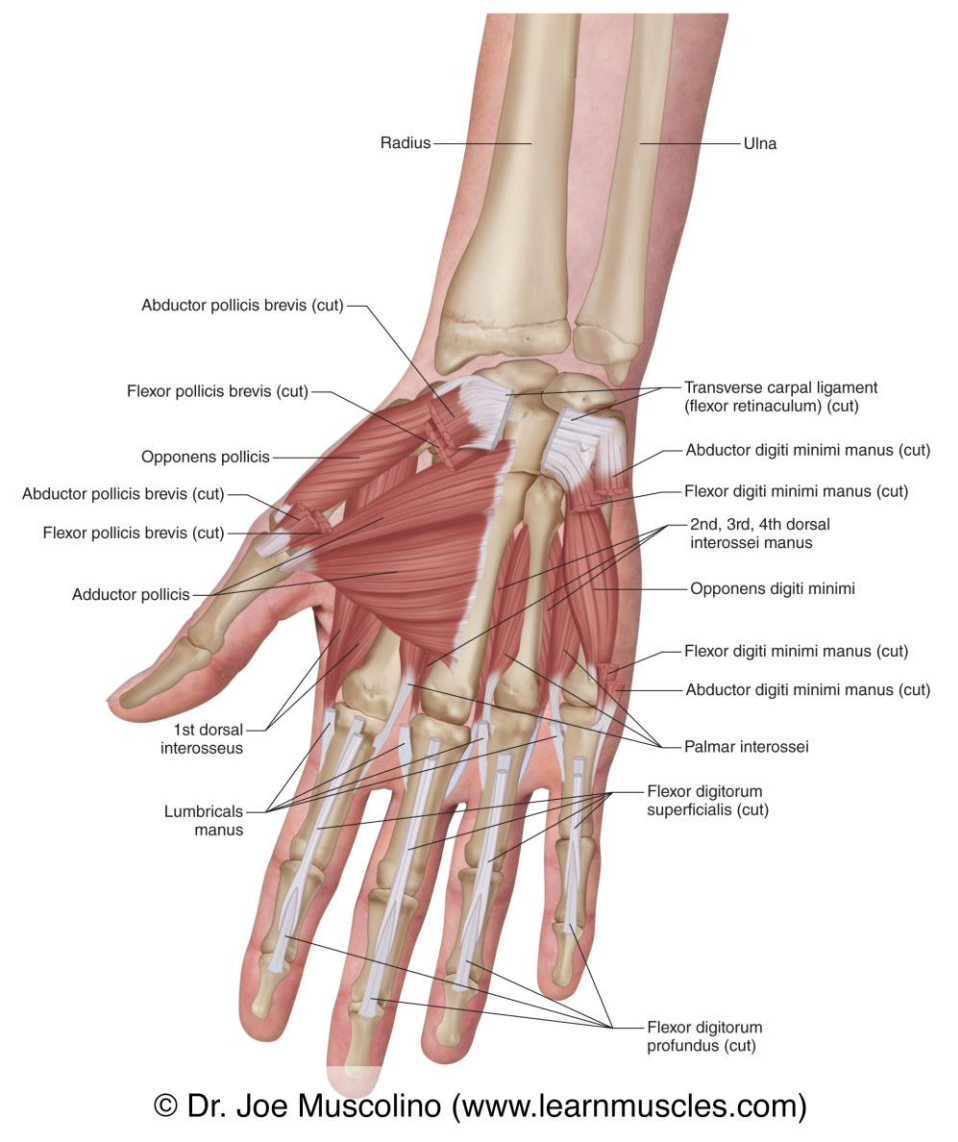
- Primary Muscles for Extension
  - ECRL
  - ECRB
  - ECU
- Secondary Muscles (act on the wrist and hand)
  - ED
  - EI
  - EDM
  - EPC
- Primary Radial Deviators
  - Abductor Pollicis Longus
  - Extensor Carpi Radilais Longus
  - Extensor Carpi Radialis Brevis

Muscles Acting on the Wrist



- Primary Wrist Flexors
  - FCU
  - FCR
  - PL
- Secondary Wrist Flexors- (act on wrist and hand)
  - FDP
  - FDS
  - FPL
  - EPB
  - APL
- Ulnar deviators
  - Flexor Carpi Ulnaris
  - Extensor Carpi Ulnaris

Intrinsic Hand Muscles



- Thenar
  - APB
  - FPB
  - OP
  - AP
- Hypothenar
  - FDM
  - ADM
  - ODM
  - PB
- Digits
  - Lumbricals
  - Interossei

Wrist

- Wrist Extensors:
  - Main Function: Position and stabilize wrist during active gripping
  - Position of Power: 30-35 degrees
    - Strongest grip position.
    - Weak wrist extensors = weak grip!
- Wrist Flexors:
  - Finger flexors also act as wrist flexors but the wrist extensors must be able to

counteract the force of the wrist and finger flexors combined.

  - Wrist / finger flexors produce 70% more power than extensors! .

  - ALL THE REASON TO AVOID FLEXION EXERCISES EARLY!!!
  - ***General rule: No grip strengthening until full finger extension is achieved actively (WITH A STABLE EXTENDED WRIST ~30 DEGREES)***

  - ***General Rule: Tight flexors = No chance.***
    - ***Proactive solutions need to be made early to prevent wrist/finger flexor tightness.***

The Architecture of the Hand

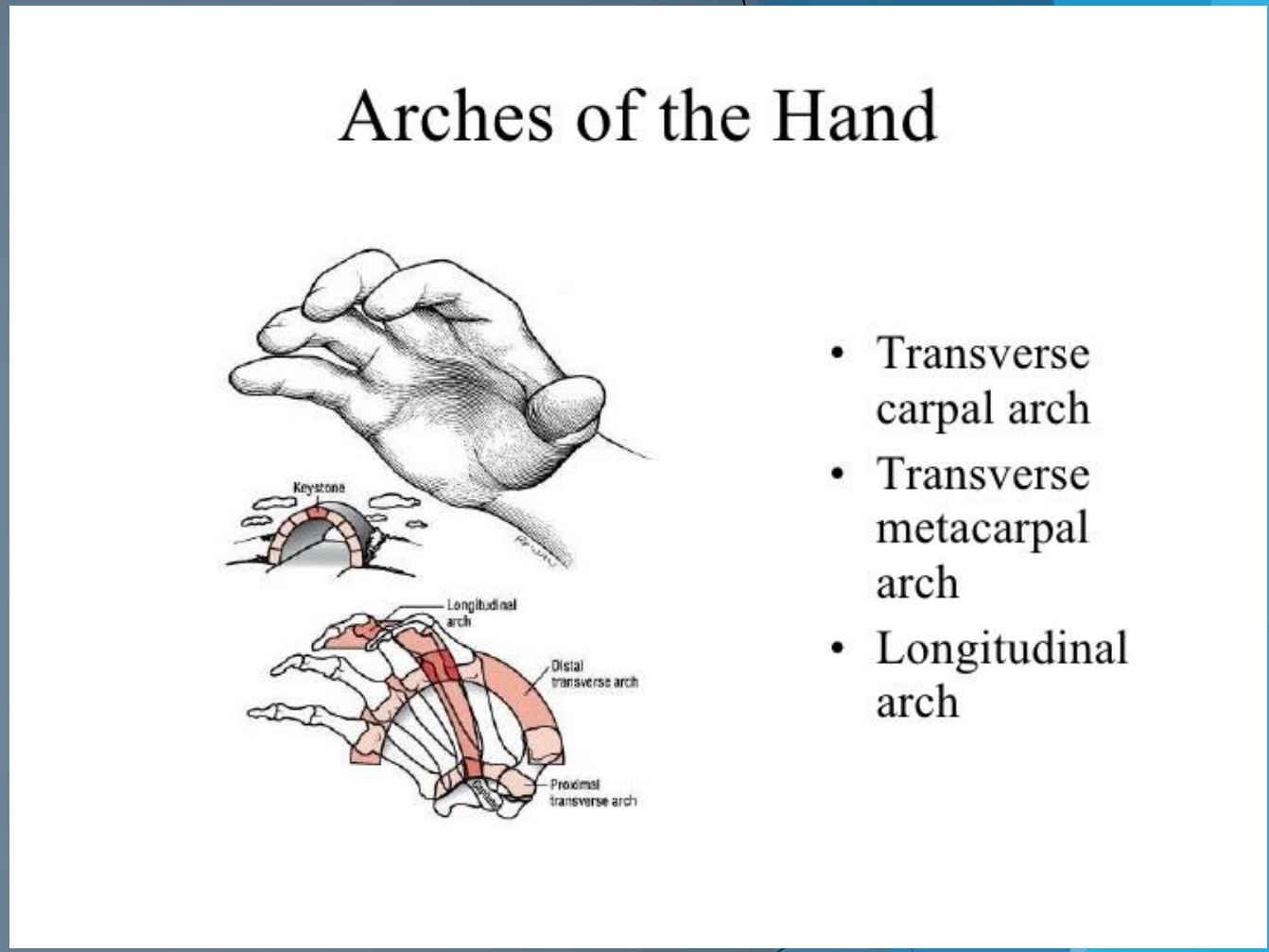
- Grasping objects requires the hand to change shapes.
  - Happens within the palm and the digits of the hand.

- Hand on a flat surface
  - Contact at the thenar & hypothenar emminences
  - The palmar surface
  - Metacarpal heads
  - Metacarpals and digits spread

- Function: Contact of the hand
  - Pushing something away.
  - Support for balance
  - Non grasping

Arches

- Grasping object- the hand/palm hollows
  - Requires 3 axes or arches
    - Transverse
    - The Transverse Carpal arch
      - The Metacarpal arch
    - Longitudinal
      - At each finger with the thumb
      - Allows for point contact with the thumb



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The Arches of the Hand

- Oblique arch- (figure 7- red, 8, 9)
  - The most important is the linking of the thumb and first finger.
  - Most extreme- little finger
    - (functional relevance?)

Carpals and metacarpals-

- Keystone for the functional contours/arching of the hand.
  (the platform for digit opposition/prehension)

- 2nd metacarpal head moves very little

- 4th and 5th metacarpals move significantly
  - Thus- we need to maintain mobility in the lateral metacarpals to allow for functional grasping
  - Last 3 move anteriorly and slightly lateral

- What happens if we are unable to hollow the palm?
  - Flat hand architecture

Hollowing Concavity of the Palm

- Radial aspect of the hand
  - Thenar
  - Metacarpals 1,2,3
- Midpoint aspect of the hand
  - Metacarpals 2-3
  - Little mobility (rotation)
    - Z axis
- Ulnar aspect of the hand
  - Hypothenar
  - Metacarpals 4-5
  - High degree of mobility (rotation)
    - Z axis
- Hand concavity: conforms to the shape of the object in a way that will provide adequate grip forces for the desired task.

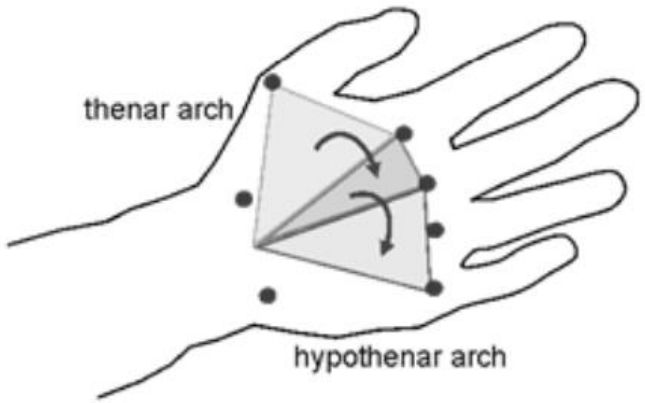


Figure 6. Kinematic palmar arch of the hand. The kinematic characterization of the palmar arch captures the hollow concavity of the palm by capturing the articulation between three planes. The thenar arch is defined by the articulation of two intersecting planes: carpus-index MP-middle MP; carpus-thumb MP-index MP. The hypothenar arch is formulated by the articulation of two intersecting planes: carpus-index MP-middle MP; carpus-middle MP-little MP.

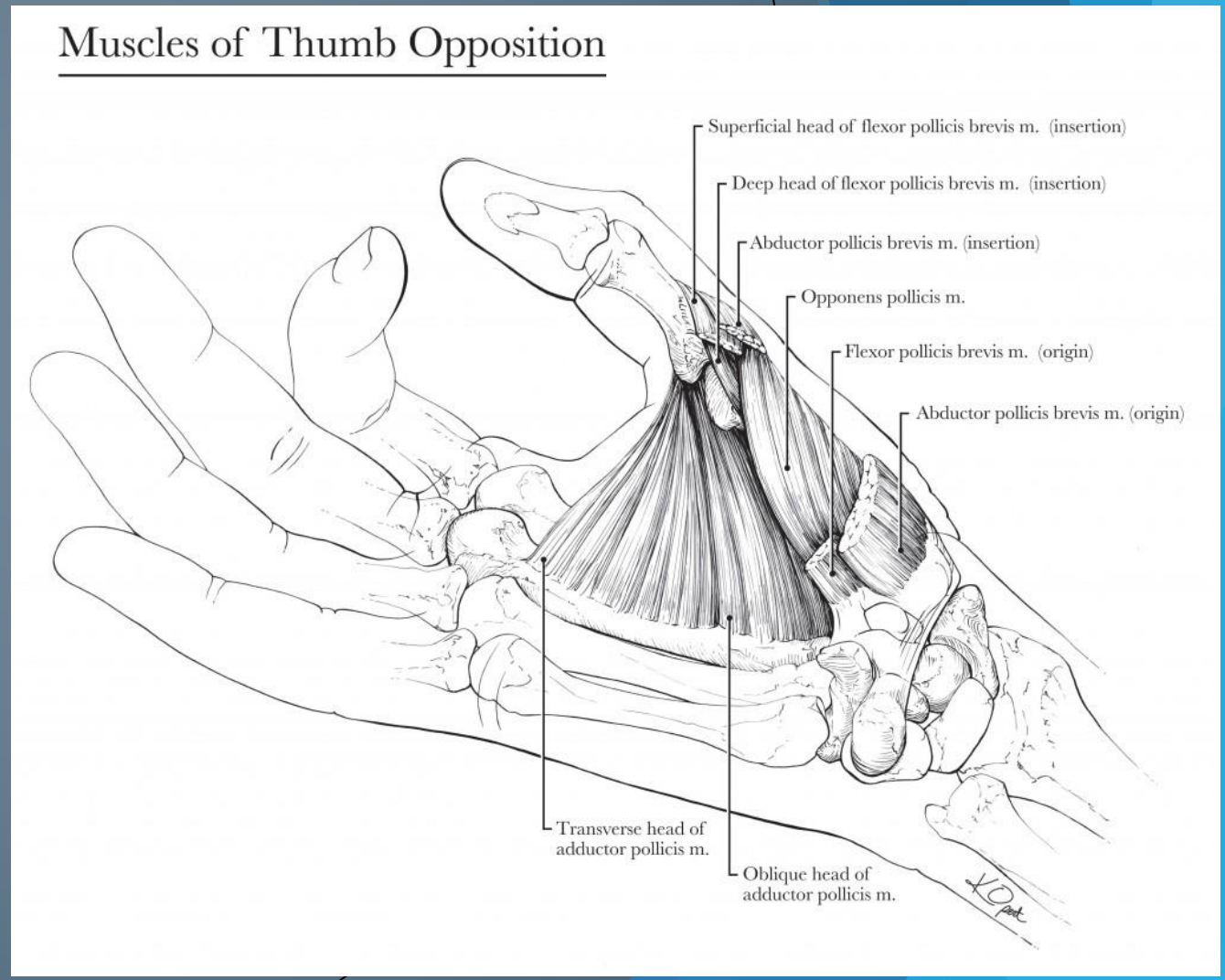
Thenar compartment of the arch

- Requires 3 Elementary Movements at the 1st metacarpal
  - Thumb extension (radial plane)
  - Thumb Abduction (palmar plane)
  - Rotation (medial in direction)

- Thumb itself has 5 degrees of freedom of movement.

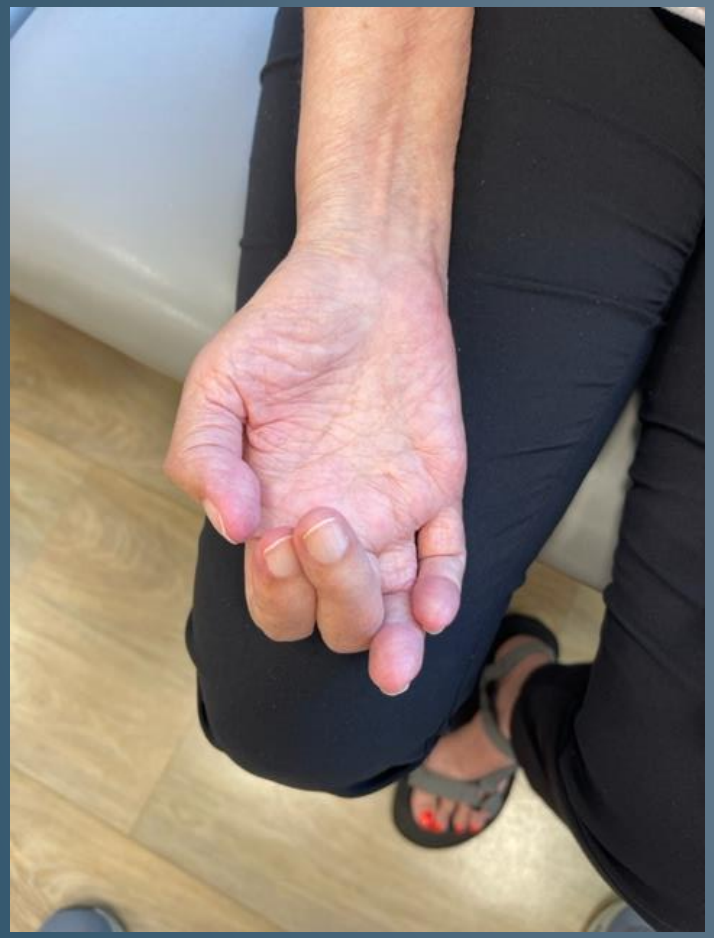
AP and OP: Place the thumb into isometric position of opposition.

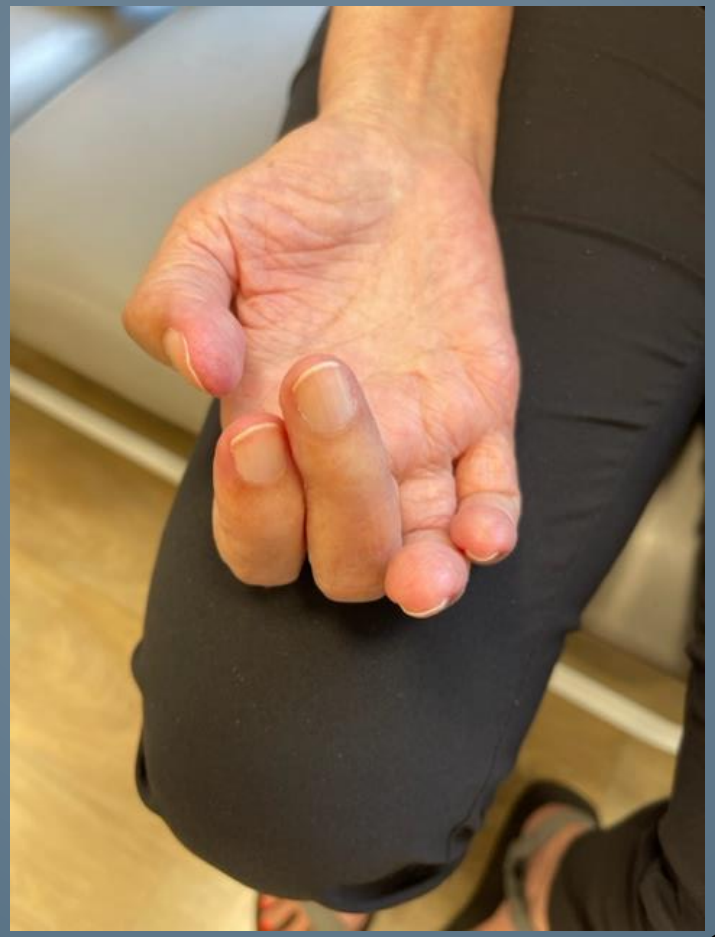
- Flexors/Extensors act as movers while the AP/OP maintain isometric position



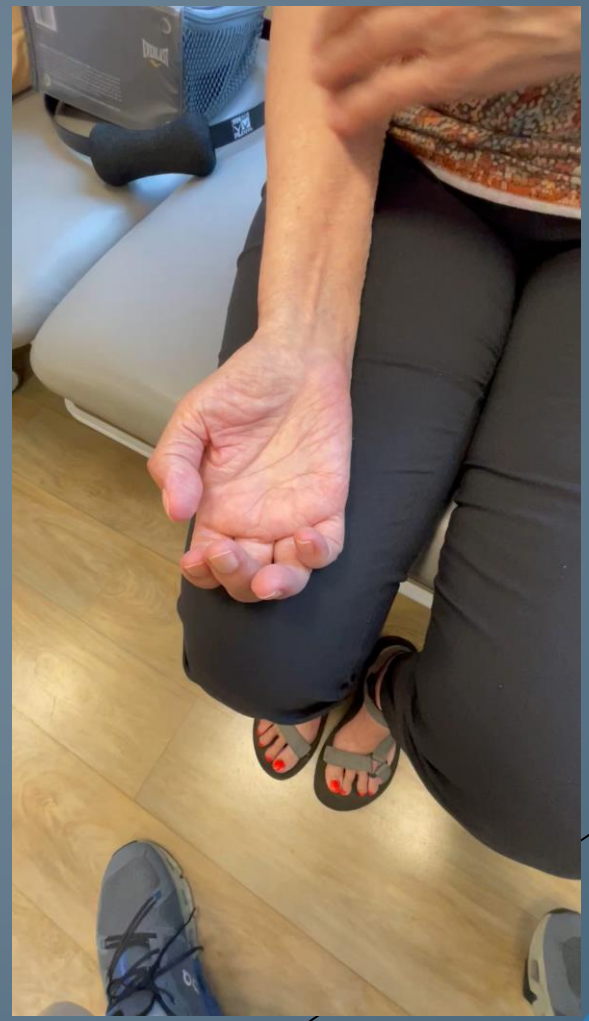
The plane of opposition vs. “the plane of the palm”

- Insert hand photo





Building that Arch
Building Thumb out of the “Plane of the palm”



Achieving opposition- Not just the thumb

- Observe the radial aspect of the hand vs. ulnar.
  - Motion of the 1st metacarpal vs. 4/5 metacarpals

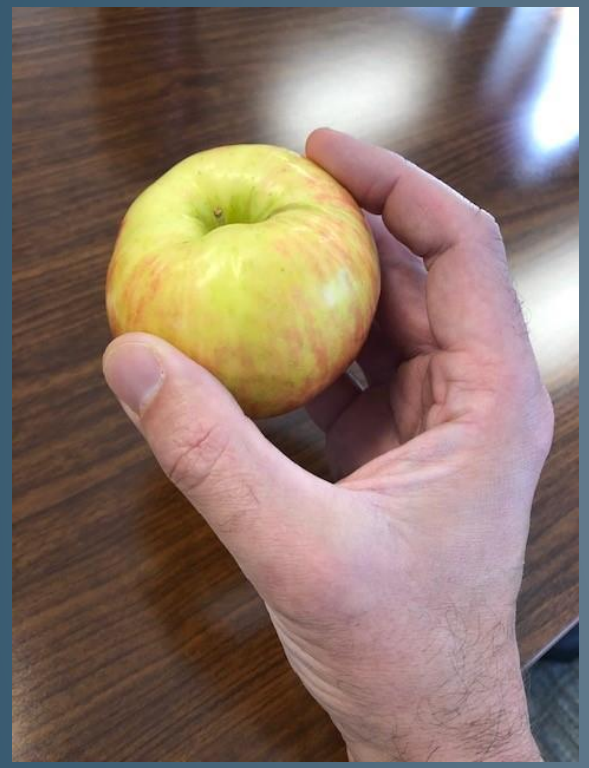
Opposition of the thumb

- Critical for the ability to achieve skilled grasps
  - Cylindrical grasps
  - Pinching/prehension
  - Effortless Graded grasping

Grading of force

- Functional Grasping-
  - Sophisticated balance of flexion and extension on objects at all times.
    - Requires a high degree of sensation
    - Requires the ability to selectively activate or inhibit the flexors/extensors.
      - Extrinsic and intrinsic forces

Analyze the Arches/Hand shaping

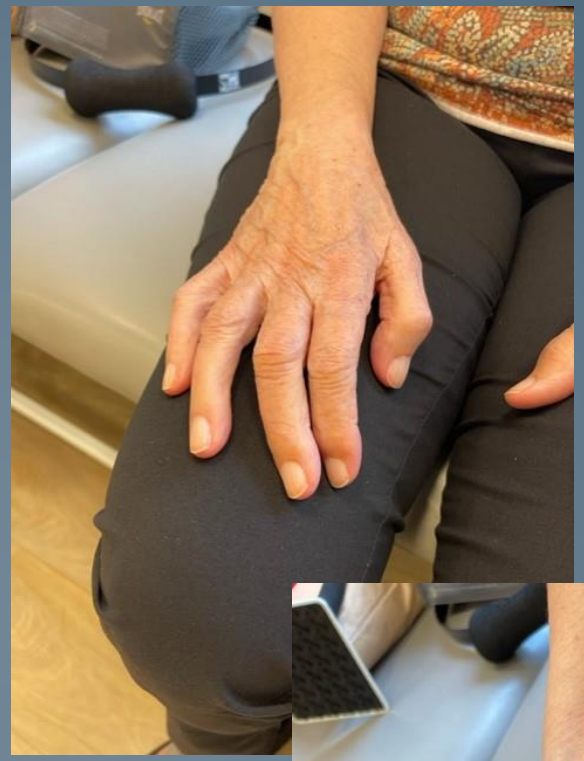


- What is the radial aspect of the hand doing?
- What is the ulnar aspect of the palm and hand doing?
- Where is the object stabilized?
- How much flexion / extension is occurring at the MCP/IP's in D2-5
- How much flexion / extension is occurring at CMC/MP/IP
- How much medial rotation is occurring at the thumb metacarpal?

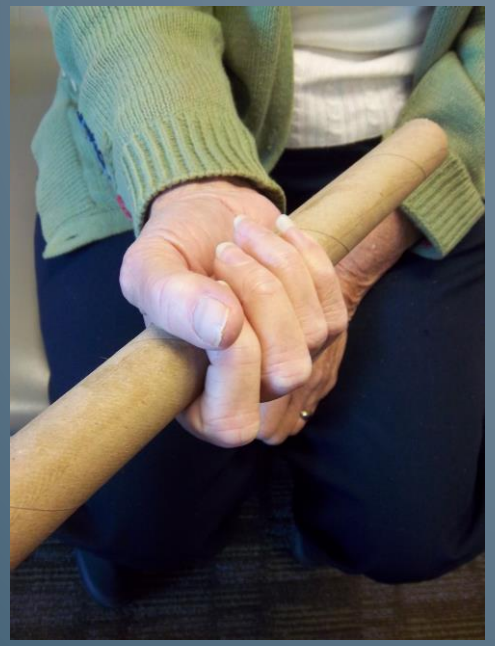
The Weak Flattened Hand

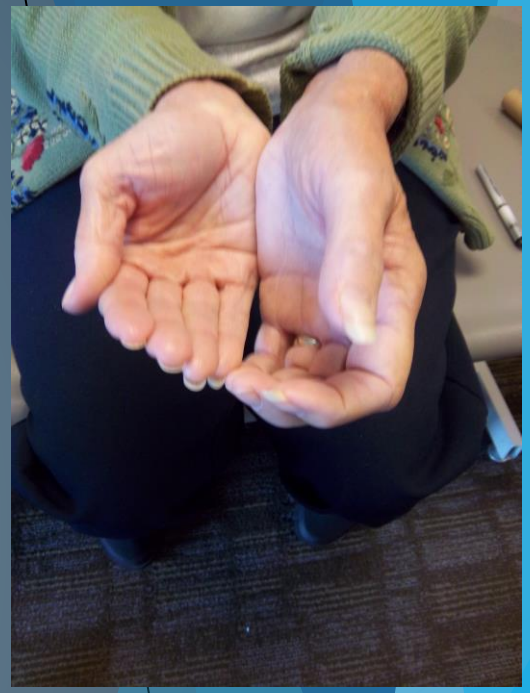
- When both thenar and hypothenar muscles are weakened-
  - flattening of the transverse palmar arch occurs.
  - Postural dysregulation of the hand

- Thumb- purpose—placed in a position of opposition
  - To allow tip to tip contact with each finger.
  - Specific to humans
  - Allows adaptability of the hand



Power Grasp- Break down in the Oblique Arch



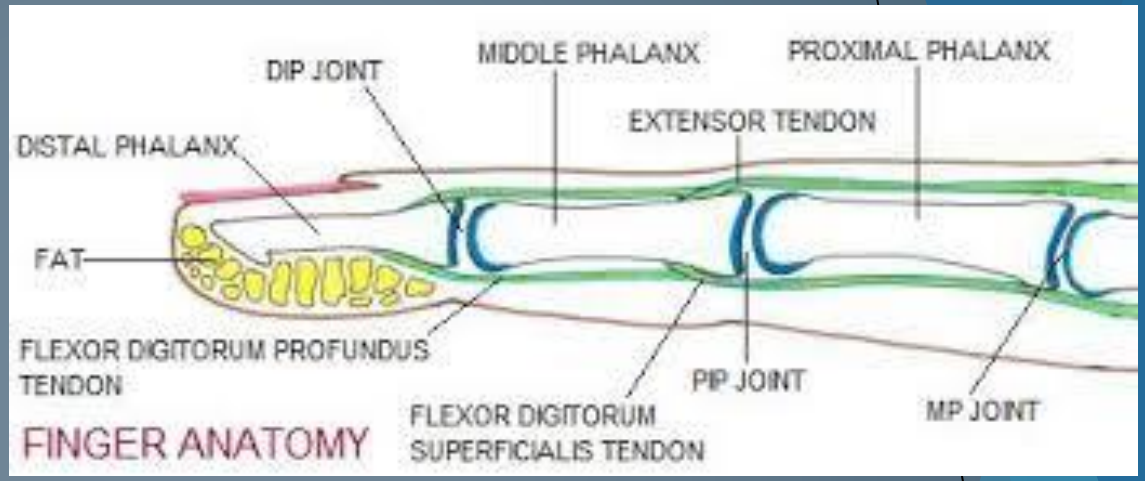


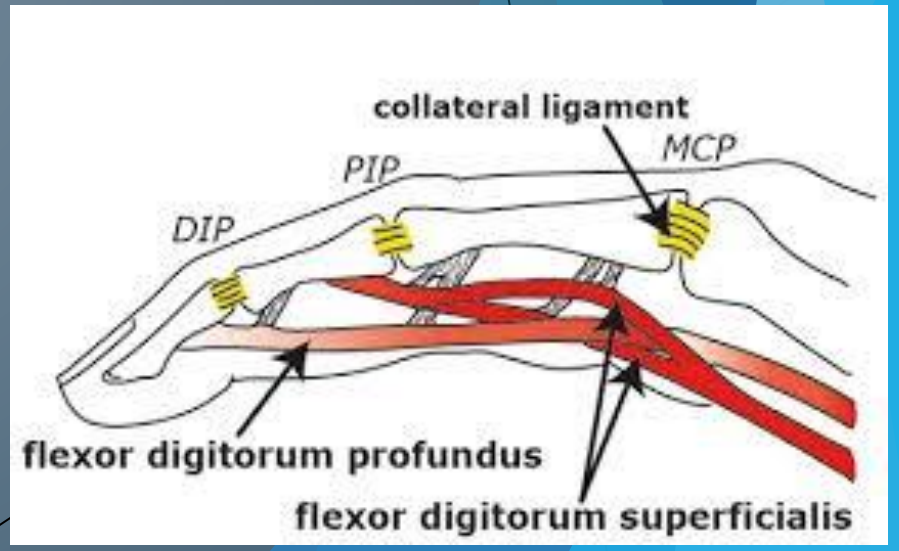
Oblique Arch= Power Grasp's Bestie

- Where is the object stabilized in this patient's hand?
- What is the dynamic in joint(s) in this video?
- What components of distal function need to be improved by watching this short video?

Muscle action of the fingers- Flexion

- How do we close the hand?
  - Long flexors- FDP/FDS primary
    - Flex the PIP (FDS)
    - Flex the DIP (FDP)
    - Flex the MP's- only after the IP's are flexed
      - Last pulley in the line
  - Intrinsic action of the hand
    - Primary flexor of at the MP joint



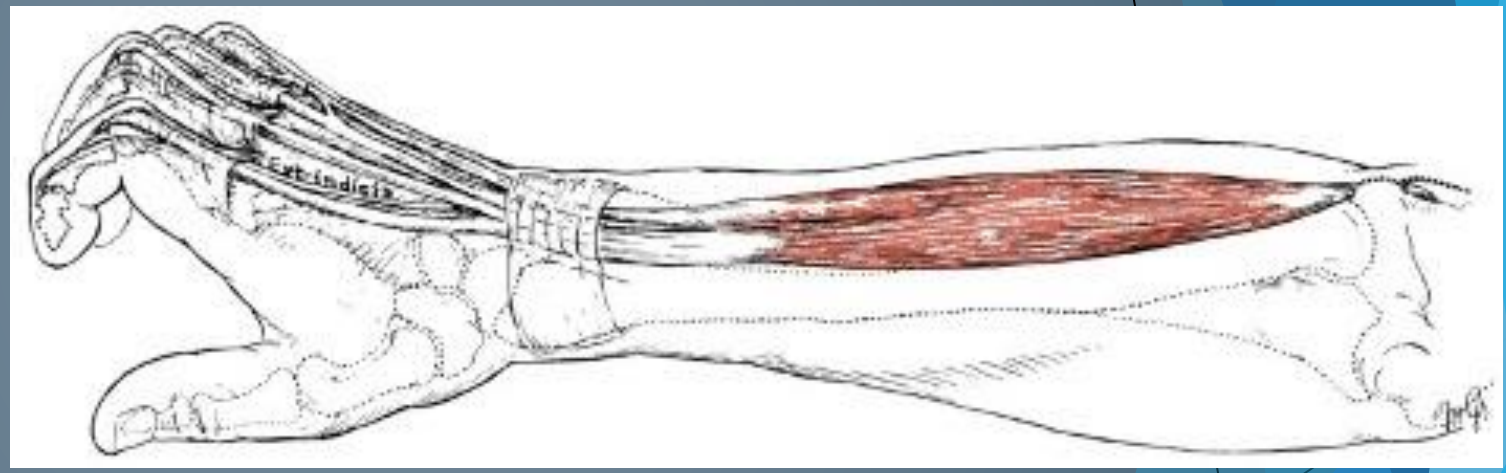


Muscle action of for finger extension

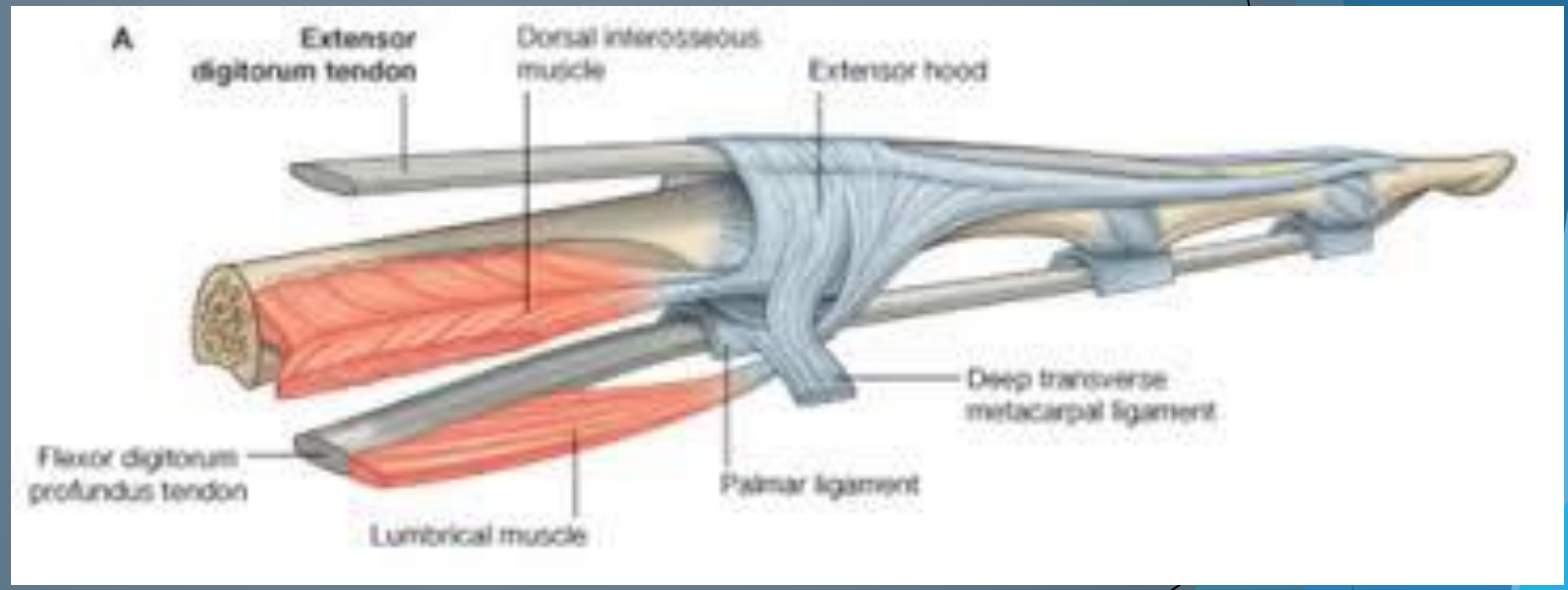
- Extensor Digitorum Communis (EDC)
  - Distal tendon insertion
    - Extension at the MCP

    Joint only
    - Crosses the PIP joint

    Causing flexion at P2



How do we extend the IP's?
Action of the extensor mechanism



Muscle action for finger extension

- Complex synergistic action of:
  - Extensor Digitorum
  - The Interossei (DABs and PADs)
  - Lumbricals
  - Wrist stabilizers

Anybody remember the extensor hood?

Simplified- As one joint flexes, the anatomy of the tendons either block or allow flexion/extension of the of other joints.

Developing Finger Extension

- Finger extension is driven primary by the Corticospinal Tract.
- Finger flexion can be volitional (driven by the CST)
  - or confused as spasticity.

- ***Hint: If you patient can develop finger extension and wrist extension- they will more than likely have no problem with the flexors.***

- Tightness and spasticity of the wrist flexors.
  - Greatest resistance to opening the fingers.

- Reciprocal Innervation
  - To initiate finger extension→ We must first inhibit wrist and finger flexion.

- Finger extension: Force couple of extrinsic extensors and intrinsic extensors
  - Extrinsic = EDC

Hand shaping

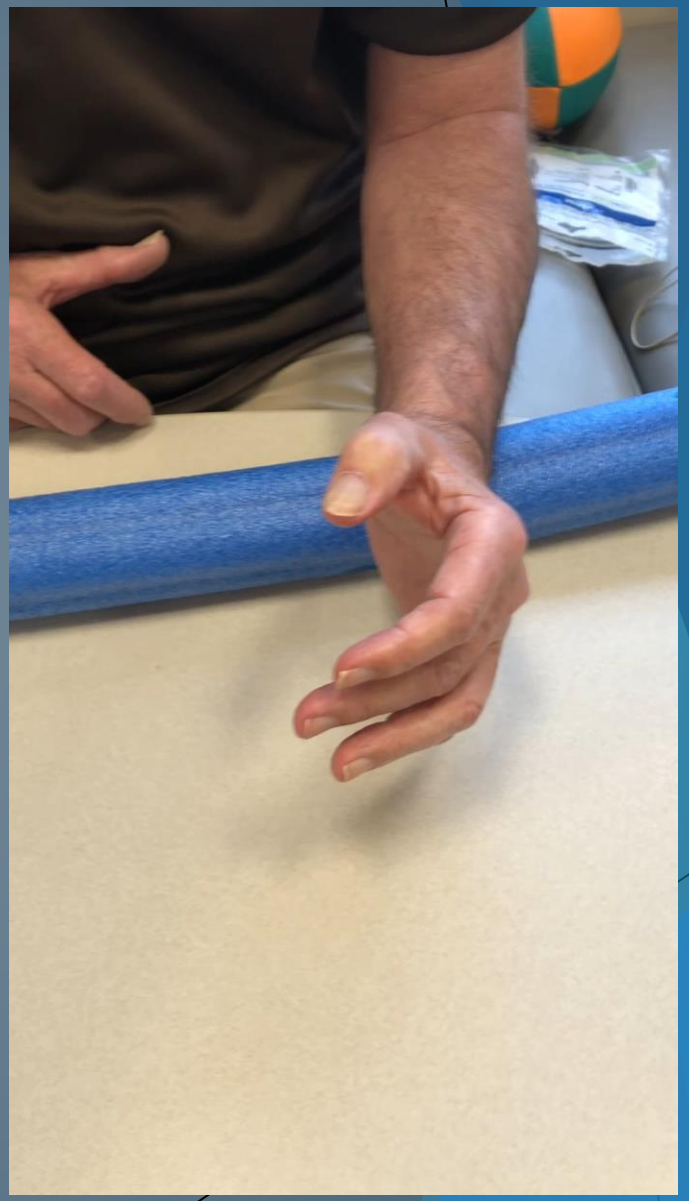
- The size and shape of the object dictates:
  - The degree of finger span to retrieve the object.
  - The action of the hand to hold the objects with the least amount of effort.
    - What arch characteristics are needed?
    - Where is the best place in the hand to stabilize the object?
  - Is the method your patient is using to hold an object efficient?
    - Compare affected hand vs. non-affected for movement analysis.

Hand Aperture:

- Span (Aperture)
  - When the digits need to spread the largest distance away from each other
    - Important for grasping large objects
      - Palming a basketball
      - Piano

Object Retrieval

Thumb and fingers moving Simutaneously



Assessment of Grasp and Hand Function

- **Wrist and Forearm**
  - What is position of the wrist for object/function
  - Neutral pronation/supination? Position of pronation needed? Supination?
- **Object stability**:
  - Where is the contact of the object stabilized?
- **Position of the thumb**
  - What position is the thumb in for this object/function?
- **Arches of the hand**
  - How do the arches of the hand support this object?
  - Radial aspect vs. ulnar
- **Strength demand**
  - How much strength is needed for this grasp
  - Where is strength needed?
    - Grasp, Wrist, Proximal joints ?
- **Flexion/Extension demands of the MCPs, PIP's and DIPs**
- **Mobility :**
  - What is the mobile joint (s)

Defining Grasp purpose and type

- Nappier (1996)
  - Grasps are divided into Power and Prehension
  - Power= stability
  - Prehension= fluidity

- ***Non-prehensile*** – object is not gripped.
  - Platform
  - Contact motion

- ***Grasp***- Stable relationship between the hand and object

- ***Prehensile-*** Seized, held partly or wholly
  - Including grasp and manipulation.

- ***Manipulation***
  - Motion occurring within the hand

TABLE 1 | Some significant definitions of human hand movement.

Researcher	Definition					
	Object shape		Hand surface			Hand shape
Schlesinger's classification 1919	Cylinder	Sphere	Tip	Palmer	Lateral	Hook
						

Napier (1956)	**Prehensile:** object is seized and held partly or wholly		
	Non-prehensile: object is lifted or pushed, and no grasping or seizing is involved		
	Action goal: requirements for accomplishing the task		
	Action goal	Power	Hold objects stably
		Precision	Pinch small or large objects, or impart the motion of objects
Kamakura et al. (1980)	**Contact areas:** the contact area between hand and object while grasping without changing contact		
	Grip contact areas	Power	Wide, including a part of the palm, almost entirely on the volar side
		Intermediate	Including radial aspects of index, middle finger, palm is not included
		Precision	Between the pulp or tip of the fingers and that of the thumb
		No thumb	On opposition sides between fingers, thumb is not involved

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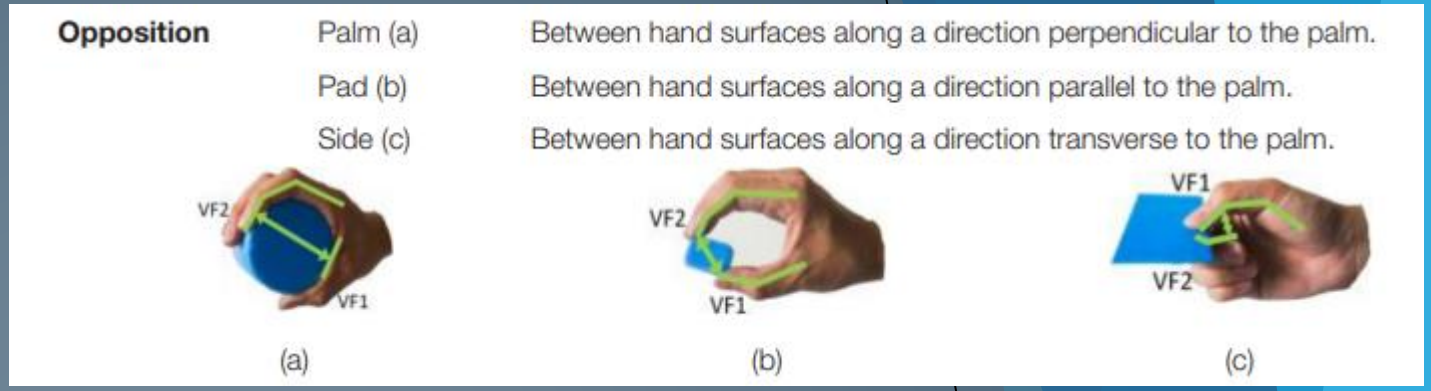
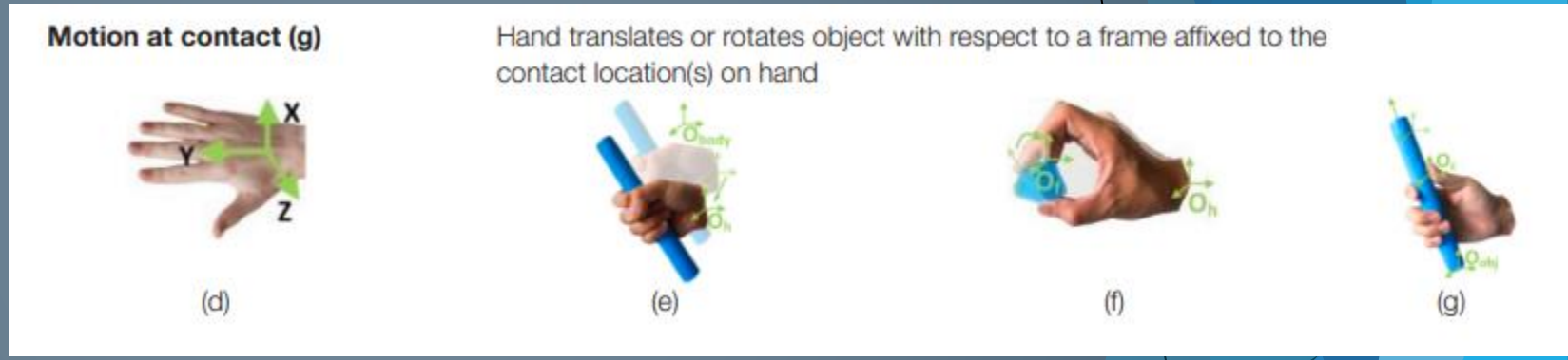
Figure 2: Selected grasps and corresponding objects for small and large object sizes.

Types of Grasps

- Palmar
- Hook
- Lateral
- Cylinder
- Spherical
- Pinch
- Combos: Think Coffee Mug





Types of Grasp

Complexity of Grasps-- Depends on:

- Variety of muscles needed
- Contact of the palm or finger pads needed
  - Distance from palm = more complex
- Position of the thumb

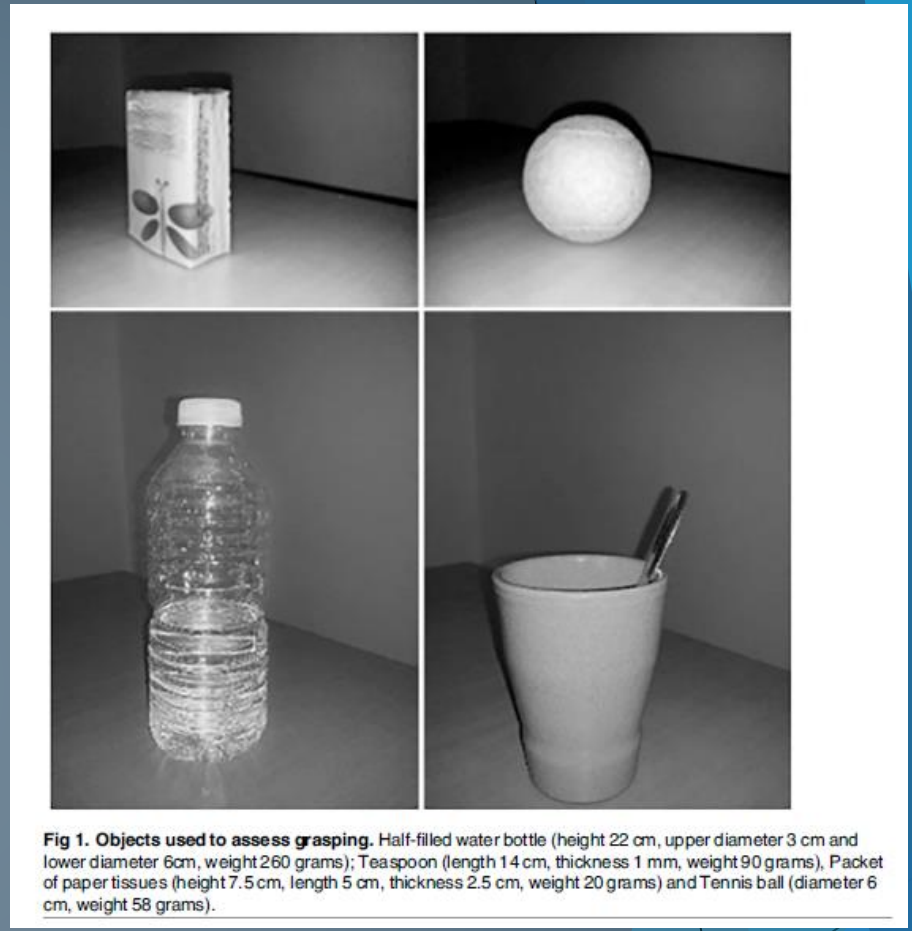


Fig 1. Objects used to assess grasping. Half-filled water bottle (height 22 cm, upper diameter 3 cm and lower diameter 6cm, weight 260 grams); Teaspoon (length 14 cm, thickness 1 mm, weight 90 grams), Packet of paper tissues (height 7.5 cm, length 5 cm, thickness 2.5 cm, weight 20 grams) and Tennis ball (diameter 6 cm, weight 58 grams).

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Figure 2: Selected grasps and corresponding objects for small and large object sizes.

Types of Grasp

- Modes of prehension
  - ***Bidigital-*** use of two finger. Classic pincer.
    - Pulp to pulp- used for larger items (pencil)
    - Tip to tip- used for very thin items (coin, paper)
    - Pulp to side (lateral)- (coin)
  - ***Interdigital-*** only grip that does not include the thumb
  - ***Plural***- Digital- involves thumb and more than one other finger
    - Tri-digital
    - Tetra-digital
    - Penta-digital- use all of the fingers with the thumb in various positions of opposition
  - ***Dynamic movement-associated grips***- object is stabilized in the hand somehow with the digits moving to manipulate part of the object.
    - Lighter, spray bottle, tying a knot

Hand grasp/ prehension taxonomy

Includes grasp and manipulation

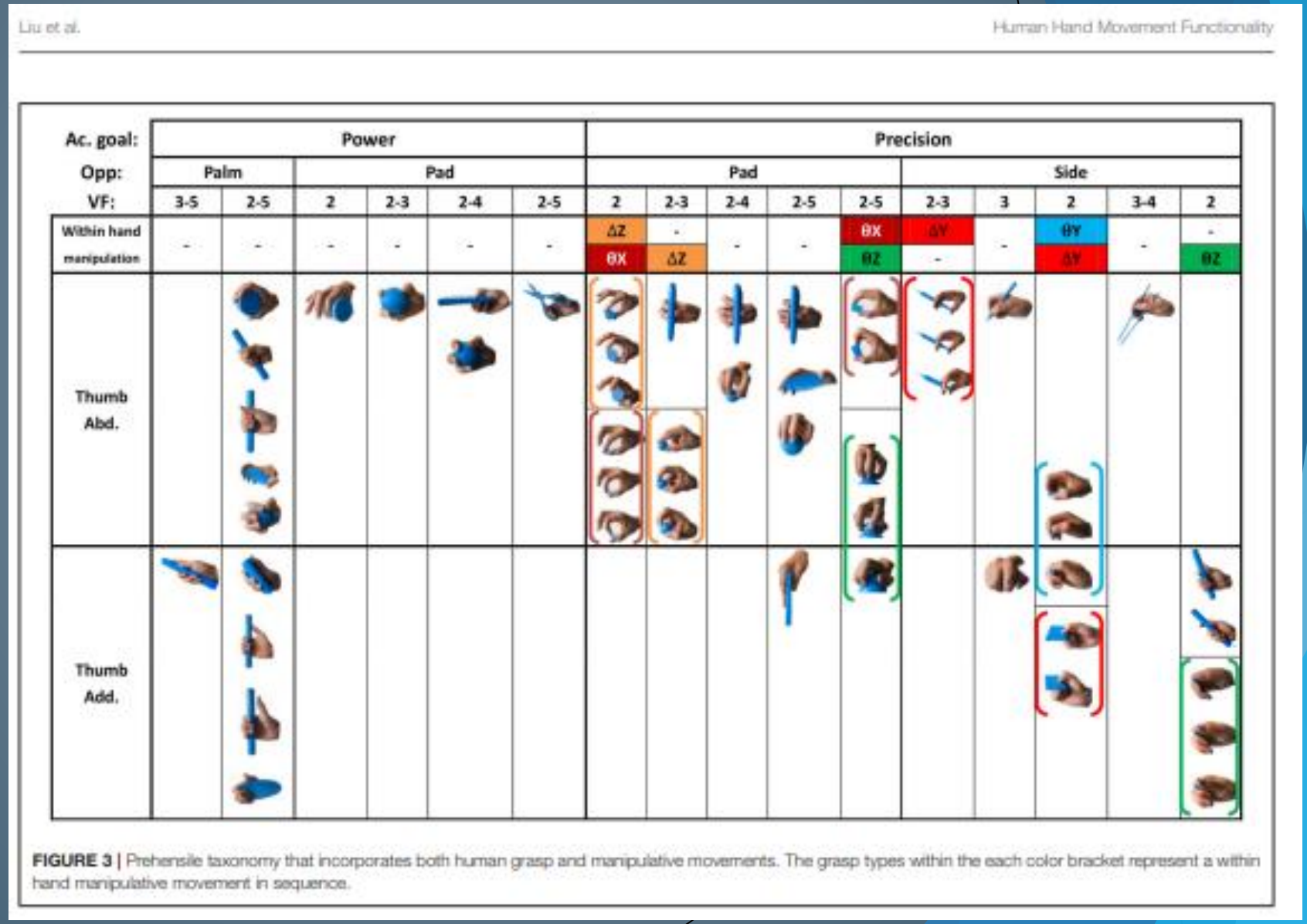


FIGURE 3 | Prehensile taxonomy that incorporates both human grasp and manipulative movements. The grasp types within the each color bracket represent a within hand manipulative movement in sequence.

Taxonomy of cylinder prehension

- Thumb position varies
  - Abducted position
  - Adducted position
- Sequence of lifting
  - Follow the gold brackets

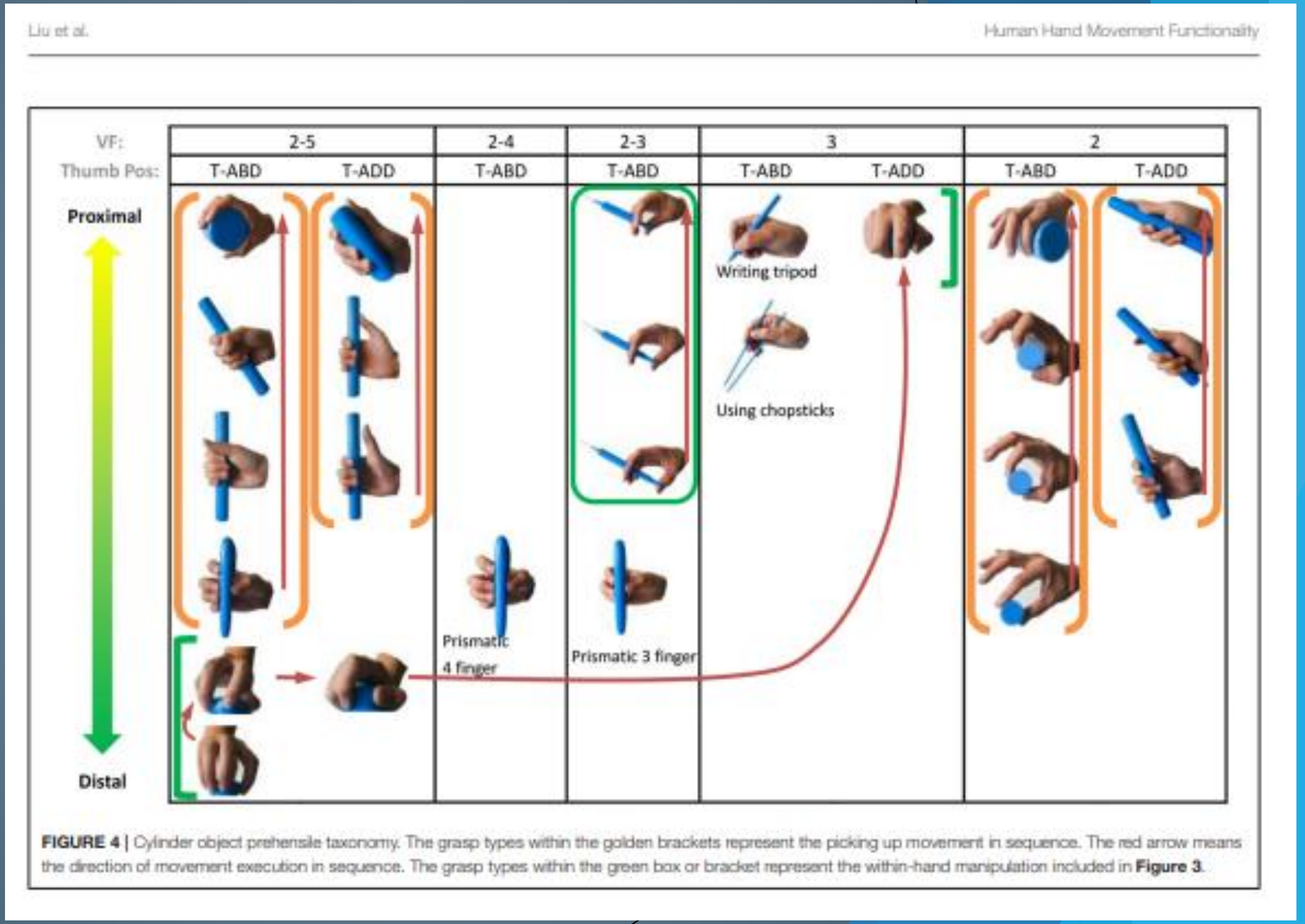


FIGURE 4 | Cylinder object prehensile taxonomy. The grasp types within the golden brackets represent the picking up movement in sequence. The red arrow means the direction of movement execution in sequence. The grasp types within the green box or bracket represent the within-hand manipulation included in **Figure 3**.

Taxonomy of Sphere Prehension

- Thumb position varies
  - Abducted position
  - Adducted position
- Sequence of lifting
  - Follow the gold brackets

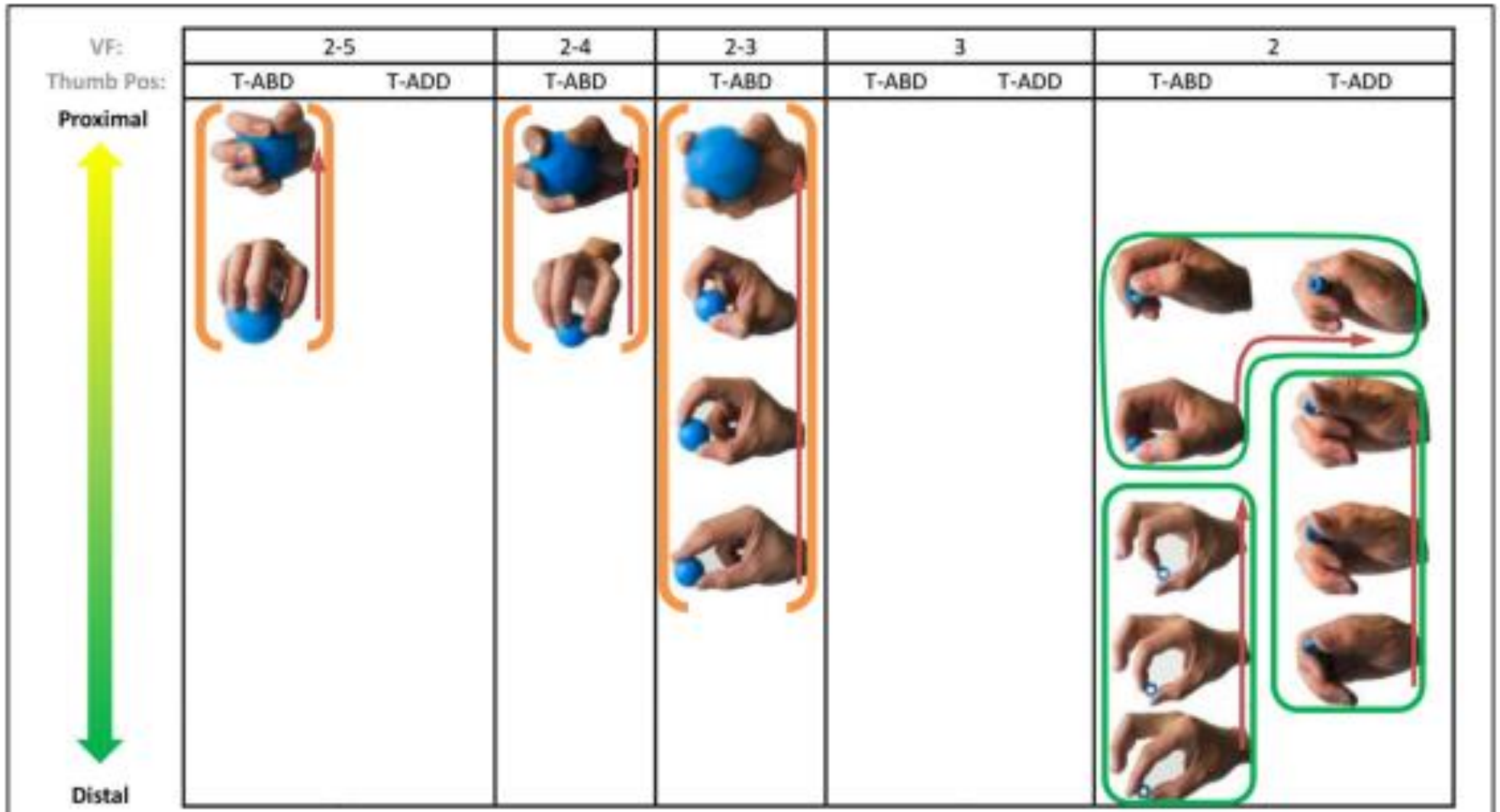


FIGURE 5 | Sphere object prehensile taxonomy. The grasp types within the golden brackets represent the picking up movement in sequence. The red arrow means the direction of movement execution in sequence. The grasp types within the green box or bracket represent the within-hand manipulation included in **Figure 3**.

Taxonomy of the Flat Object Prehension

Thumb position varies
- Abducted position
- Adducted position

Sequence of lifting
- Follow the gold brackets

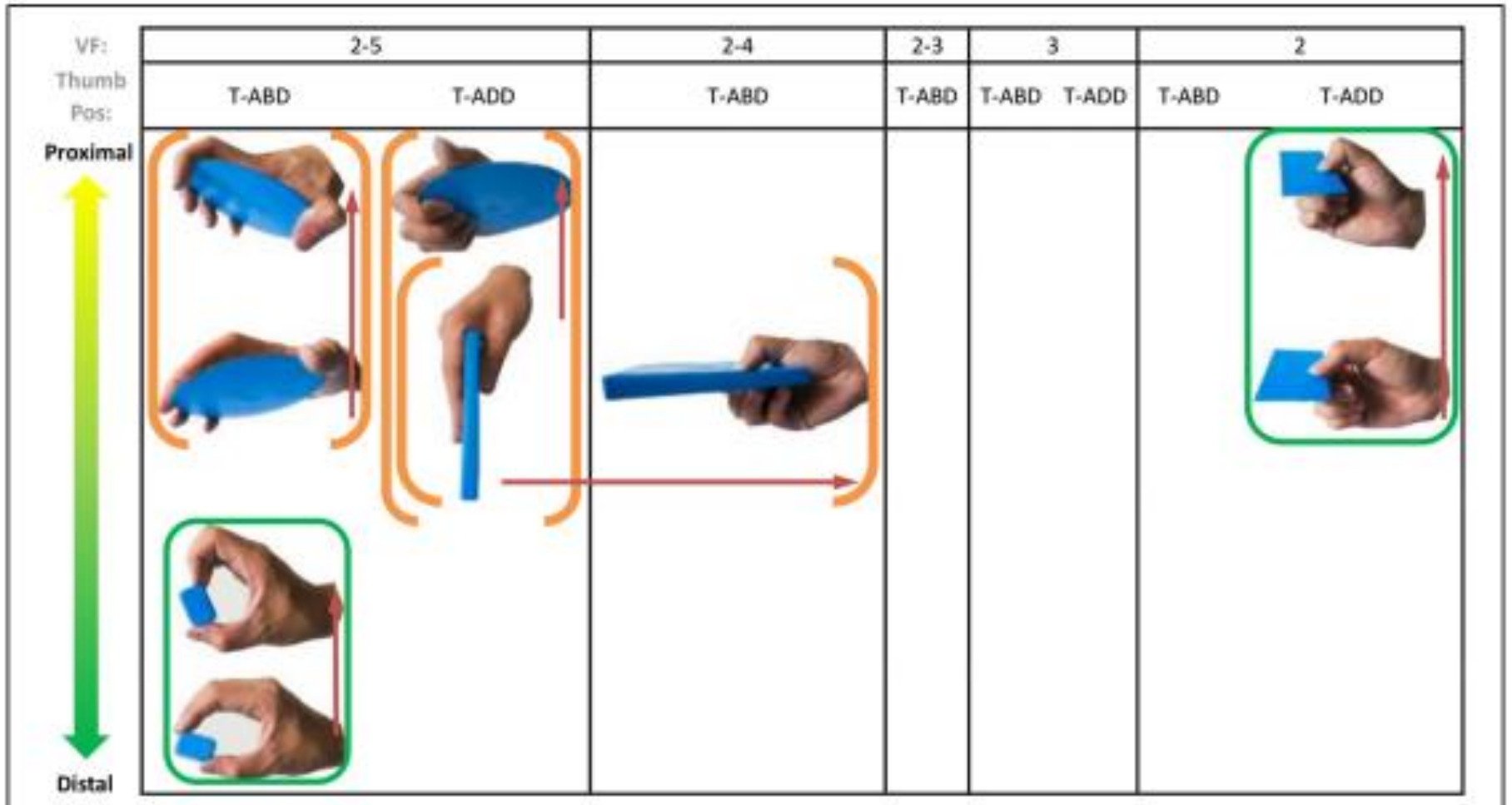
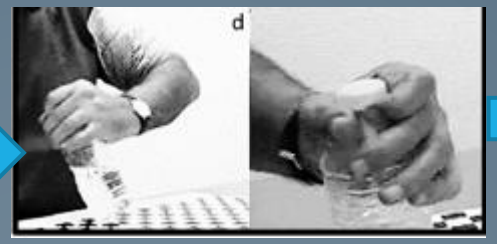


FIGURE 6 | Flat object prehensile taxonomy. The grasp types within the golden brackets represent the picking up movement in sequence. The red arrow means the direction of movement execution in sequence. The grasp types within the green box or bracket represent the within-hand manipulation included in **Figure 3**.

Complexity of Grasp Types

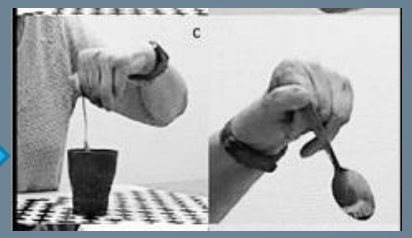
Grip Complexity

- Palmar Contact



- FDS and FDP can be used indiscriminately.
- Requires little force grading

- Lateral Pinch



- Can be performed primarily with thumb flexors only or adductor
- Additional precision if IP stays extended

- Finger pad contact with thumb opposition

- Requires balance of extrinsic flexors and intrinsic to choose degree of flexion/ext needed at each joint
- Requires grading of force
- Requires thumb intrinsic to allow for opposition

- 2-point and 3-point Pinches

Requires all of the skills needed for Finger pad + selective shaping of the hand + selective finger differentiation

Grasp Selection

- Purpose of the function
  - Hold
  - Transfer
  - Within hand manipulation
  - Hybrid
  - Platform
  - Rest
  - Contact
  - Free Motion

- Degree of Involvement from the Wrist and Arm

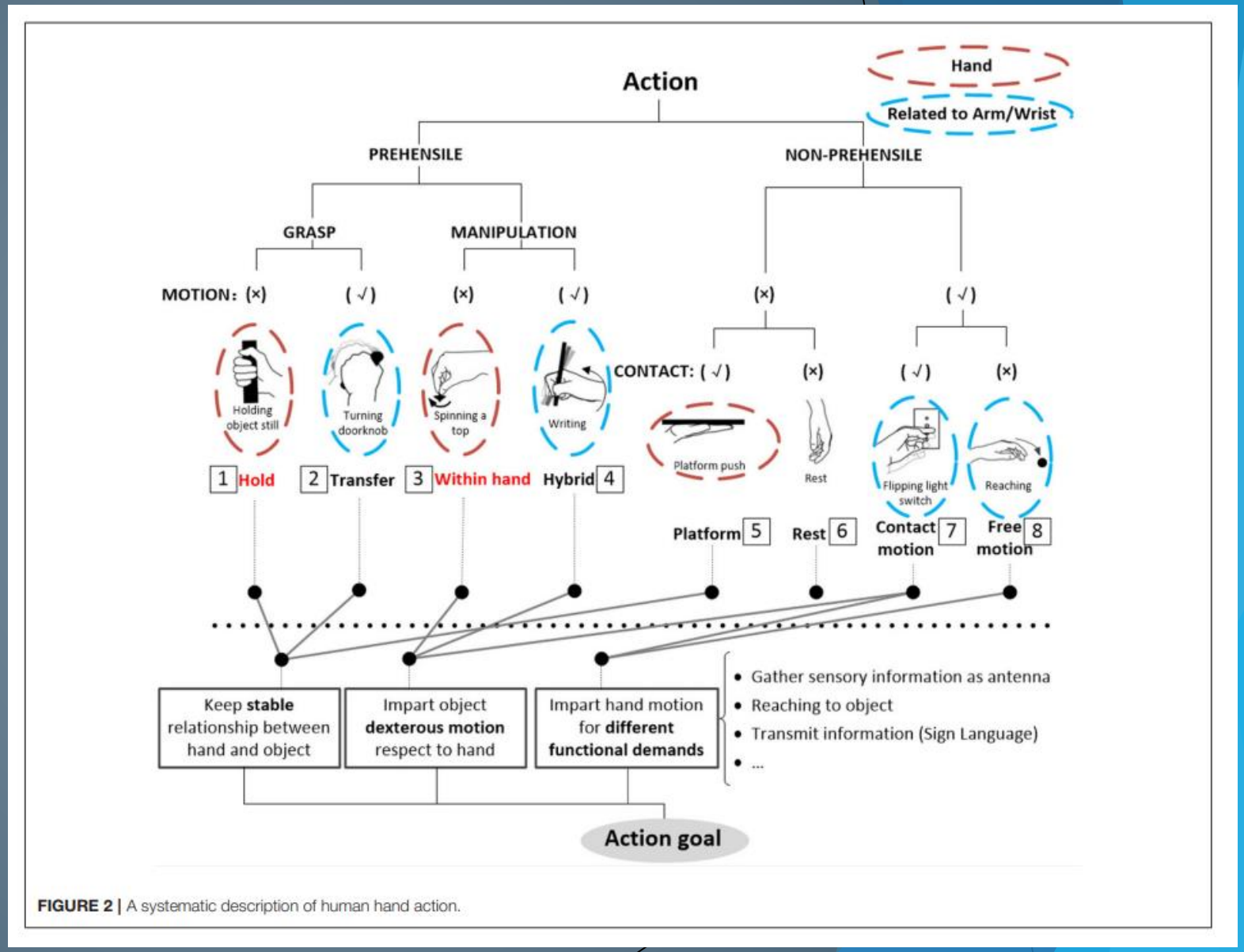


FIGURE 2 | A systematic description of human hand action.

RESEARCH ARTICLE

Functional classification of grasp strategies used by hemiplegic patients

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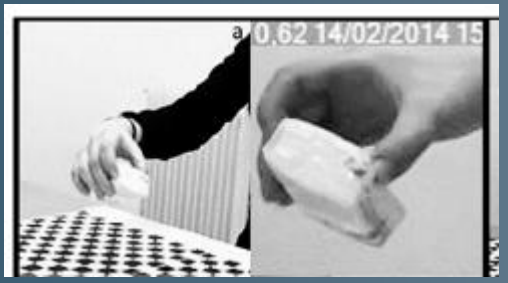
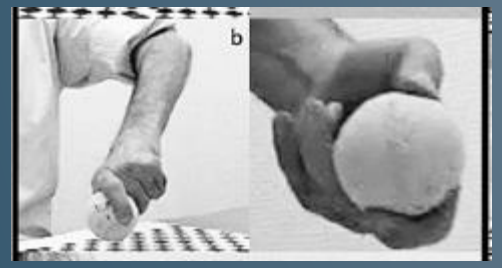
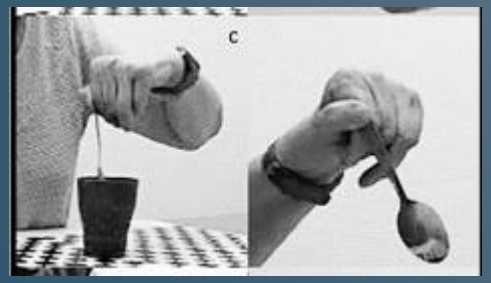
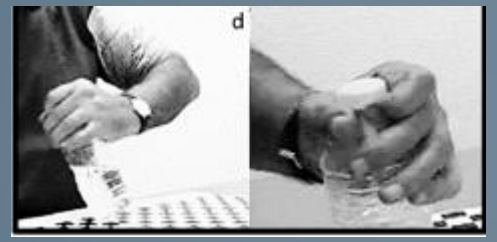
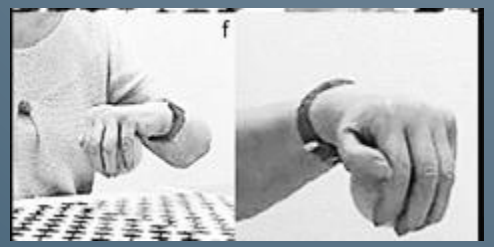


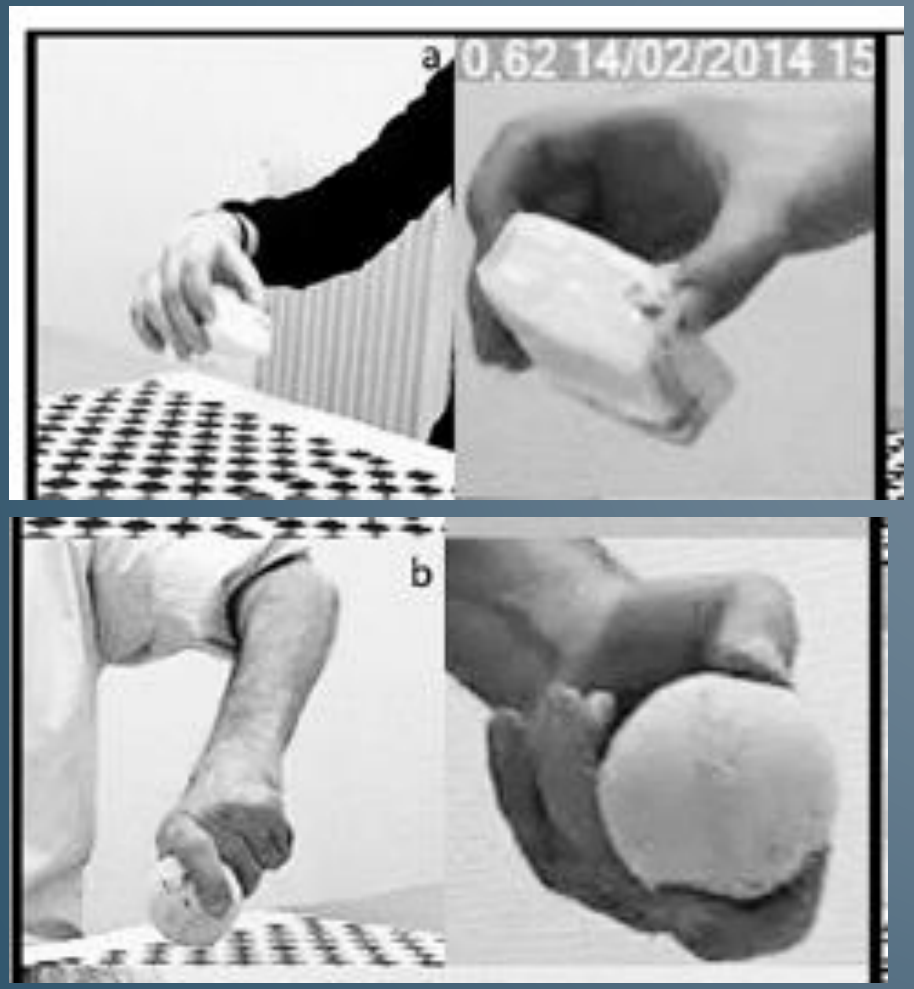






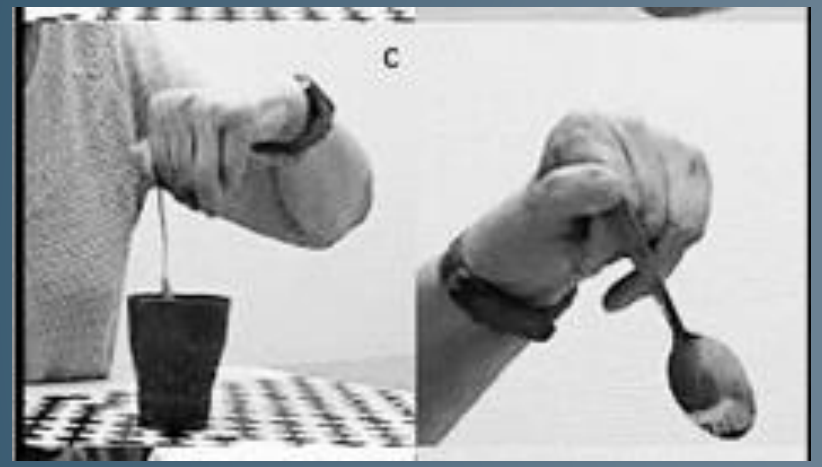


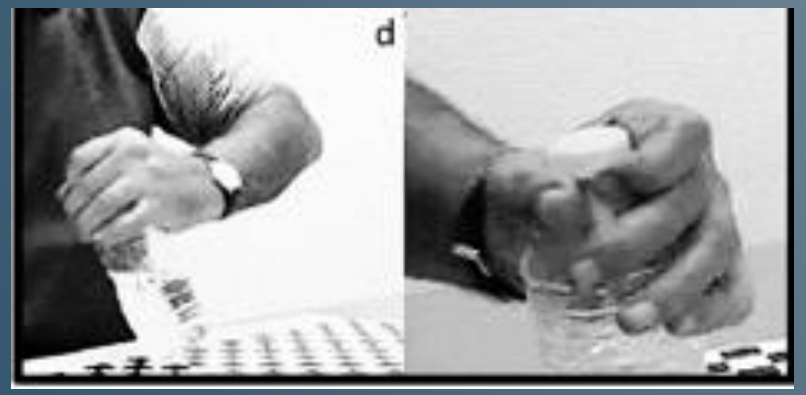
Proficient and Maladaptive Grasps Utilized by Stroke Survivors



- Multi-pulpar grasp
  - Involves the distal pad of any finger.
  - Thumb positioned in opposition
  - Palm is not used.
  - ***Used by patients with high ARAT scores (median 43).***
  - Poor stability of the wrist→ use.
    - Weakness or spasticity.
- Pluri-digital
  - Involves the thumb and one or more digits.
  - Proximal phalanxes are involved– the palm is not.
- Used half as often in healthy subjects than patients.
- ***Patients that used it- marked good to moderate recovery.***
- 3 Low level patients used this grasp but needed to wedge it into their hand- unable to place by opening hand.

Proficient and Maladaptive Grasps Utilized by Stroke Survivors





Lateral pinch

- Involves the pad of the thumb into the lateral side of the index finger.
- Used by patients with wide range of impairment.

Palmar

- Involves the palm and all of the fingers.
- Fingers wrap around the object.
- Thumb is in opposition to the other fingers.
- Only 5 patients used this grasp- requires large degree of thumb opening.

Proficient and Maladaptive Grasps Utilized by Stroke Survivors

Digito-palmar

- Involves the palm in opposition to one of all of the fingers.
- Correlated with low FMA and ARAT scores.
- 74% of the patients using this grasp had spasticity of the thumb adductor muscle.

Raking

- Involves the palm and D2-5.
- Thumb is not involved.
- Correlated with high degree of tendonesis and spasticity of the wrist/finger flexors.

Proficient and Maladaptive Grasps Utilized by Stroke Survivors

Ulnar-

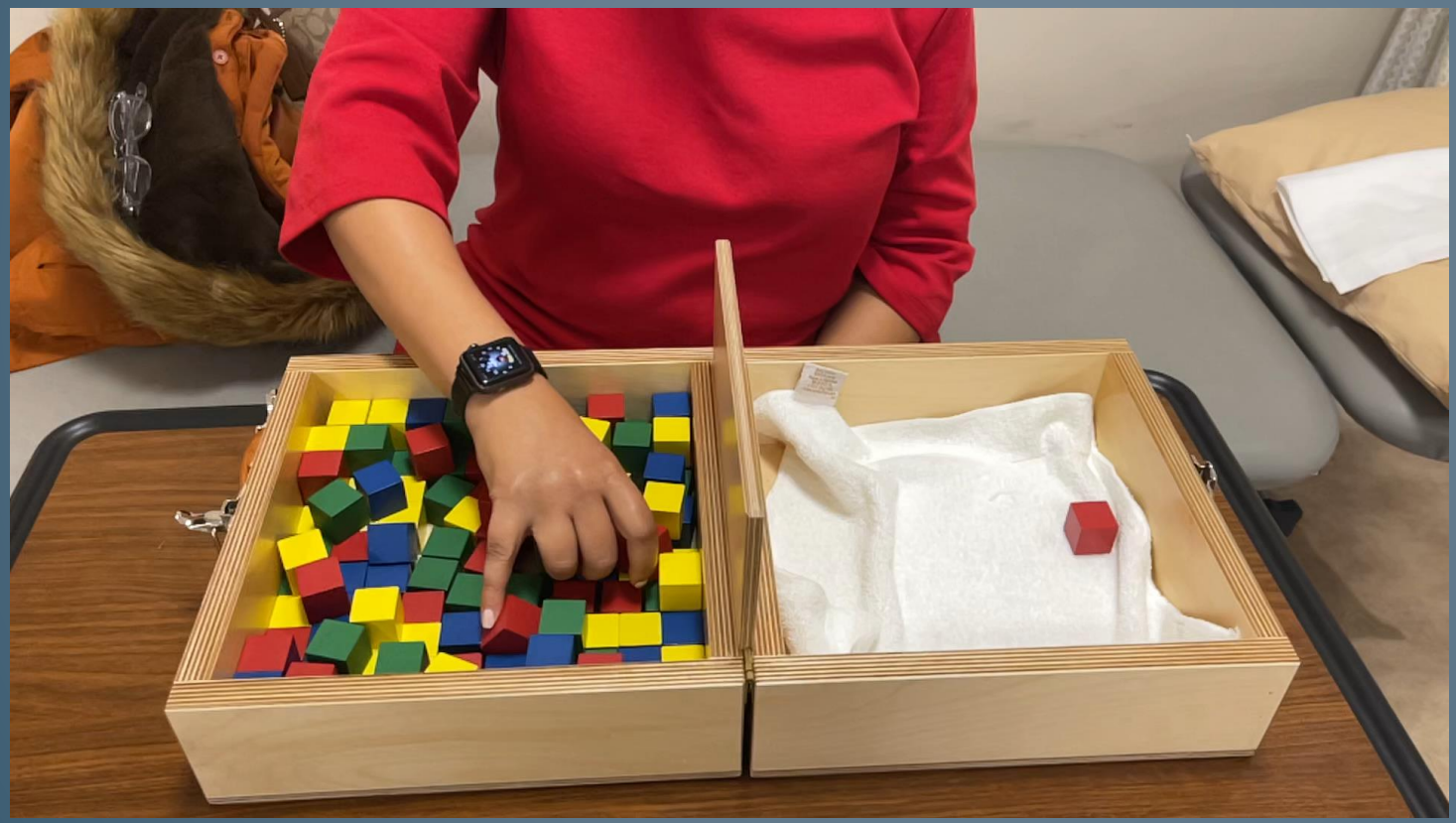
- Involves the thenar side of the palm and D4-5 which are flexed.

Interdigital

- Involves the lateral side of the fingers.
- Thumb is seldom involved.
  - Sometimes envelops object for increased stability.
  - Palm is not involved.

Thumb proficiency- compared

Thumb proficiency- compared



Effective Grasping vs. Maladaptive Grasping

- Standard Grasps (4 used in Healthy Subjects)
  - Multi pulpar
  - Pluri-digital
  - Palmar- used rarely (10% , 23%)
    - Tennis ball, water bottle respectively
  - Lateral Pinch
- Alternative grasp types (compensatory)
  - Digito-palmar
  - Raking
  - Ulnar
  - Interdigital
  - Fail

Proficient and Maladaptive Grasps Utilized by Stroke Survivors

Table 3. Distribution of the grasp-types across the 456 trials for each object.

	Tissue Packet	Tennis Ball	Water Bottle	Spoon	Total
	Patients/HS	Patients/HS	Patients/HS	Patients/HS	Patients/HS
Multipulpar	**28% / 80%**	16% / 20%	10% / 10%	15% / 10%	17% / 30%
Pluri-digital	24% / 20%	**25% / 70%**	**30% / 67%**	21% / **50%**	**25% / 52%**
Lateral-pinch	0% / 0%	0% / 0%	4% / 0%	**41%** / 40%	11% / 10%
Palmar	0% / 0%	3% / 10%	10% / 23%	0% / 0%	4% / 8%
Digito-palmar	6% / 0%	7% / 0%	11% / 0%	4% / 0%	7% / 0%
Raking	5% / 0%	14% / 0%	5% / 0%	1% / 0%	6% / 0%
Ulnar	3% / 0%	0% / 0%	9% / 0%	4% / 0%	4% / 0%
Interdigital	0% / 0%	0% / 0%	0% / 0%	12% / 0%	3% / 0%
Fail	34% / 0%	34% / 0%	21% / 0%	3% / 0%	23% / 0%

HS: Healthy Subjects. The highest percentages are shown in bold. The grasps are ranked with multipulpar first, then according to their frequency of use in the control group, then in the patient group.

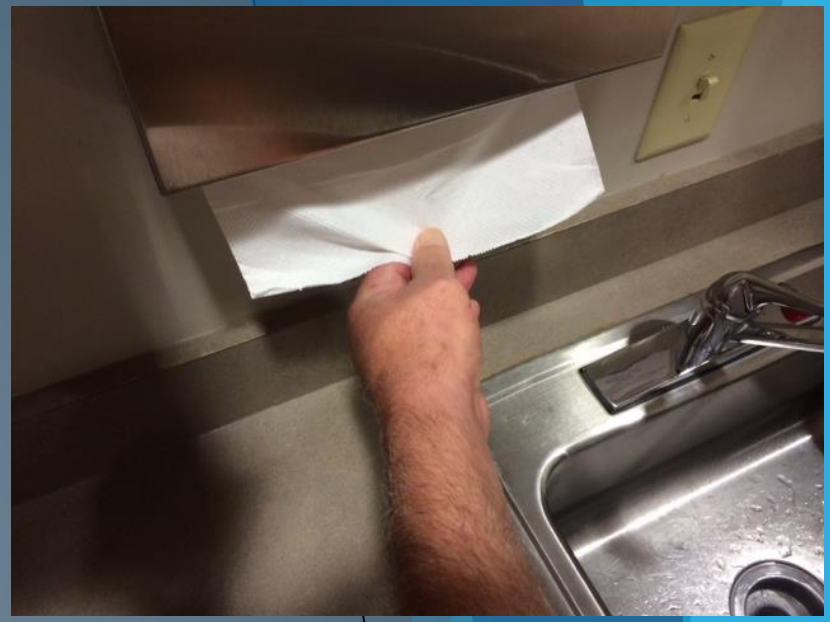
Healthy Subjects (right column)– Used only 4 grasps throughout 4 objects.
Multi-pulpar , Pluri-digital , Palmar, Lateral pinch

Patients (left column)- used 9 different grasps.

Theme for use of standard grasp = active motion of the thumb – mostly opposition

Pinch

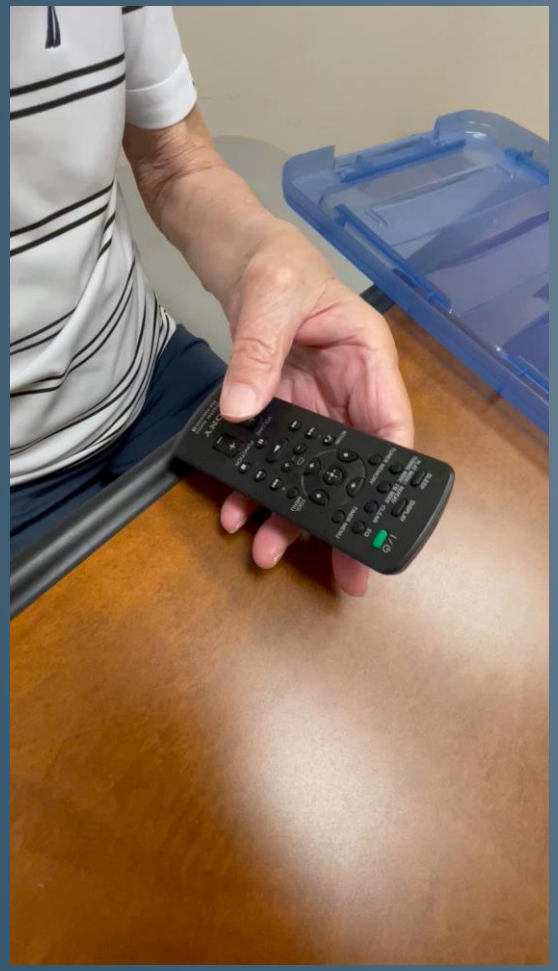
- Demand of the thumb
  - MP flexion with IP ext
  - MP flex with IP flexion
- Lateral pinch vs. oppositional pinch

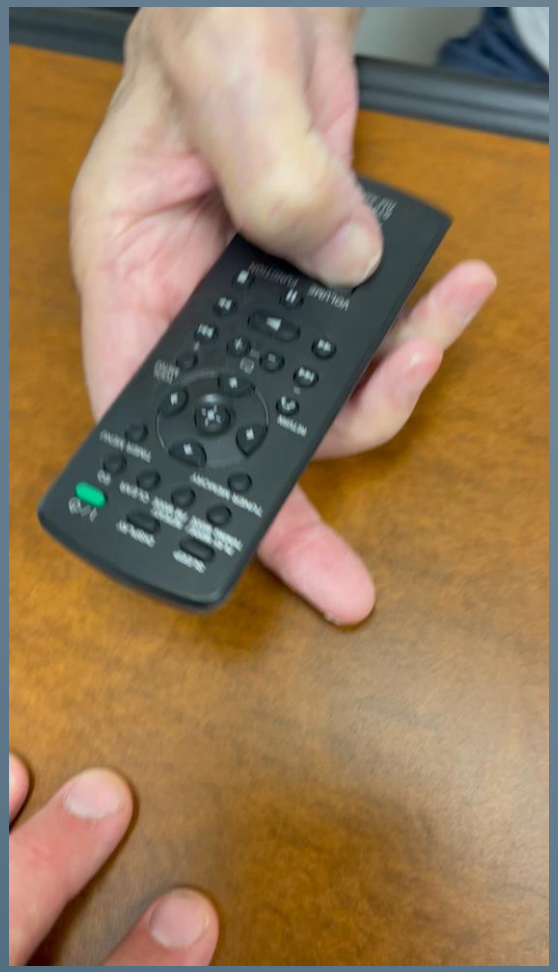


When do we use IP extension at the thumb?

When do we use IP flexion at the thumb?

Stabilization of objects in the palm of the hand





References

- Arnet, U., Muzykewicz, D. A., Fridén, J., & Lieber, R. L. (2013). Intrinsic hand muscle function, part 1: Creating a functional grasp. *The Journal of Hand Surgery*, *38*(11), 2093–2099. https://doi.org/10.1016/j.jhsa.2013.08.099
- Cuijpers, R. H., Smeets, J. B., & Brenner, E. (2004). On the relation between object shape and grasping kinematics. *Journal of Neurophysiology*, *91*(6), 2598–2606. https://doi.org/10.1152/jn.00644.2003
- Franck, J. A., Smeets, R. J., & Seelen, H. A. (2017). Changes in arm-hand function and arm-hand skill performance in patients after stroke during and after rehabilitation. *PLOS ONE*, *12*(6). https://doi.org/10.1371/journal.pone.0179453
- García Álvarez, A., Roby-Brami, A., Robertson, J., & Roche, N. (2017). Functional classification of grasp strategies used by hemiplegic patients. *PLOS ONE*, *12*(11). https://doi.org/10.1371/journal.pone.0187608
- Johnston, J. A., Bobich, L. R., & Santello, M. (2010). Coordination of intrinsic and extrinsic hand muscle activity as a function of wrist joint angle during two-digit grasping. *Neuroscience Letters*, *474*(2), 104–108. https://doi.org/10.1016/j.neulet.2010.03.017
- Kapandji, I. A., & HonoréL. (2019). *The physiology of the joints*. Handspring Publishing.
- Liu, Y., Jiang, L., Liu, H., & Ming, D. (2021). A systematic analysis of hand movement functionality: Qualitative classification and quantitative investigation of hand grasp behavior. *Frontiers in Neurorobotics*, *15*. https://doi.org/10.3389/fnbot.2021.658075
- Michaelsen, S. M., Magdalon, E. C., & Levin, M. F. (2009). Grip aperture scaling to object size in chronic stroke. *Motor Control*, *13*(2), 197–217. https://doi.org/10.1123/mcj.13.2.197
- Sangole, A. P., & Levin, M. F. (2007). A new perspective in the understanding of hand dysfunction following neurological injury. *Topics in Stroke Rehabilitation*, *14*(3), 80–94. https://doi.org/10.1310/tsr1403-80
- Schieber, M. H., & Santello, M. (2004). Hand function: Peripheral and central constraints on performance. *Journal of Applied Physiology*, *96*(6), 2293–2300. https://doi.org/10.1152/japplphysiol.01063.2003