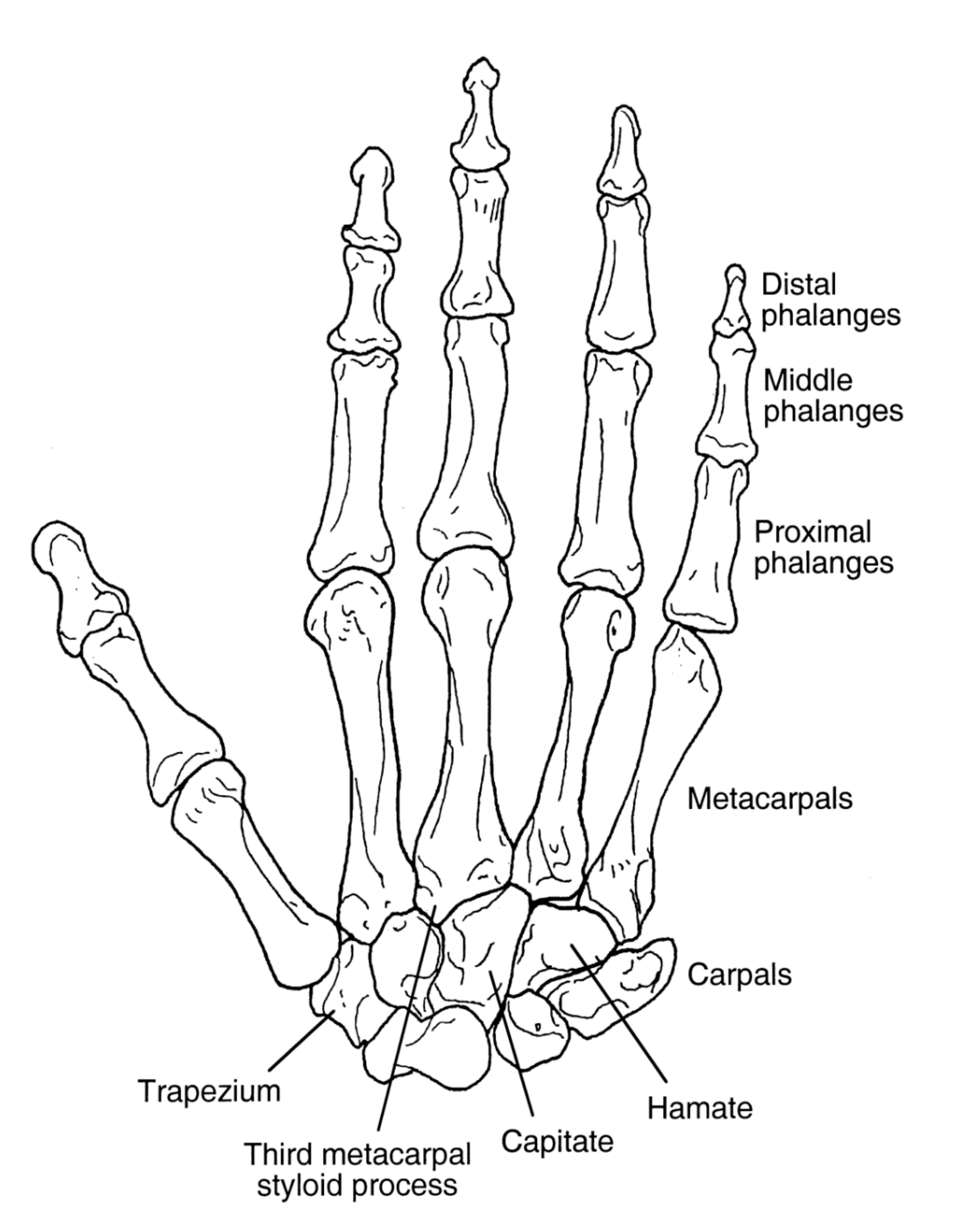
Overview of Human Hand Anatomy and Function



Churchill Livingstone

The Physiology of the Joints

I. A. Kapandji

ROTATION (PRONATION-SUPINATION)

SIGNIFICANCE

Rotation (pronation-supination) is *the movement of the forearm about its longitudinal axis.*

It involves **two joints which are mechanically linked** (Fig. 1):

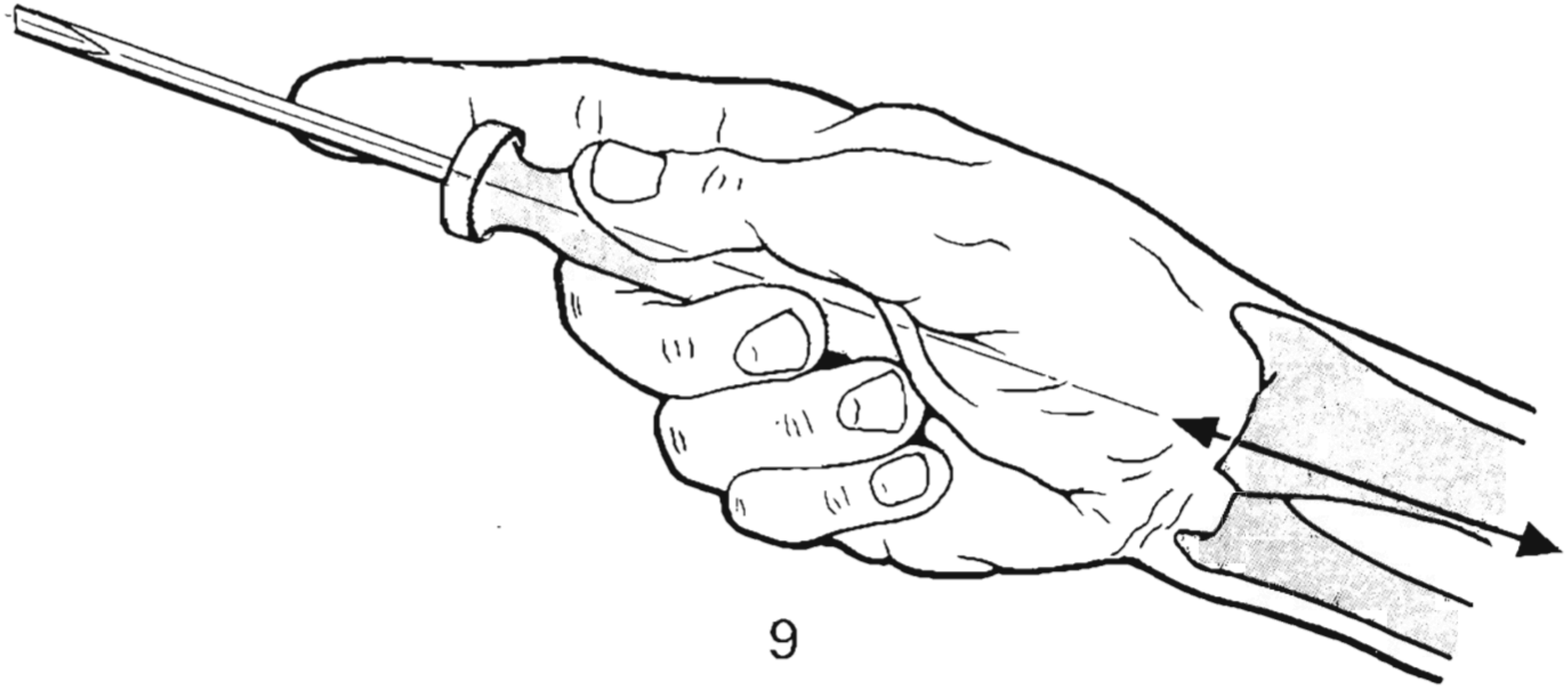
— the *superior radio-ulnar* (SRU) joint, which anatomically belongs to the elbow

— the *inferior radio-ulnar* (IRU) joint, which is anatomically separate from the wrist.

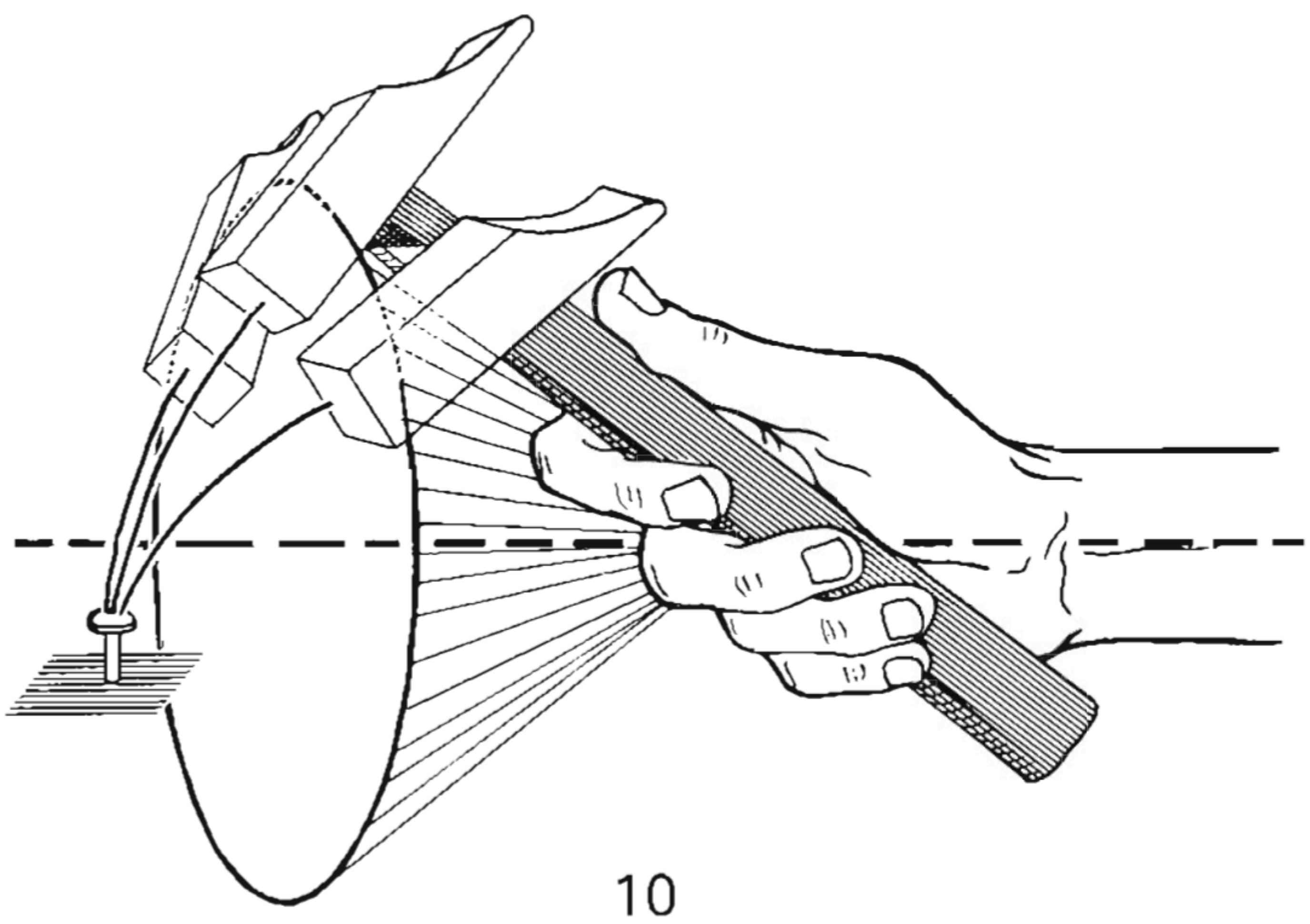
This longitudinal rotation of the forearm introduces **a third degree of freedom** in the articular complex of the wrist. Thus the hand, the effector extremity of the upper limb, can be placed in any position to grasp or support an object. Note that the presence of a synovial joint with three degrees of freedom at the wrist would have created many mechanical problems. Thus it would have been necessary to supply the mobile extremity, i.e. carpus, with bony projections to provide leverage for the rotator muscles. Also it would have been mechanically impossible for the tendons of the forearm muscles to cross the wrist, since the latter would have been free to twist on itself during longitudinal rotation. Hence the hand would have had to contain all the extrinsic muscles, at the expense of muscle efficiency and hand size.

Longitudinal rotation of the forearm itself is at once the logical and elegant solution, even if the skeleton of the forearm is complicated by the presence of a *second bone*, the radius, which not only by itself supports the hand but also rotates around the first bone, the ulna, at the level of two radio-ulnar joints.

This architectural design of the forearm appeared 400 million years ago when certain fishes left the sea to colonise the land and transform into tetrapod amphibians.



9



10

THE WRIST

SIGNIFICANCE

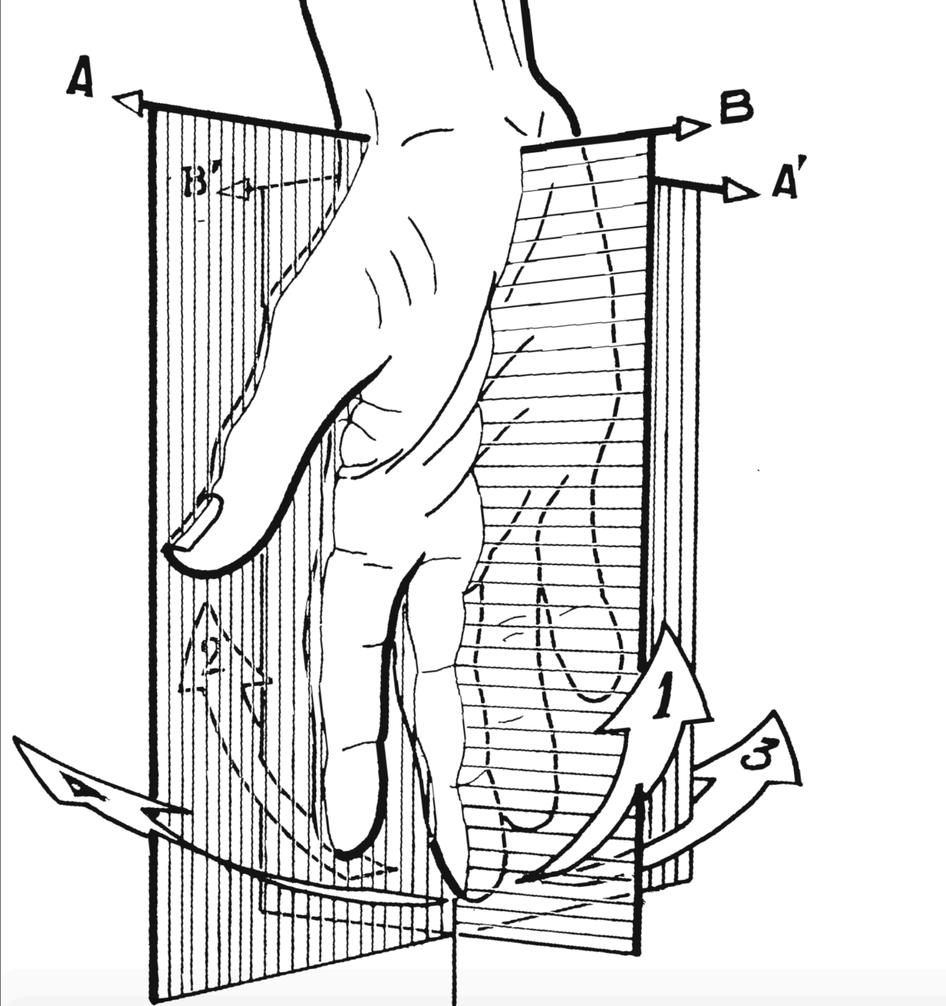
The wrist is the *distal joint of the upper limb* and allows the hand, which is the effector segment, to assume the optimal position for prehension.

The articular complex of the wrist has basically **two degrees of freedom**. When these are compounded with pronation and supination, i.e. rotation of the forearm around its long axis, *the hand can be oriented at any angle to grasp or hold an object.*

The articular complex consists of two joints:

— the radio-carpal (RC) joint (wrist joint), between the radial head and the proximal row of carpal bones.

— the mid-carpal (MC) joint between the proximal and distal rows of carpal bones.



MOVEMENTS OF THE WRIST

Movements of the wrist (Fig. 1) occur around **two axes** when the hand is in the anatomical position, i.e. in full supination:

— A **transverse** axis AA′ lying in the *frontal plane* (hatched vertically) and controlling movements of *flexion and extension*, which take place in the **sagittal plane** (hatched horizontally):

85 deg

— **Flexion** (arrow 1): the anterior (palmar) surface of the hand moves towards the anterior aspect of the forearm.

85 deg

— **Extension** (arrow 2): the posterior (dorsal) surface of the hand moves towards the posterior aspect of the forearm. (It is better to avoid the terms dorsiflexion and palmar flexion)

— An **antero-posterior** axis BB′, lying in the *sagittal plane* (hatched horizontally) and controlling movements of *adduction* and *abduction*, which take place in the **frontal** plane (hatched vertically).

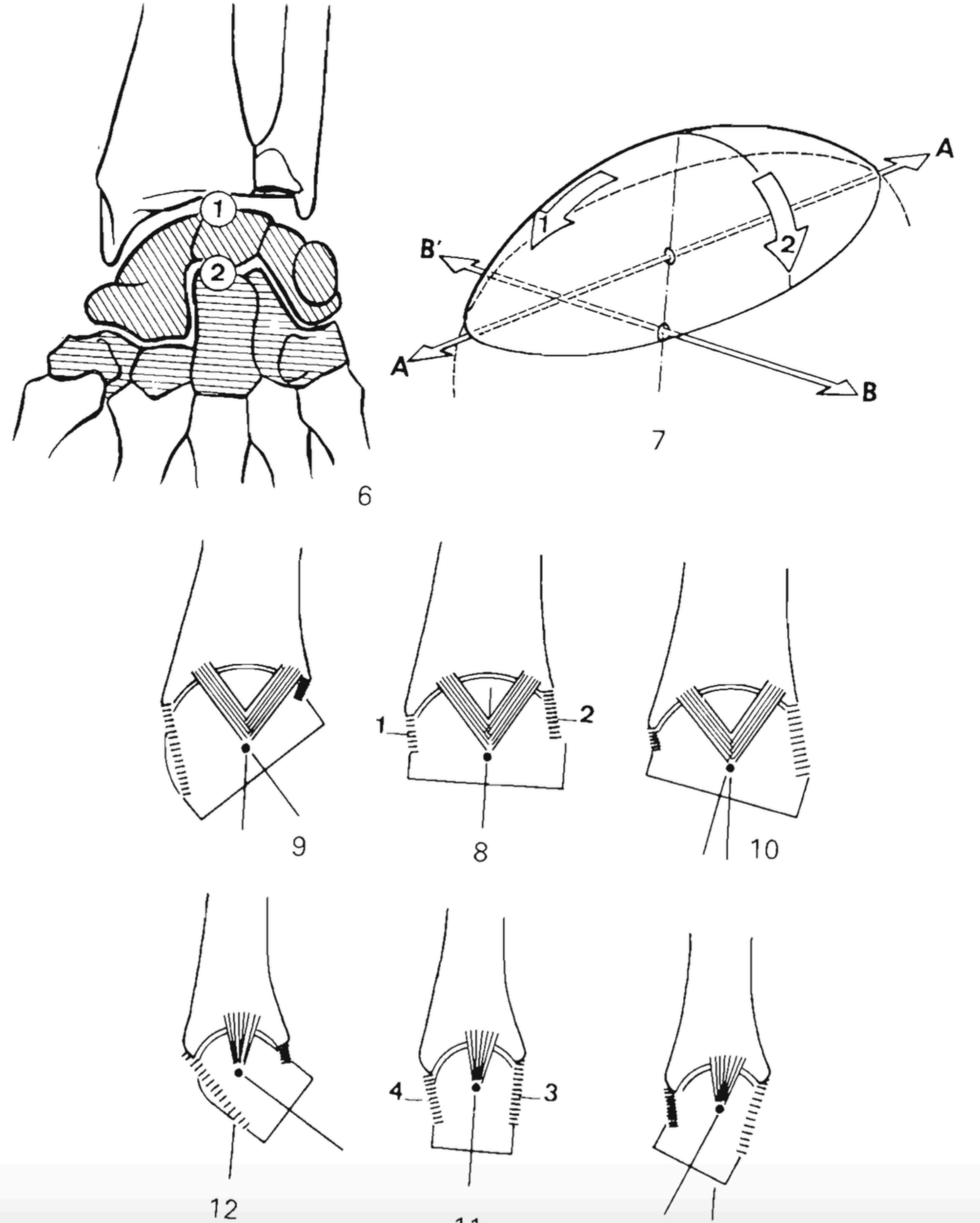
45 deg

— **Adduction** or ulnar deviation (arrow 3): the hand moves towards the axis of the body and its medial (ulnar) border forms an obtuse angle with the medial border of the forearm;

15 deg

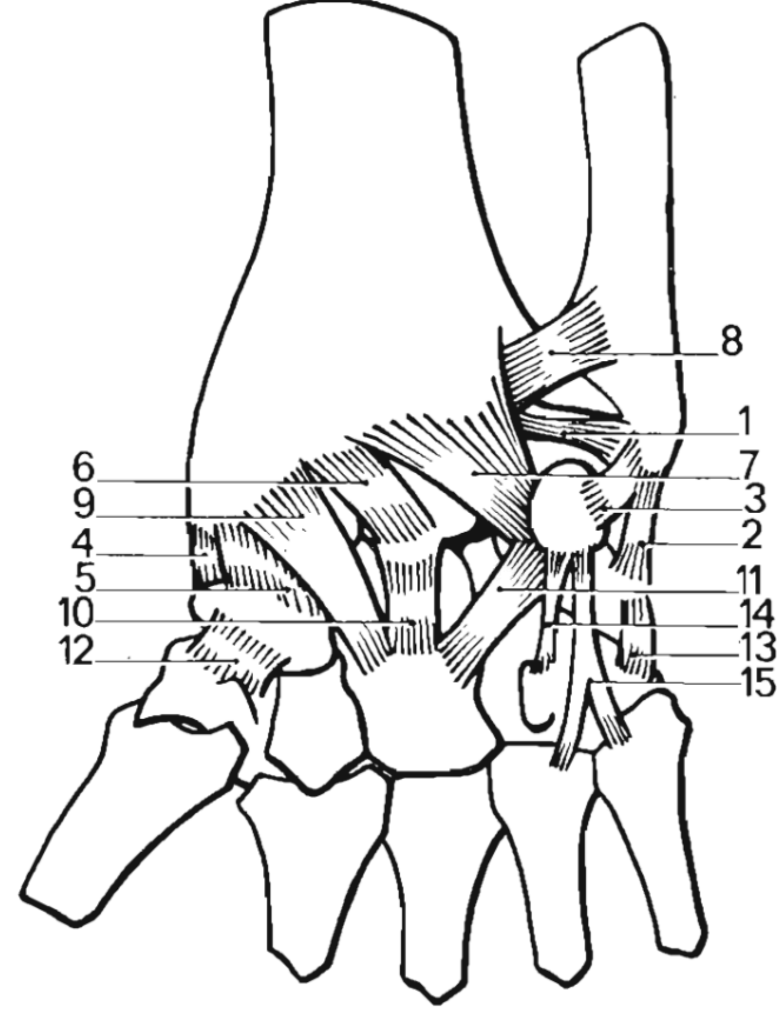
— **Abduction** or radial deviation (arrow 4): the hand moves away from the axis of the body and its lateral (radial) border forms an obtuse angle with the lateral border of the forearm.

Wrist Articular Complex

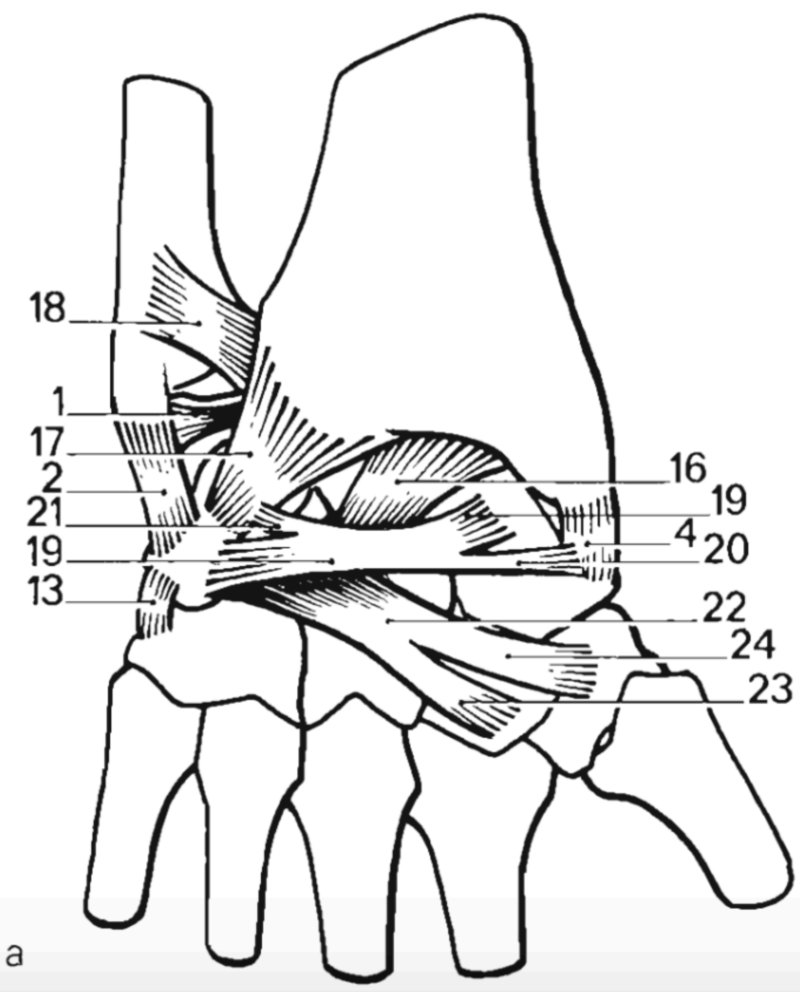


Bone locations segmented from CT scan
by Liz Marai in the late 90’s

Stabilizing Ligaments

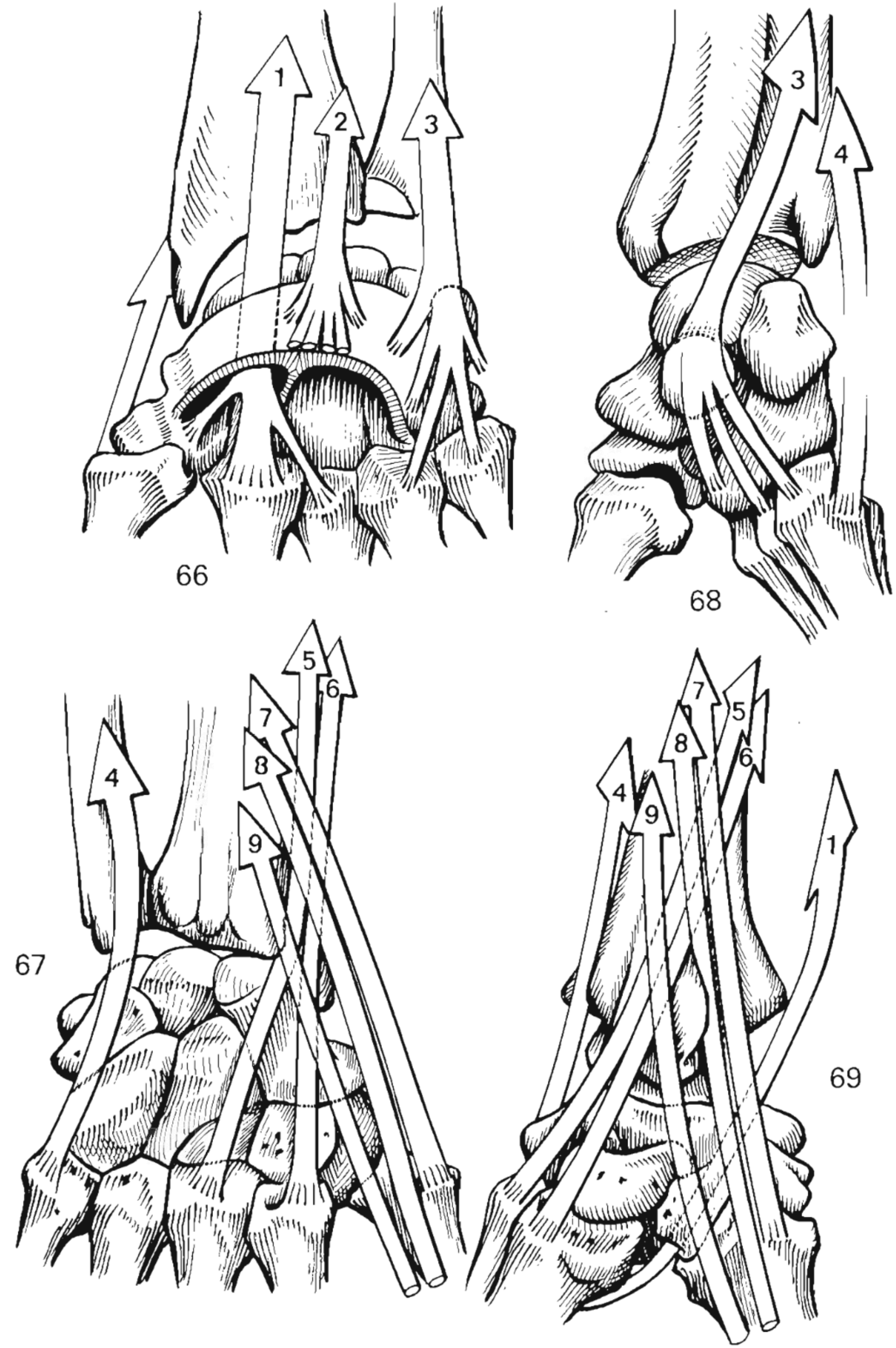


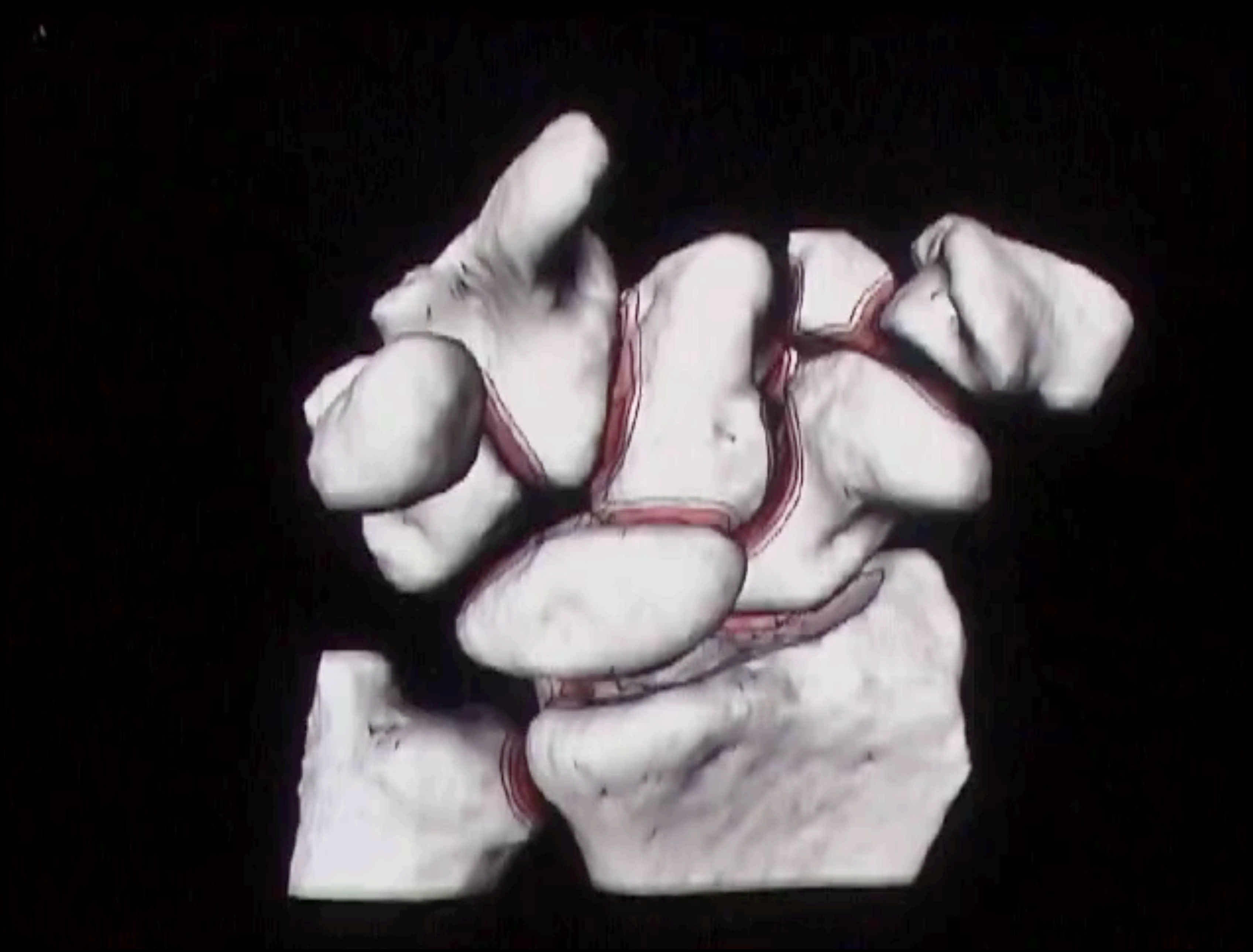
17



17 a

Muscles of the Wrist





Bone locations segmented from CT scan
by Liz Marai in the late 90’s

THE HAND

ITS ROLE

The hand of man is a remarkable instrument, capable of performing countless actions, owing to its essential function: prehension.

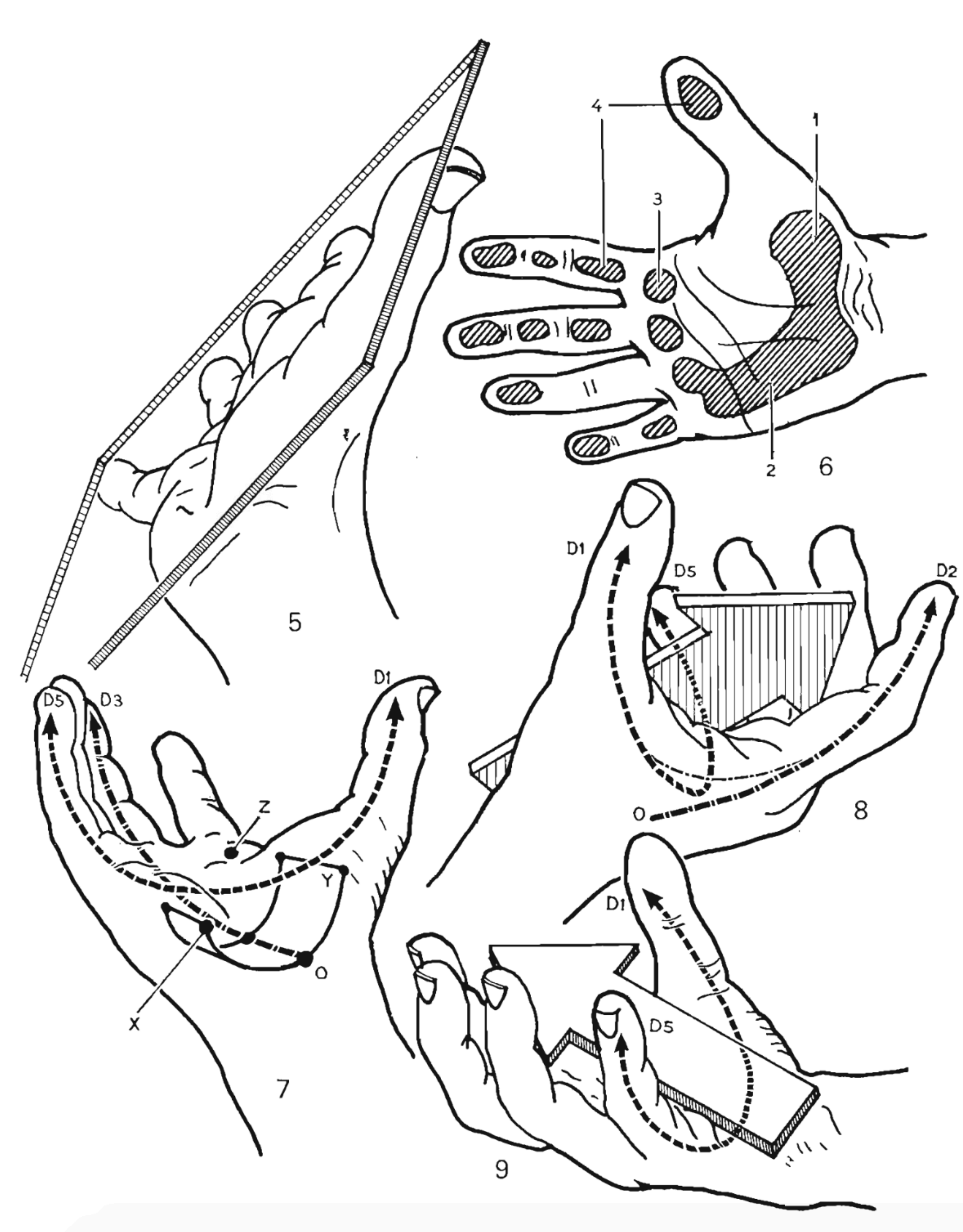
Prehension is seen in all forms of the 'hand' from the pincers of the lobster to the paw of the ape, but it attains perfection only in man. This is due to a special movement of the thumb (called opposition) which brings it into contact with each finger. Opposition is seen in the great apes, but its range is more limited than in man.

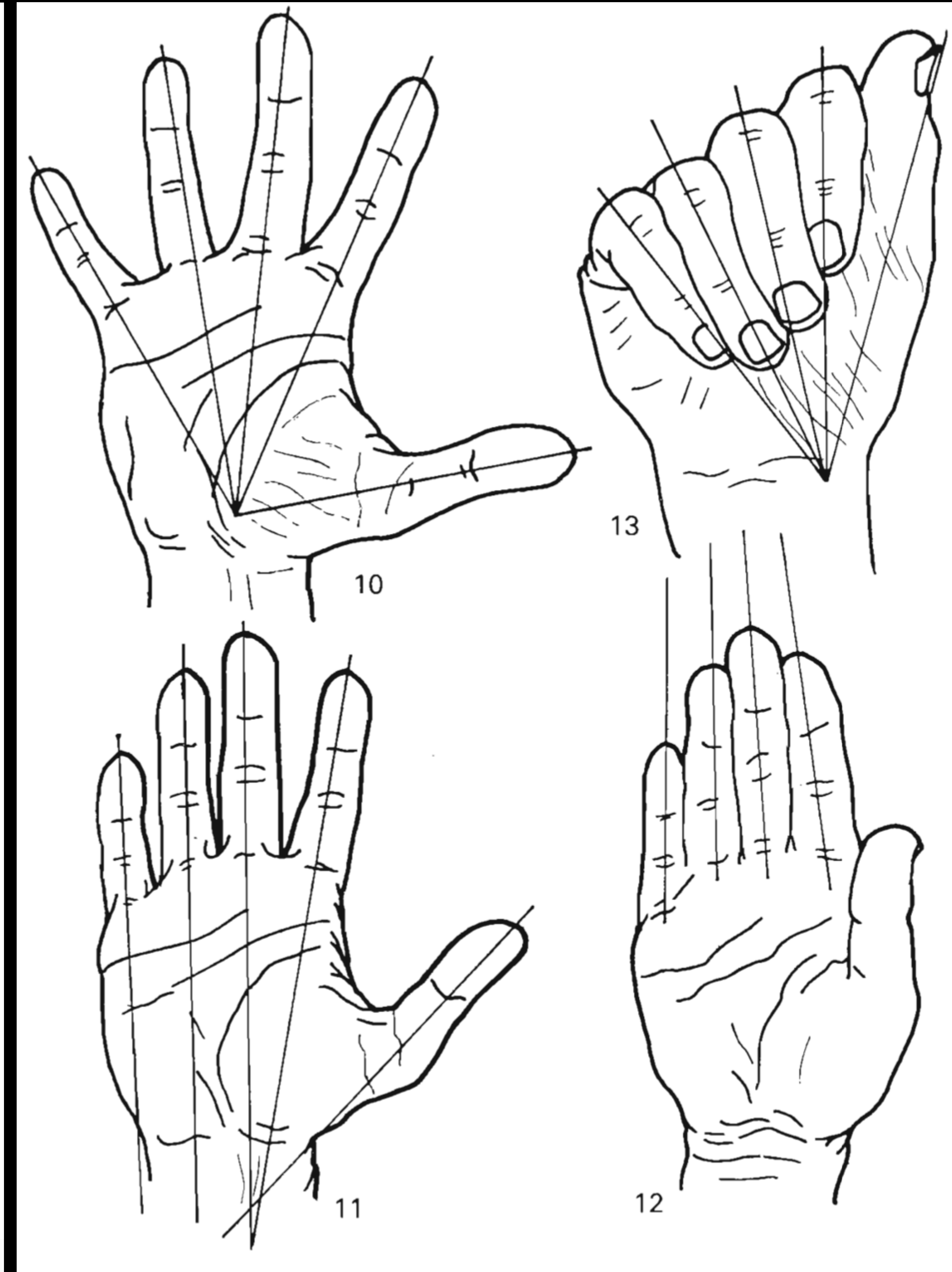
At the same time the lack of specialization in the human hand underlies its adaptability and creativity.

From the functional viewpoint the hand is the *effector organ* of the upper limb, which supports it mechanically and allows it to adopt the optimal position for any given action. However, the hand is not only a motor organ but also a very sensitive and accurate sensory receptor, which feeds back information essential for its own performance. Finally, it provides the cerebral cortex with *information regarding thickness and distance* and thus is responsible for the development of *visual appreciation* by allowing cross checking of information. Without the hand our idea of the world would be flat and lacking in contrasts.

It is essential for that particular sense, stereognosis, which is the appreciation of relief, shape, thickness, *space*. It also trains the brain in the appreciation of texture, weight and temperature. By itself the hand is able to recognise an object, unaided by the eye.

The hand therefore forms with the brain an inseparable *interacting functional pair* and this close interaction is responsible for man's ability to alter nature at will and to dominate other species.


4
1
3
2
6
5
D5
D3
D1
Z
Y
X
O
7
D1
D5
D2
O
8
D1
D5
9


10
13
11
12

THE RANGE OF MOVEMENTS OF THE METACARPO-PHALANGEAL JOINTS

Flexion has a range of about 90° (Fig. 38). It falls just short of 90° for the index but *increases progressively with the other fingers*. Also, isolated flexion of the finger (here of the middle finger) is checked (Fig. 39) by the tension developed in the palmar interdigital ligament.

Active extension is variable and can reach up to 30° or 40° (Fig. 40). **Passive extension** can reach up to 90° in people with very lax ligaments (Fig. 41)

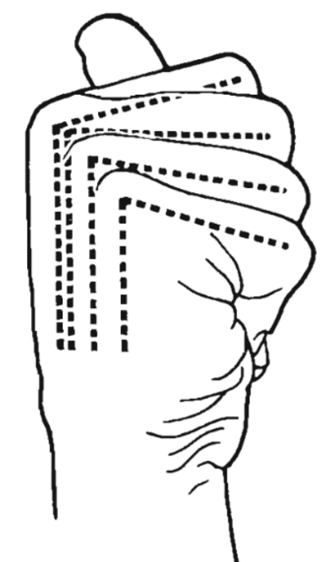
Of all the fingers (except the thumb) the index finger has the *greatest range of side-to-side movement* (30) and, as it can easily be moved alone, the terms *abduction* (A) and *adduction* (B) strictly apply here. It is to this great mobility that the index owes its name: **index = indicator.**

By a succession of the simple moveements (Fig. 43) of abduction, (A), adduction (B), extension (C) and flexion (D) the index performs the **movements of circumduction** which take place within the **cone of circumduction.** This is defined by its base (ACBD) and its apex (metacarpo-phalangeal joint). This cone is flattened transversely because of the greater range of the movements of flexion and extension. Its axis (white arrow) corresponds to *the position of equilibrium or function* of the MP joint of the index.

Condyloid joints do not normally show axial rotation and this applies to the MP joints of the four fingers as regards *active rotation*. However, owing to the laxity of the ligaments, a measure of **passive axial rotation** is possible with a range of about 60° (Roud).

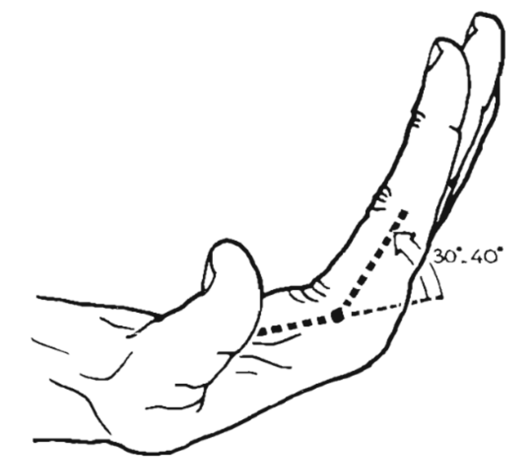
Note that with the *index finger* the range of medial rotation — or pronation — is much greater (45°) than that of lateral rotation — or supination — which is trivial.

Even if a true active axial rotation is not seen at the MP joints, there is an **automatic rotation** in the direction of supination, resulting from the asymmetry of the metacarpal head and the unequal length and tension of the collateral ligaments. This movement, which is similar to that seen in the IP joint of the thumb, is more marked in the more medial fingers and is maximal for the little finger, where it contributes to the movement of that finger towards the opposing thumb.

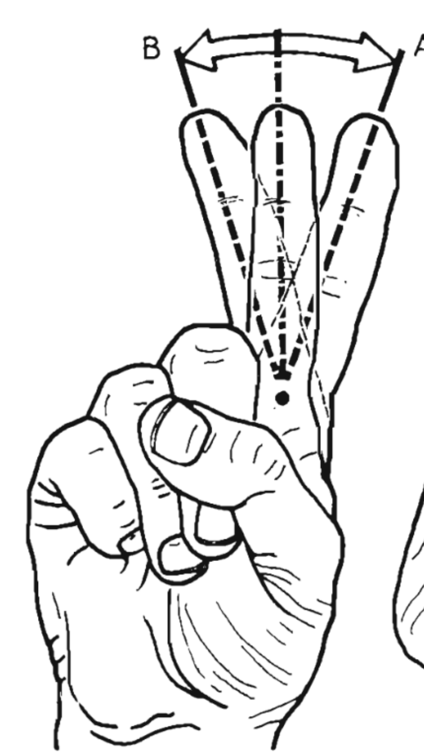


38

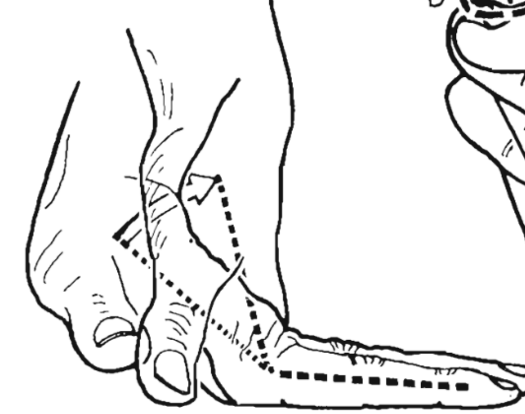
39



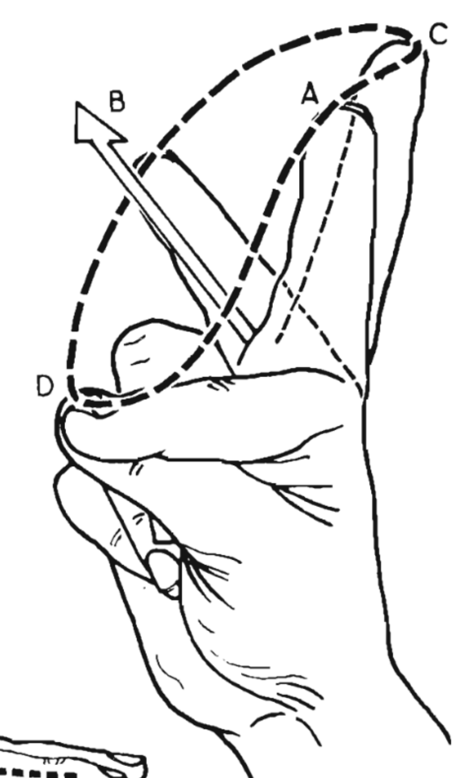
40



42



41



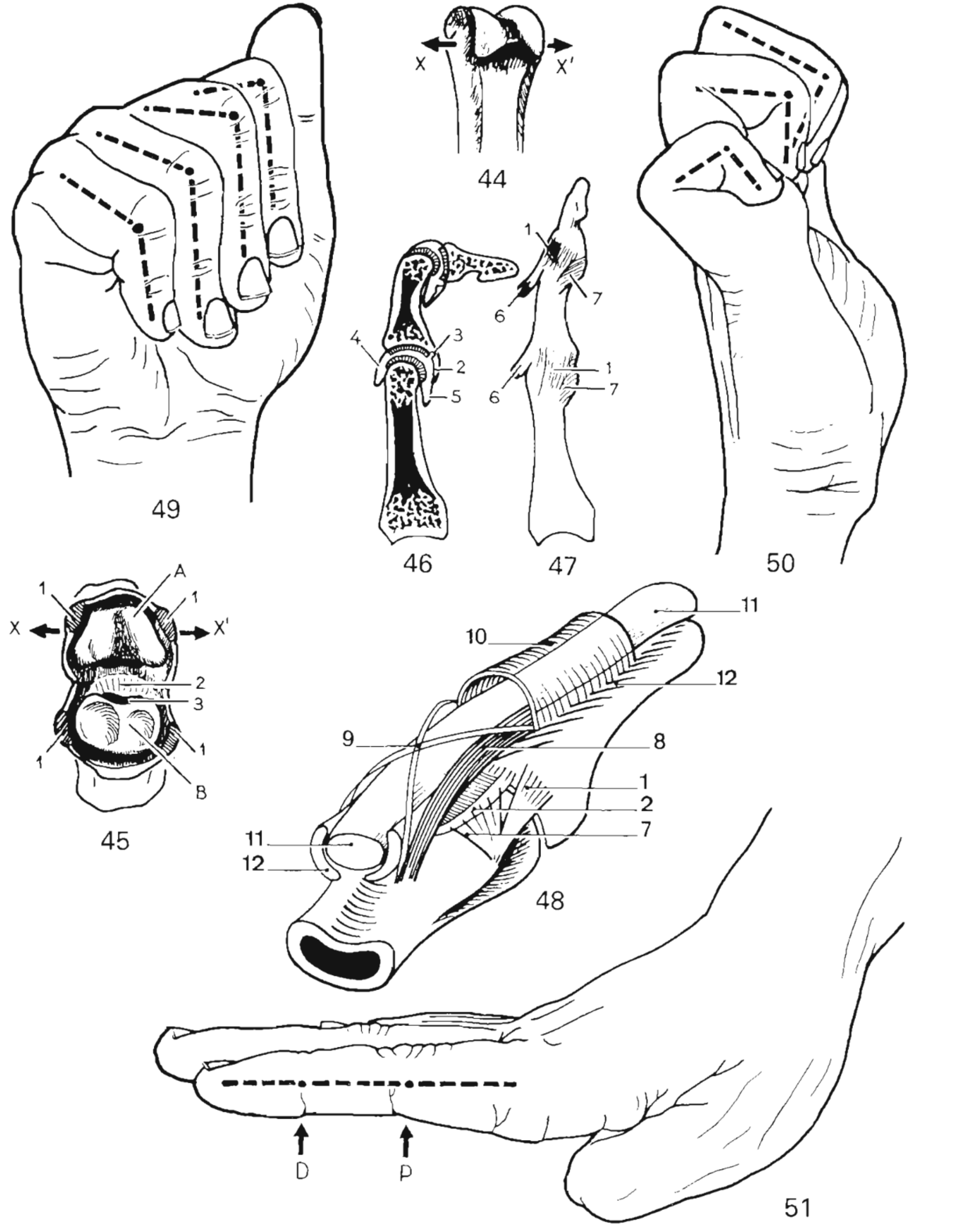
43

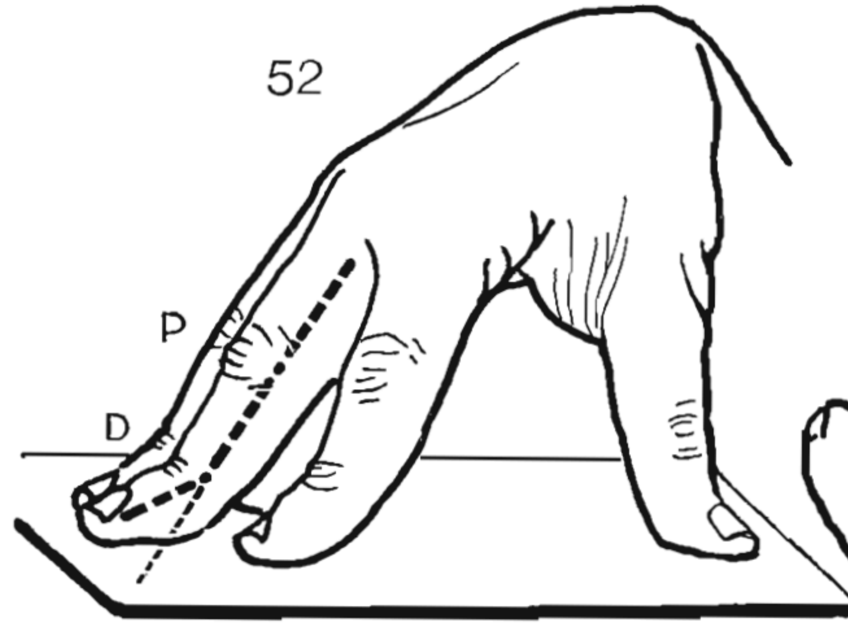
The Interphalangeal Joints

Proximal Interphalangeal (PIP)

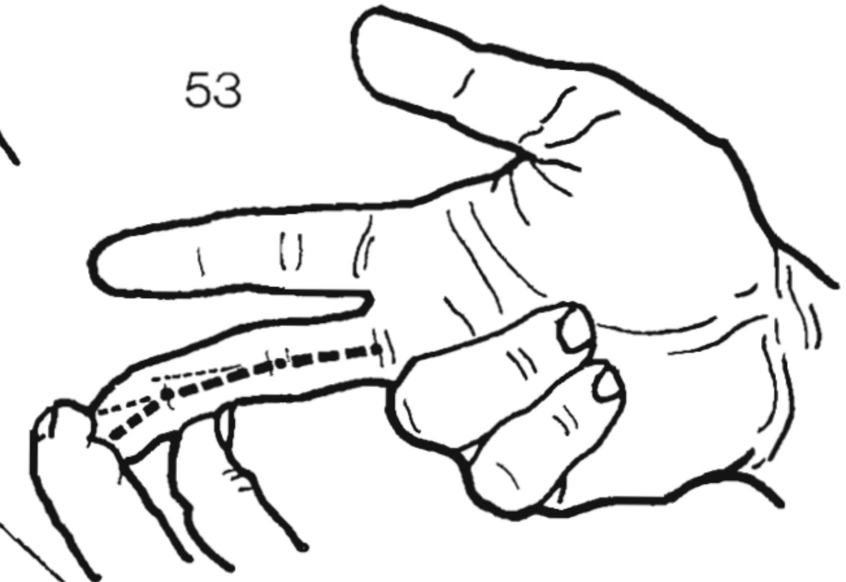
and

Distal Interphalangeal (DIP)

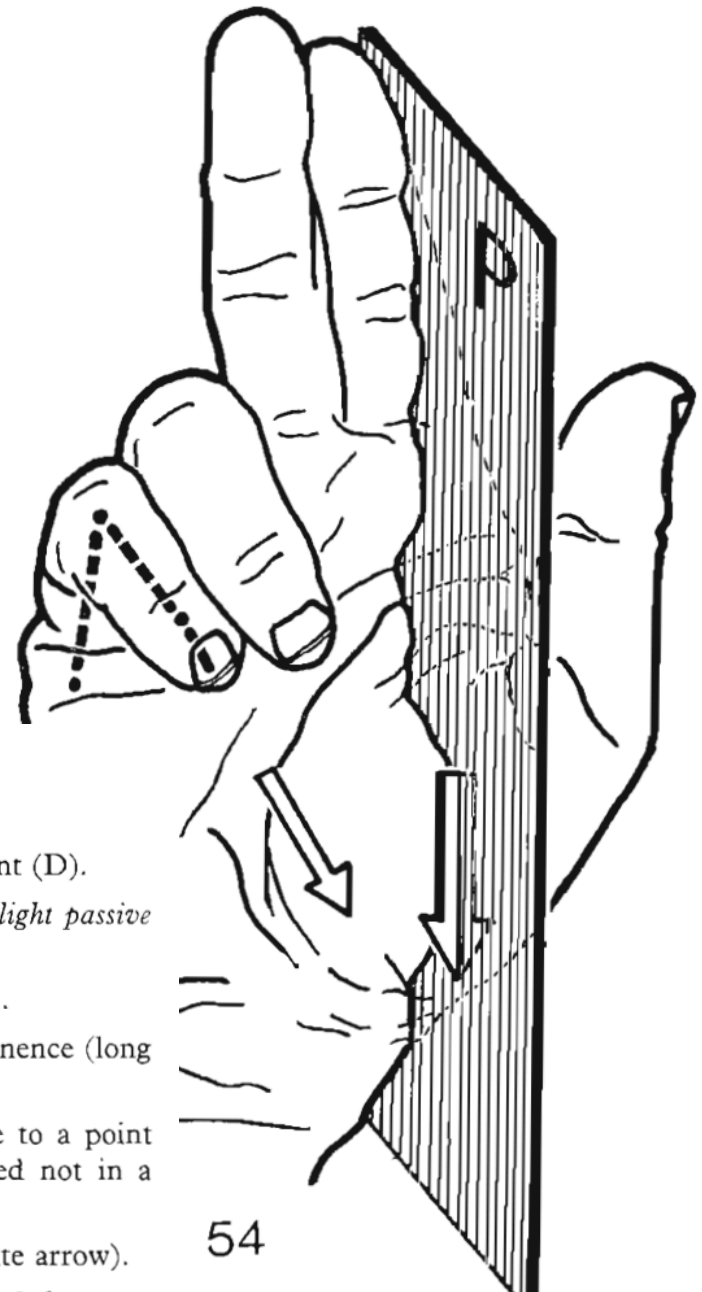




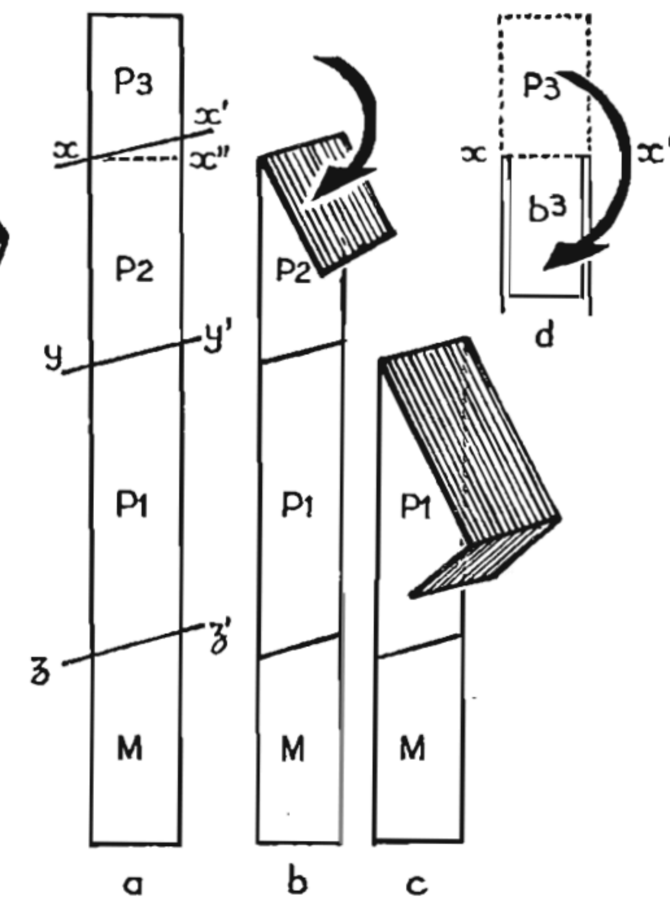
52



53



54



55

THE INTERPHALANGEAL JOINTS (continued)

Passive extension (Fig. 52) is nil at the PIP joint (P), but appreciable (30°) at the DIP joint (D).

Since the IP joints have only one degree of freedom, there is no active, but only *slight passive side-to-side movement* (Fig. 53), especially at the DIP joint.

The *plane of movement of flexion* of the last four fingers is worth discussing (Fig. 54).

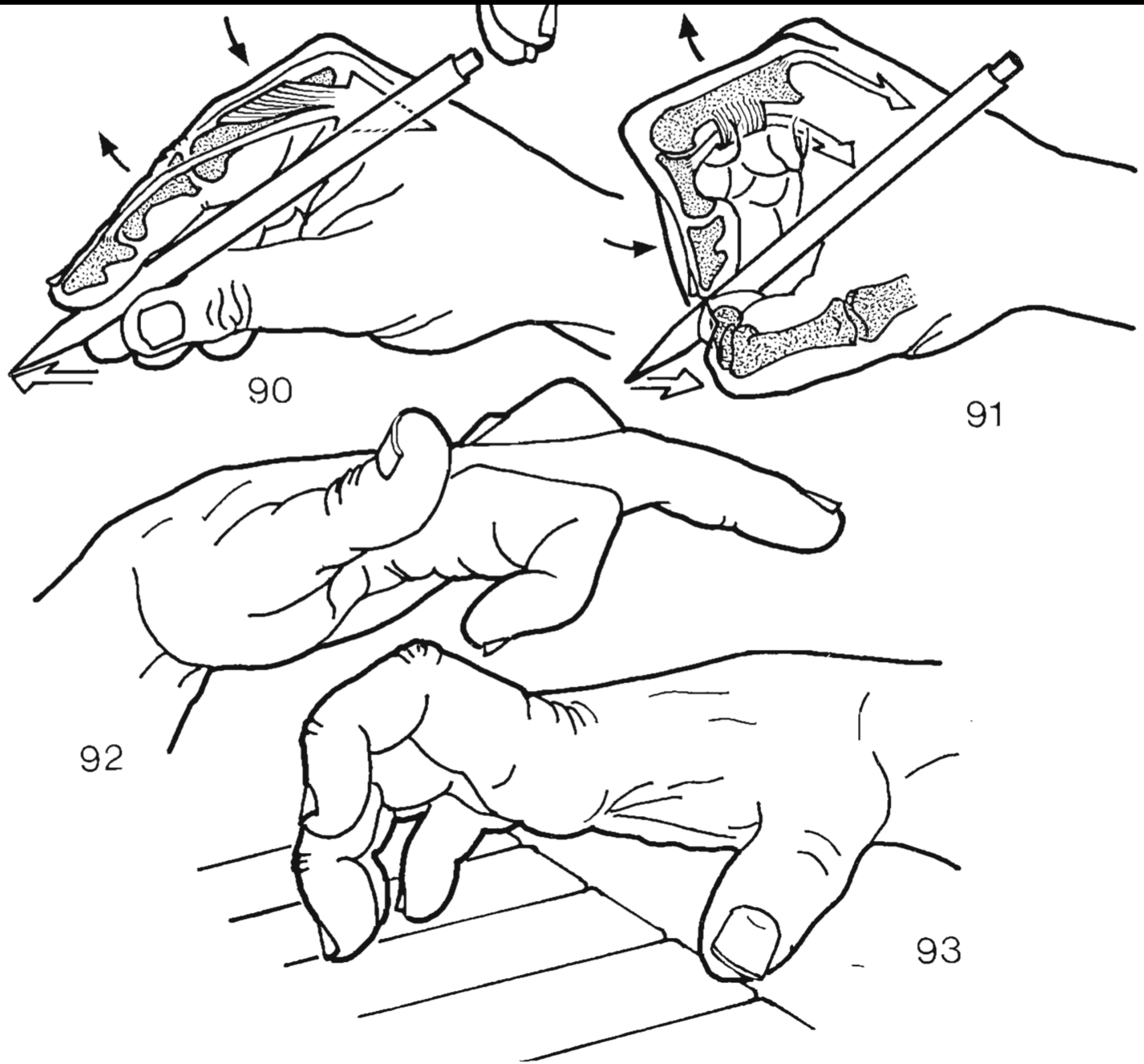
The index is flexed in *a strictly sagittal plane* (P) towards the base of the thenar eminence (long white arrow).

As shown previously (Fig. 13), the axes of the fingers during flexion all converge to a point corresponding to the 'radial pulse'. This can only occur if the other fingers are flexed not in a sagittal plane like the index, but *in an increasingly oblique plane*.

The little finger shows maximal obliquity of its plane of flexion (shown as small white arrow).

The significance of this 'oblique' flexion lies in the fact that it allows the more medial fingers to oppose the thumb like the index.

Four elementary movements?

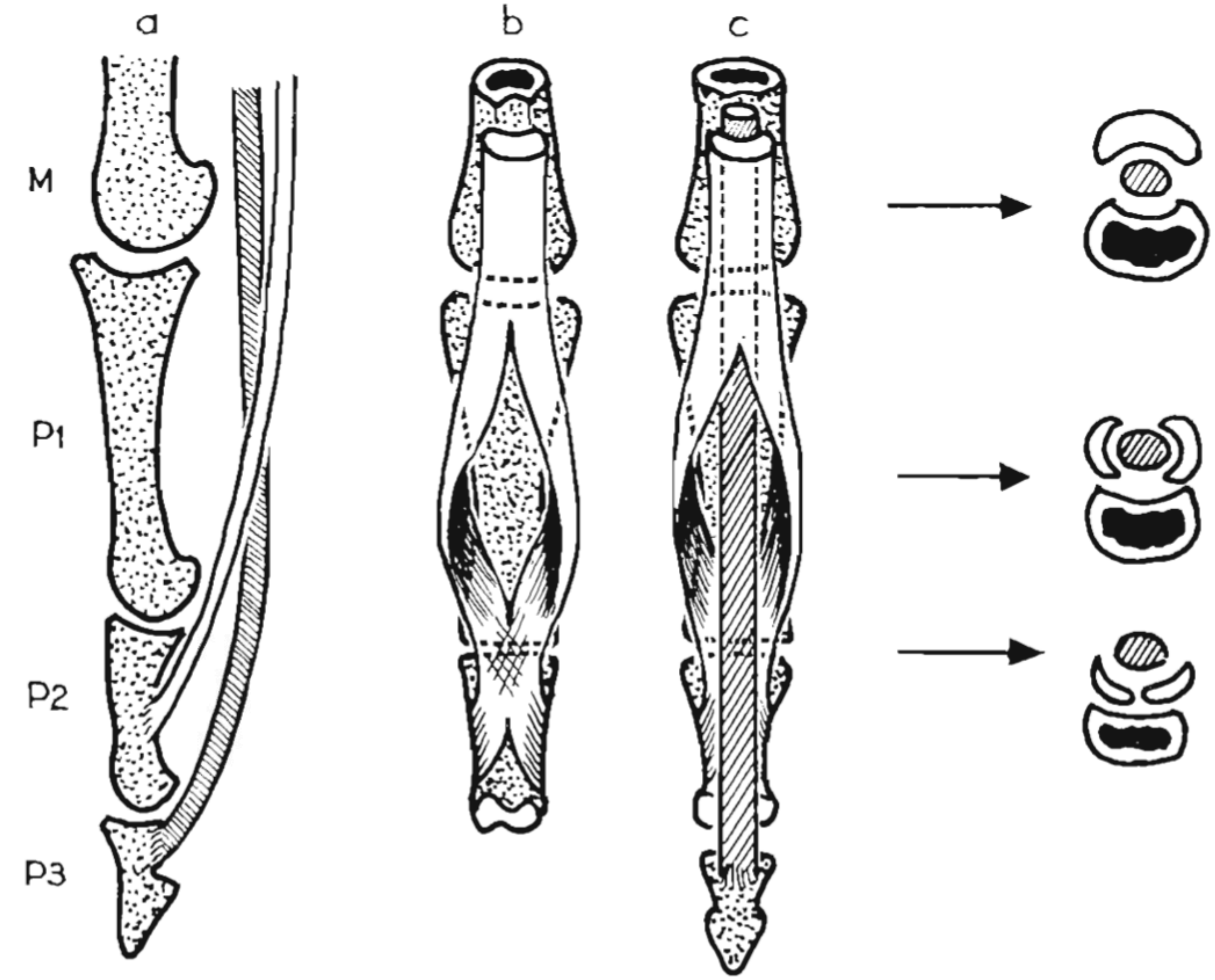


Long (Extrinsic)
Flexors of
the fingers

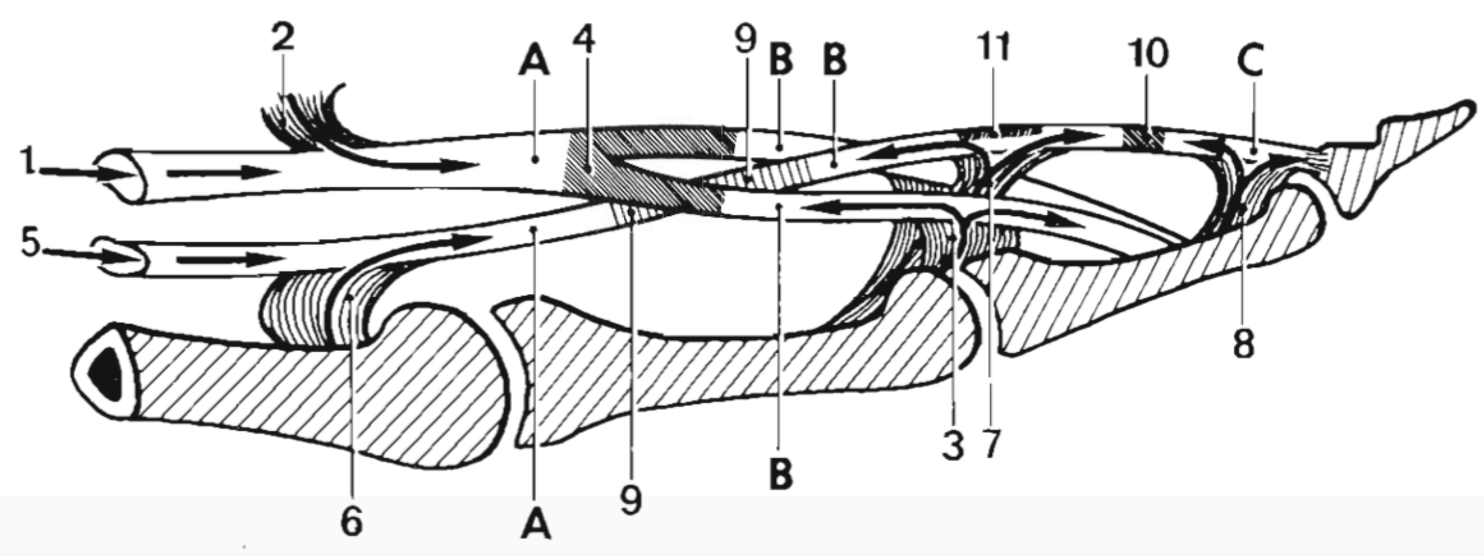
Flexor Digitorum
Profundus

and

Flexor Digitorum
Superficialus

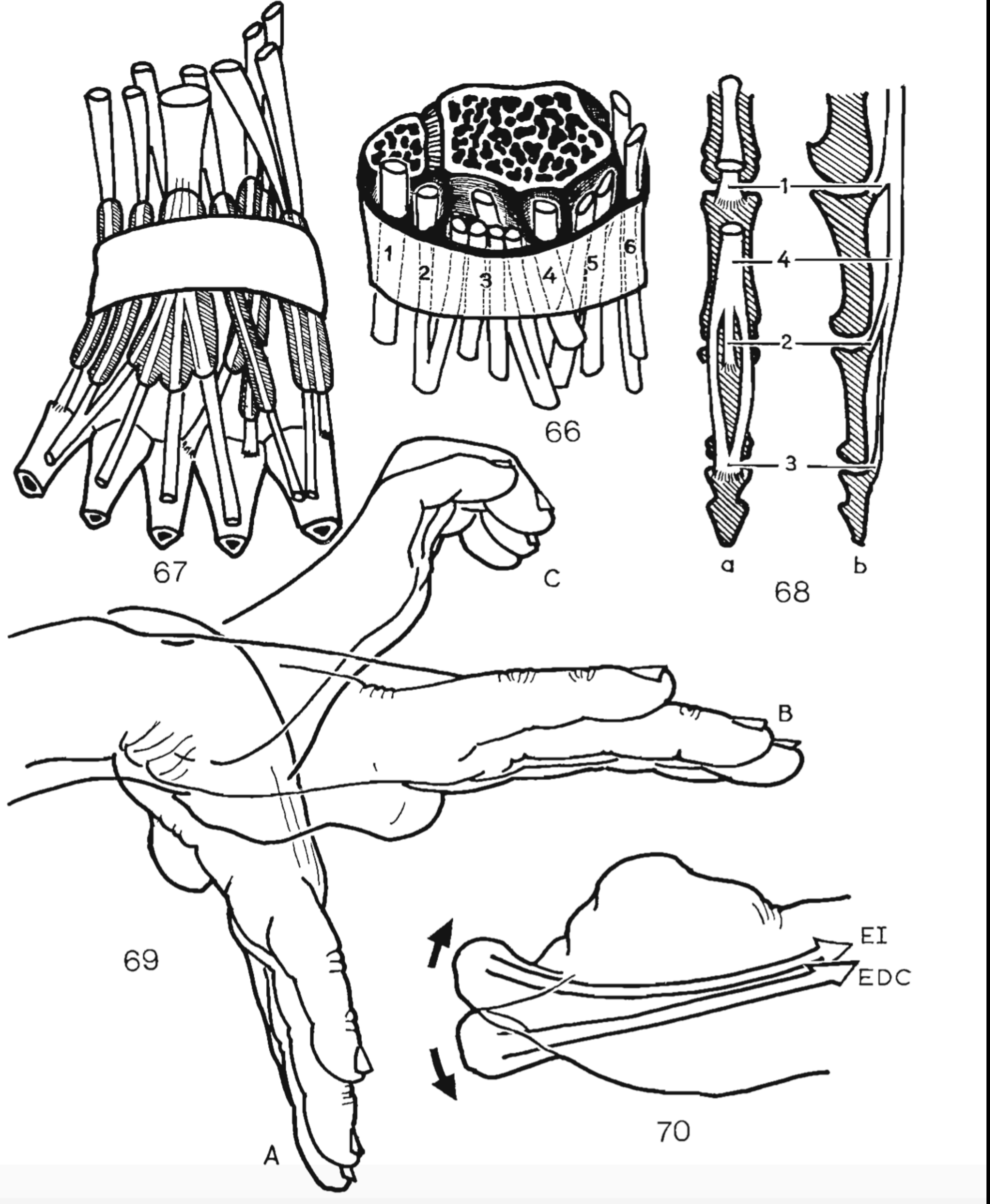


61

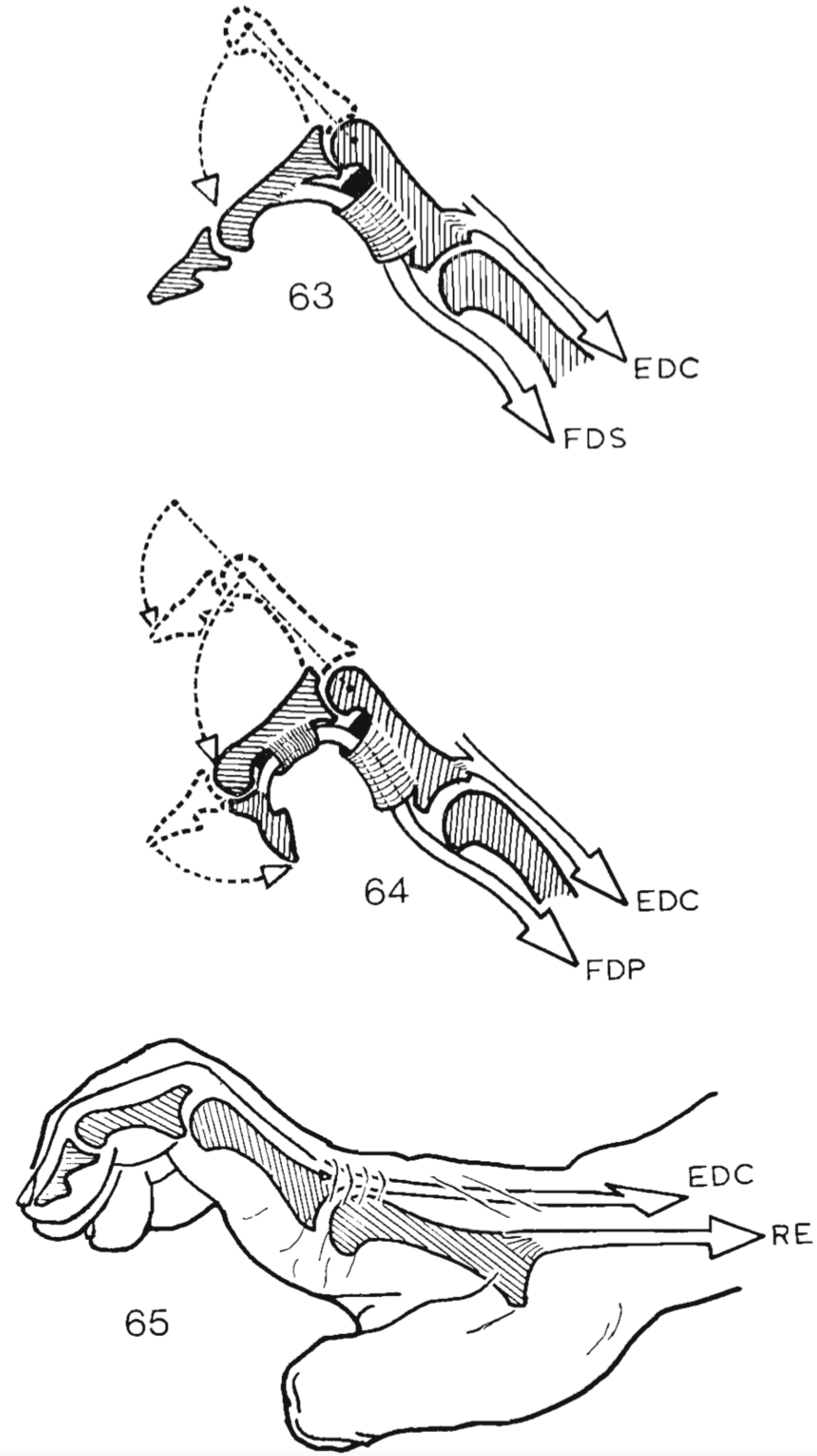


Extrinsic Extensor Web

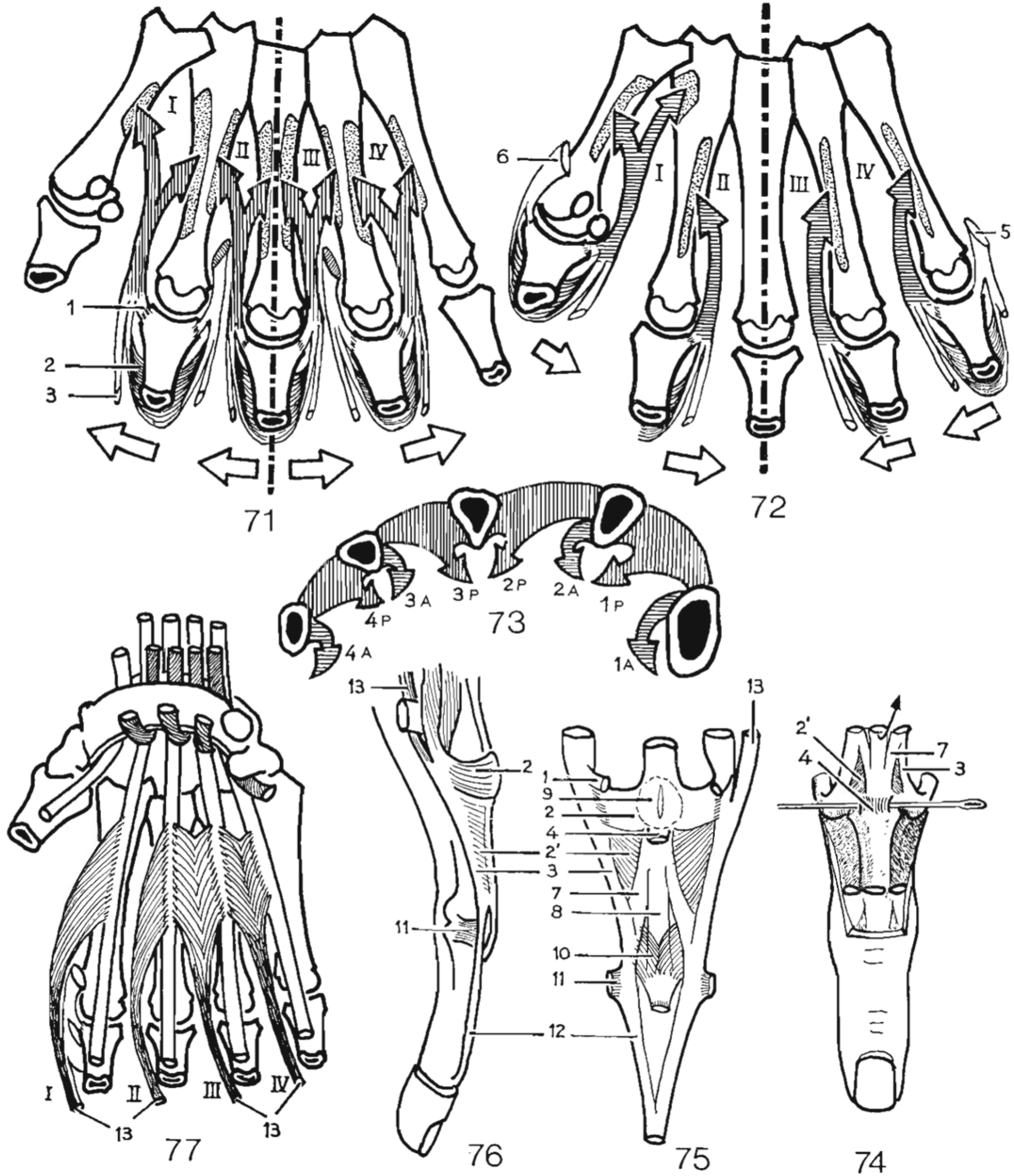
Extensor Digitorum Communis (EDC)



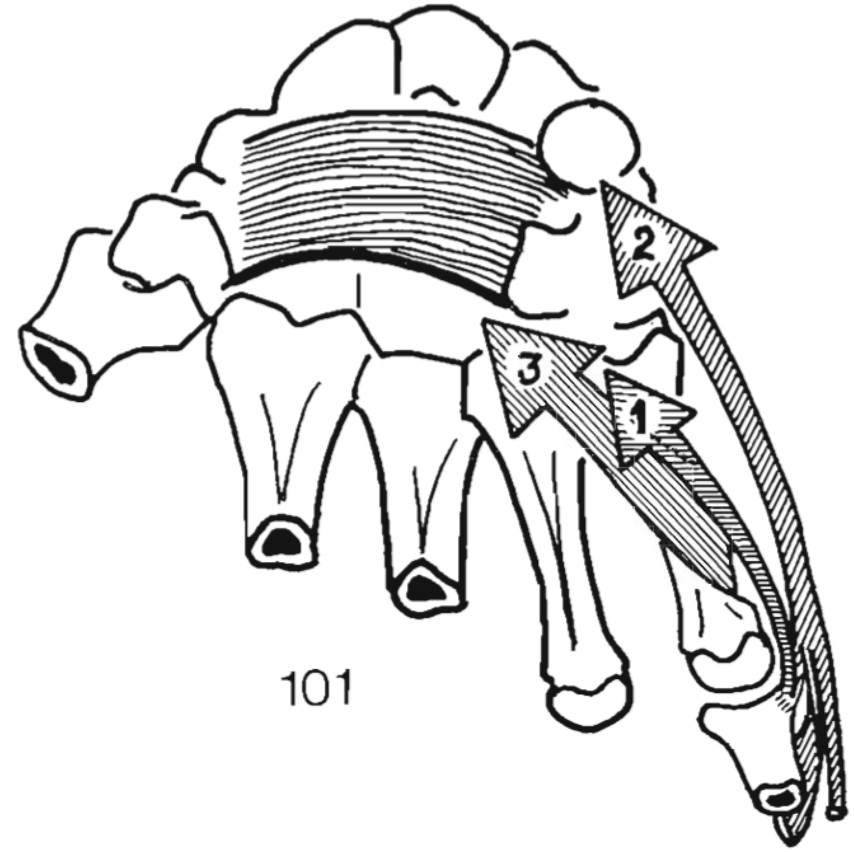
Extrinsic Flexor / Extensor Balance



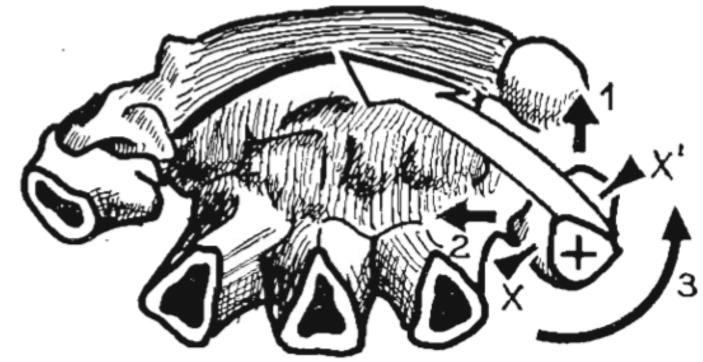
Intrinsic Interosseus and Lumbrical Muscles



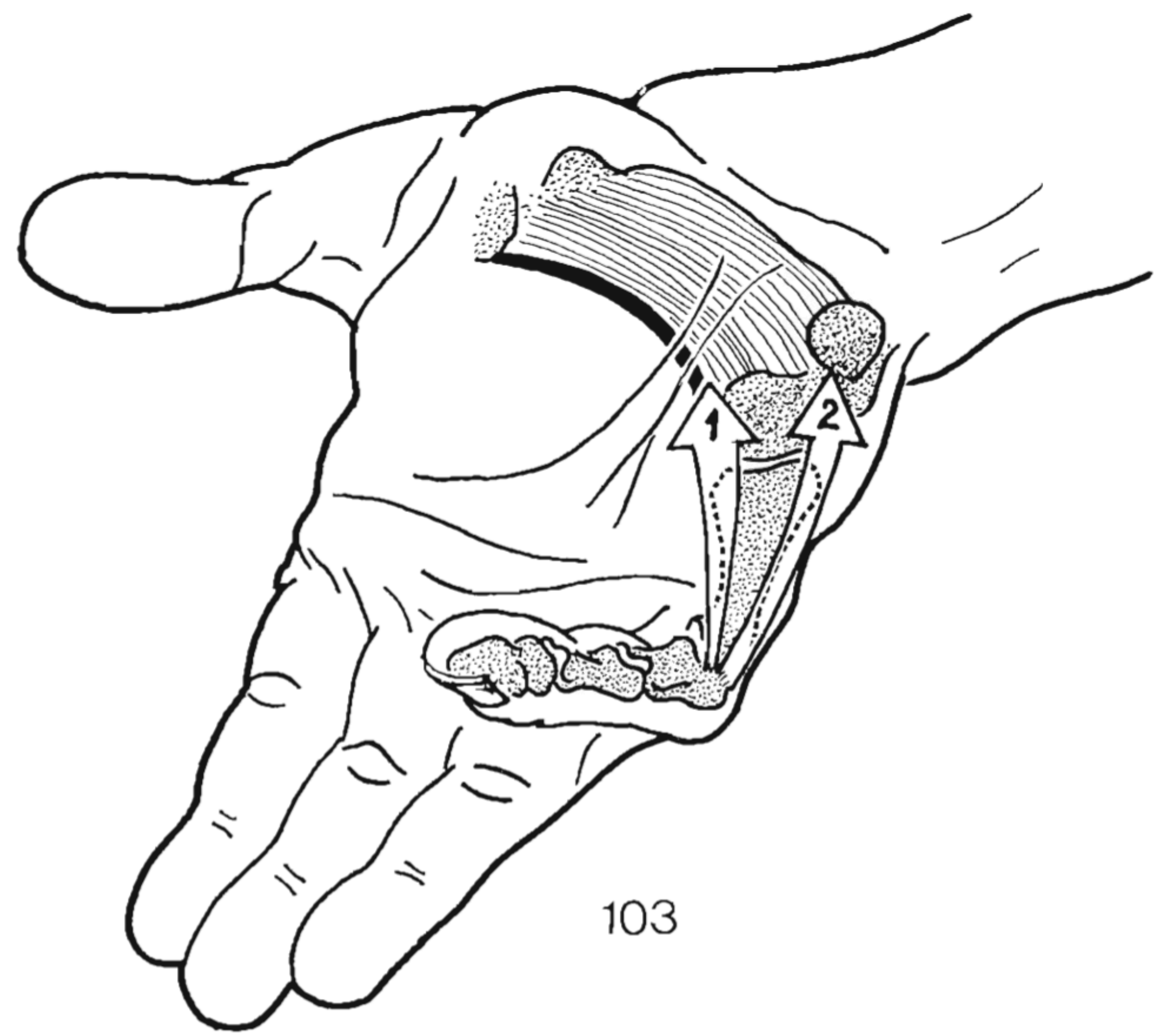
Hypothenar eminence



101



102



103

THE THUMB

The thumb plays a unique role in the function of the hand, being essential for the formation of the *pollici-digital pincers* and for the development of a *powerful grip* along with the other fingers. It can also take part in *dynamic grips* (grips associated with actions). Thus, without the thumb, the hand loses most of its capabilities.

This preeminent role of the thumb is partly due to its *location anterior to the palm and the other fingers* (Fig. 104), which allows the thumb to move towards the fingers individually or together (the *movement of opposition*) and away from them (the *movement of counteropposition*). It is also due to its remarkable *functional suppleness* secondary to the peculiar organization of its *osteo-articular column* and its *motor muscles*.

THE GEOMETRY OF OPPOSITION OF THE THUMB

Geometrically speaking (Fig. 106), opposition of the thumb consists of bringing into contact the pulp of the thumb and that of another finger so that they touch at point A′ (thumb) and A (finger). In other words, the tangential planes of the two pulps A and A′ merge in space at a single point A + A′.

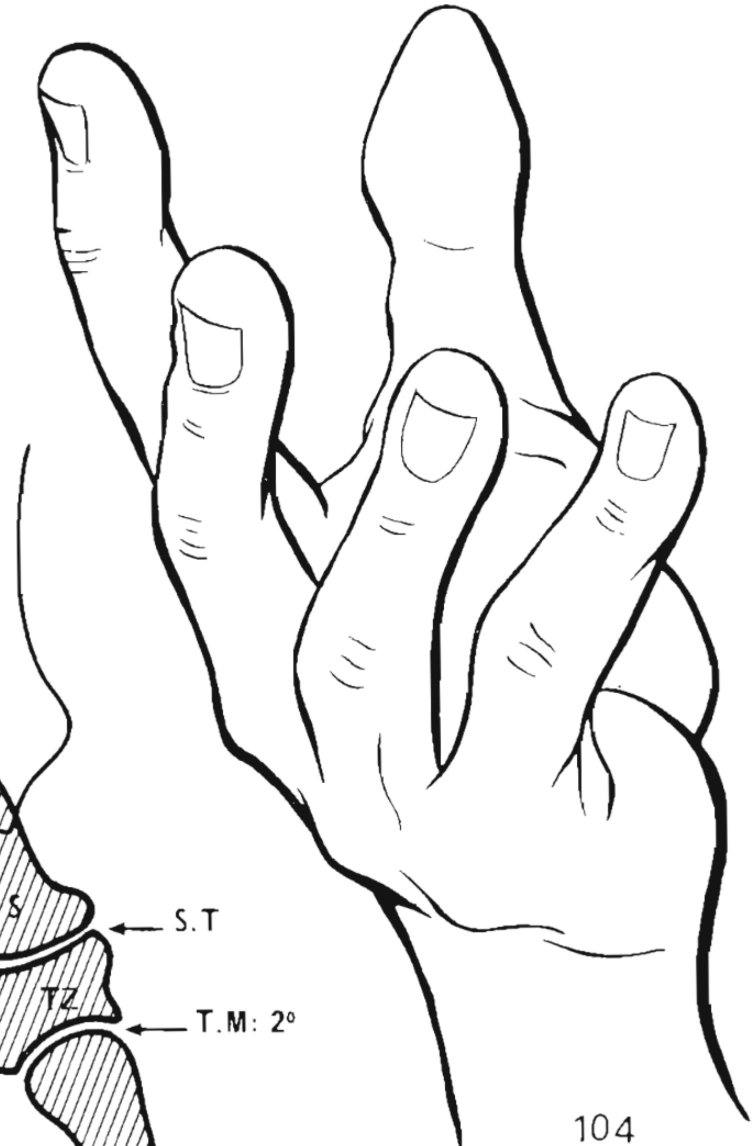
For two points to coincide in space (Fig. 107) *three degrees of freedom* are necessary in keeping with the three coordinates in space, x, y, z. *Two additional degrees of freedom* are needed for the planes of the pulps to coincide perfectly, i.e. two axes t and u are needed for rotation to occur. Since the pulps cannot come into contact 'back to back' a third degree of freedom about an axis v perpendicular to t and u is not necessary.

In sum, to achieve coincidence of these planes **five degrees of freedom** are necessary:

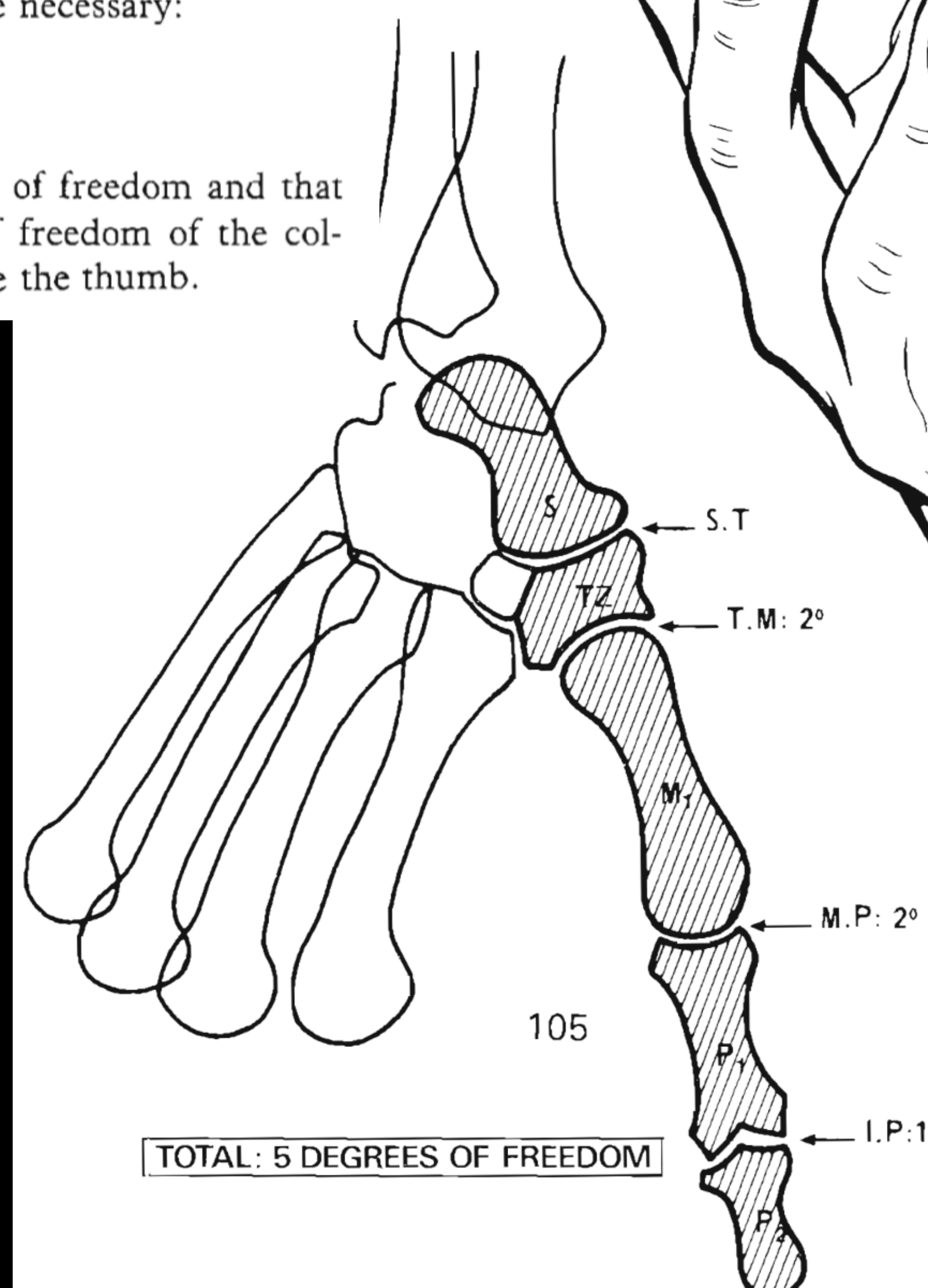
— three for coincidence of the points of contact.

— two for full coincidence of the planes of the pulps.

It can be easily demonstrated that each axis of a joint represents a degree of freedom and that these degrees of freedom can be added numerically. Thus the five degrees of freedom of the column of the thumb are both necessary and adequate to achieve opposition of the the thumb.

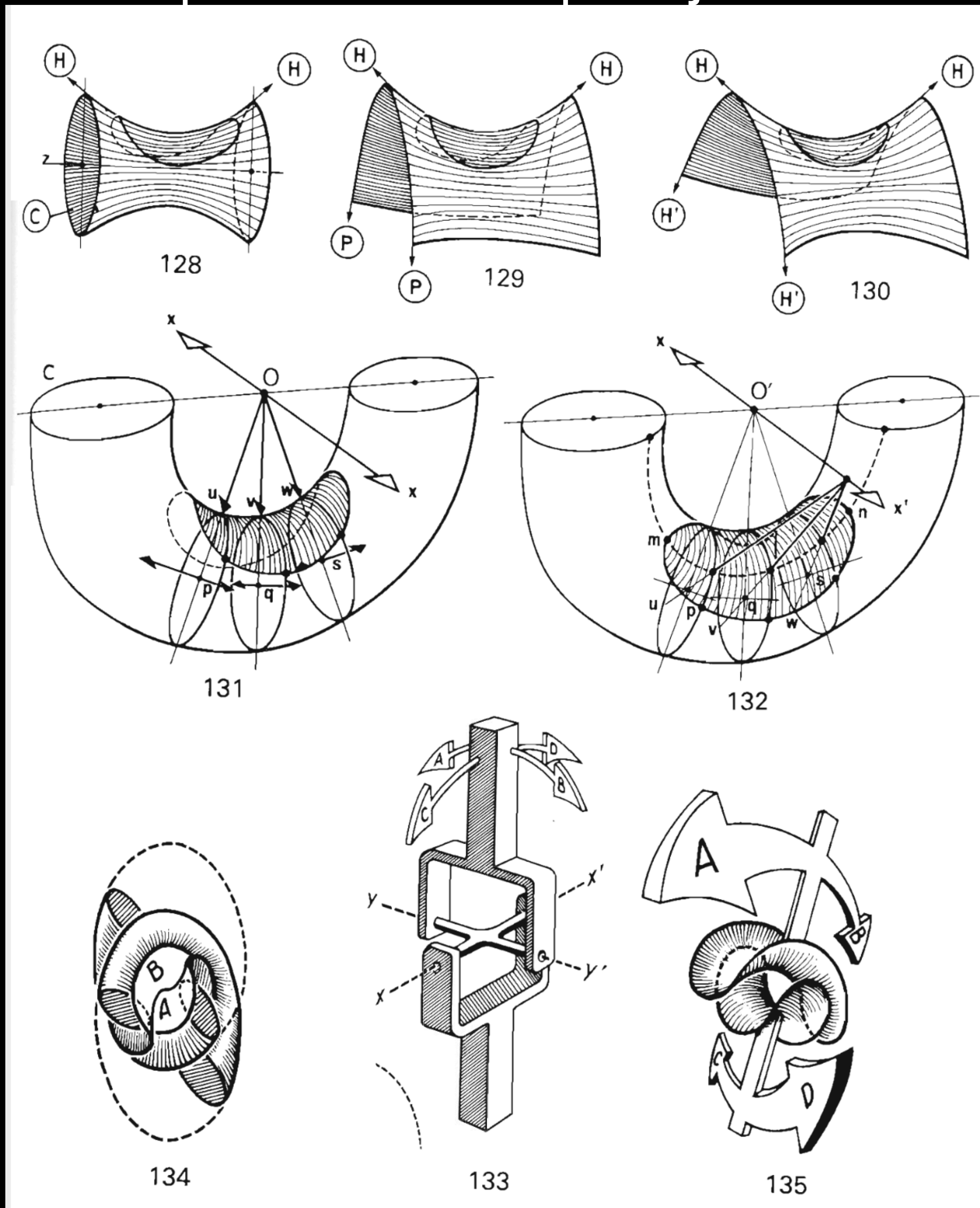


104



105

Carpometacarpal joint

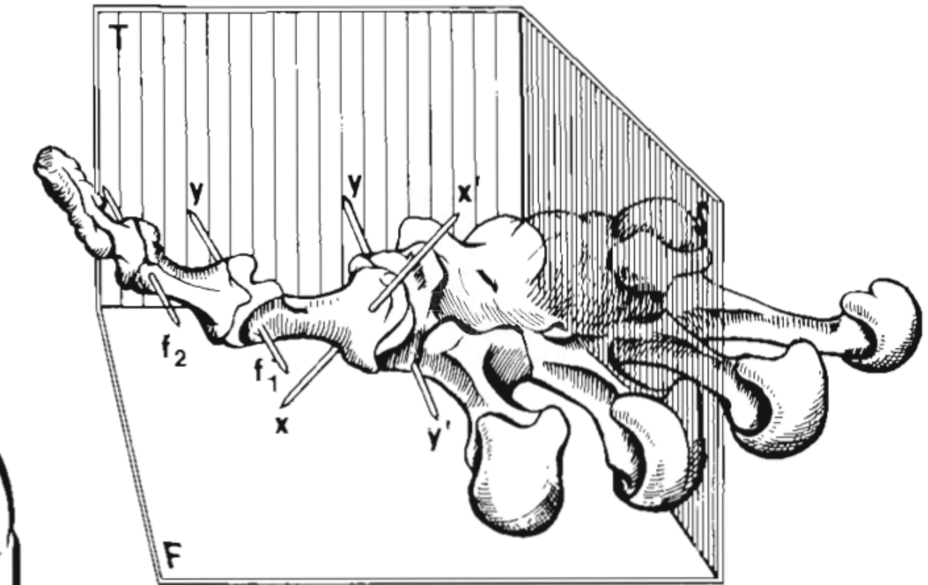


A: 15-25

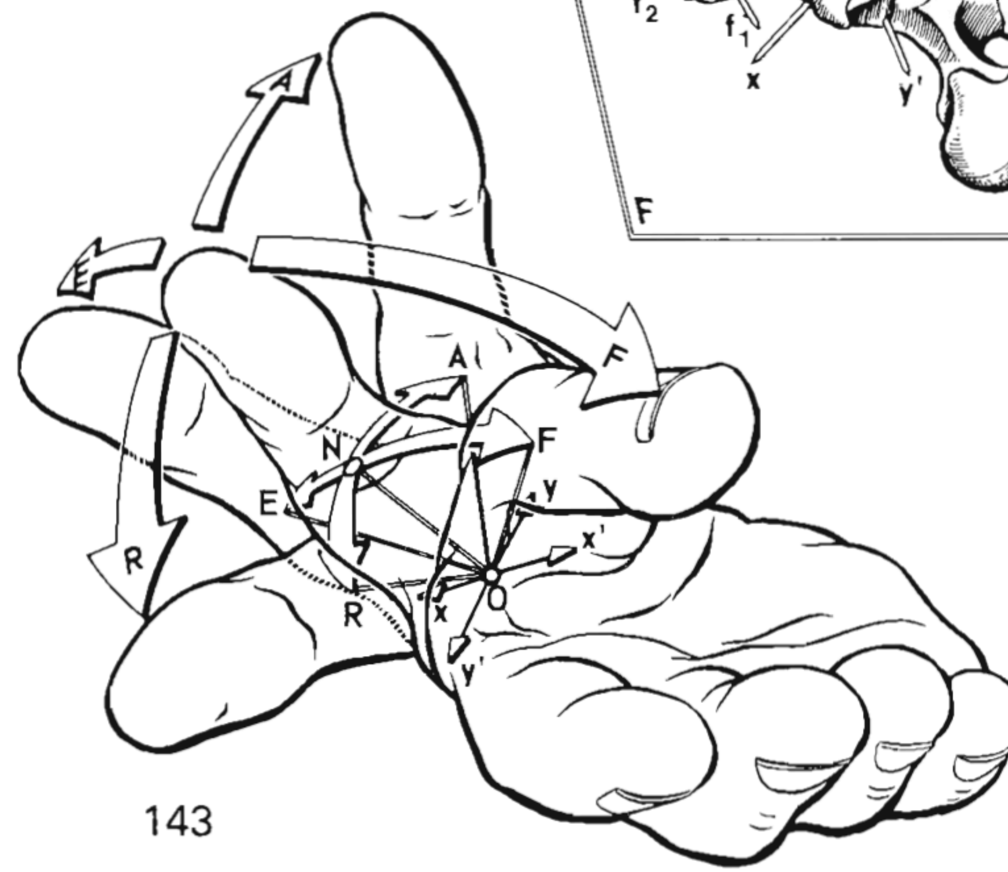
R: 25-35

F: 20-25

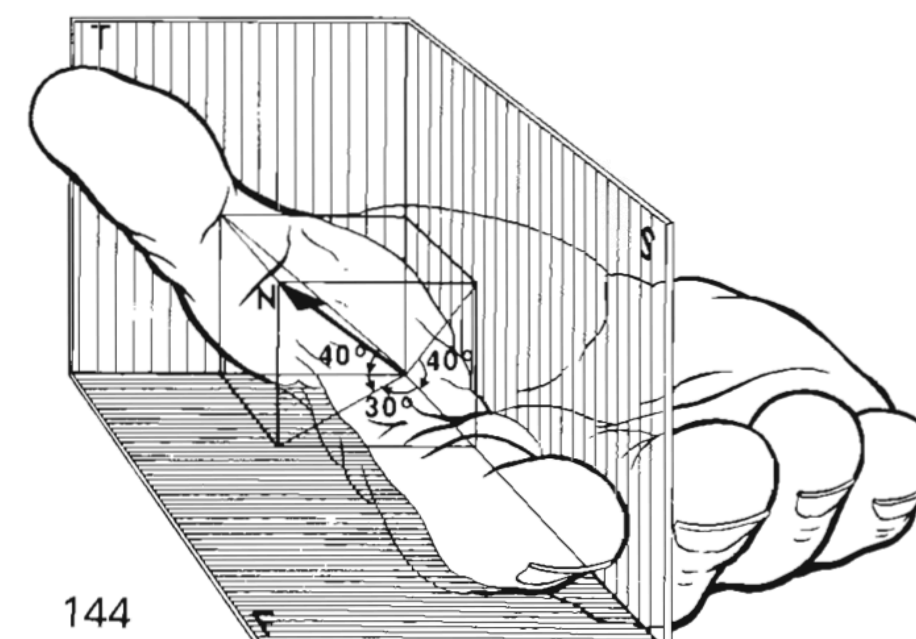
E: 30-45



142

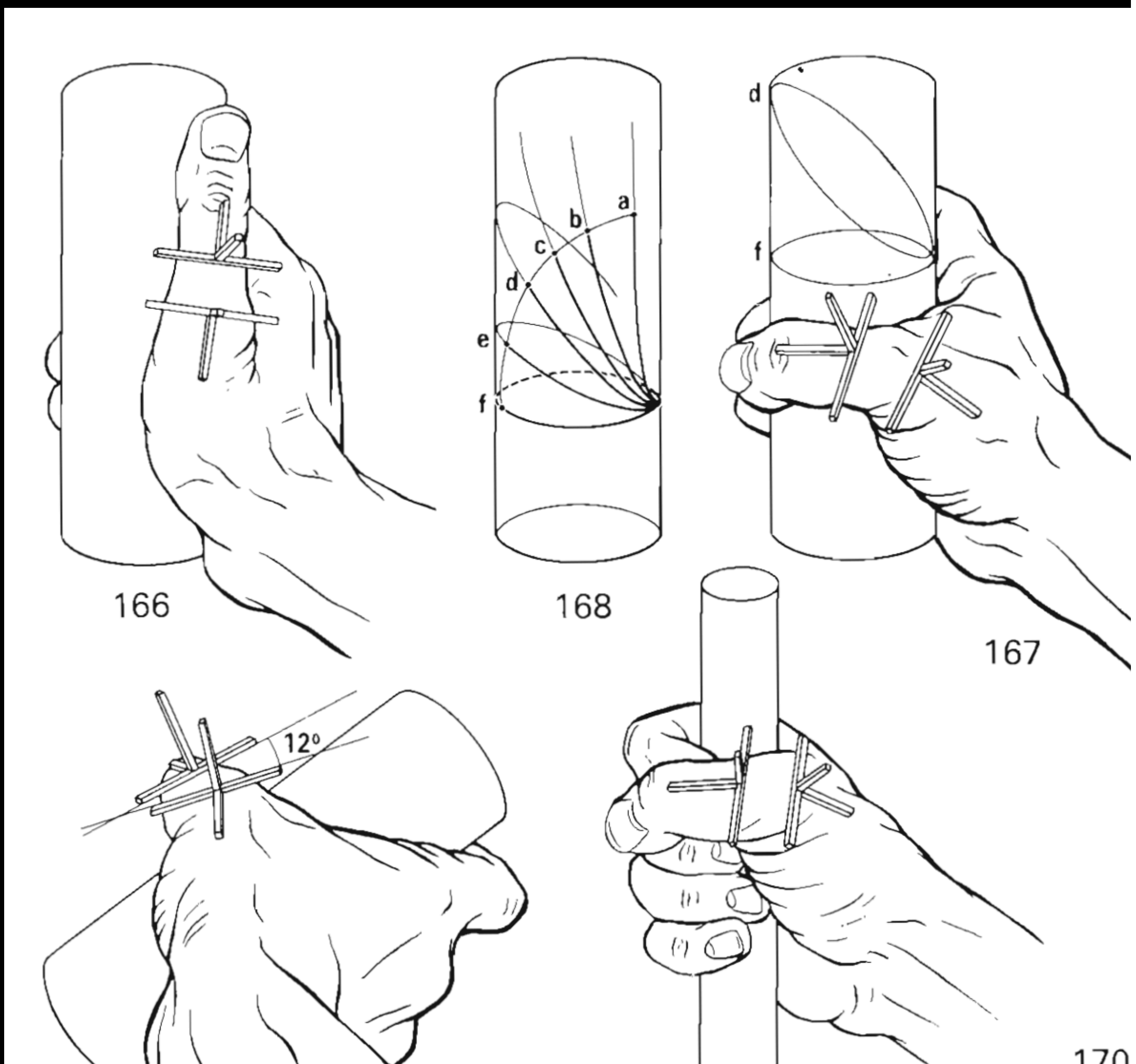


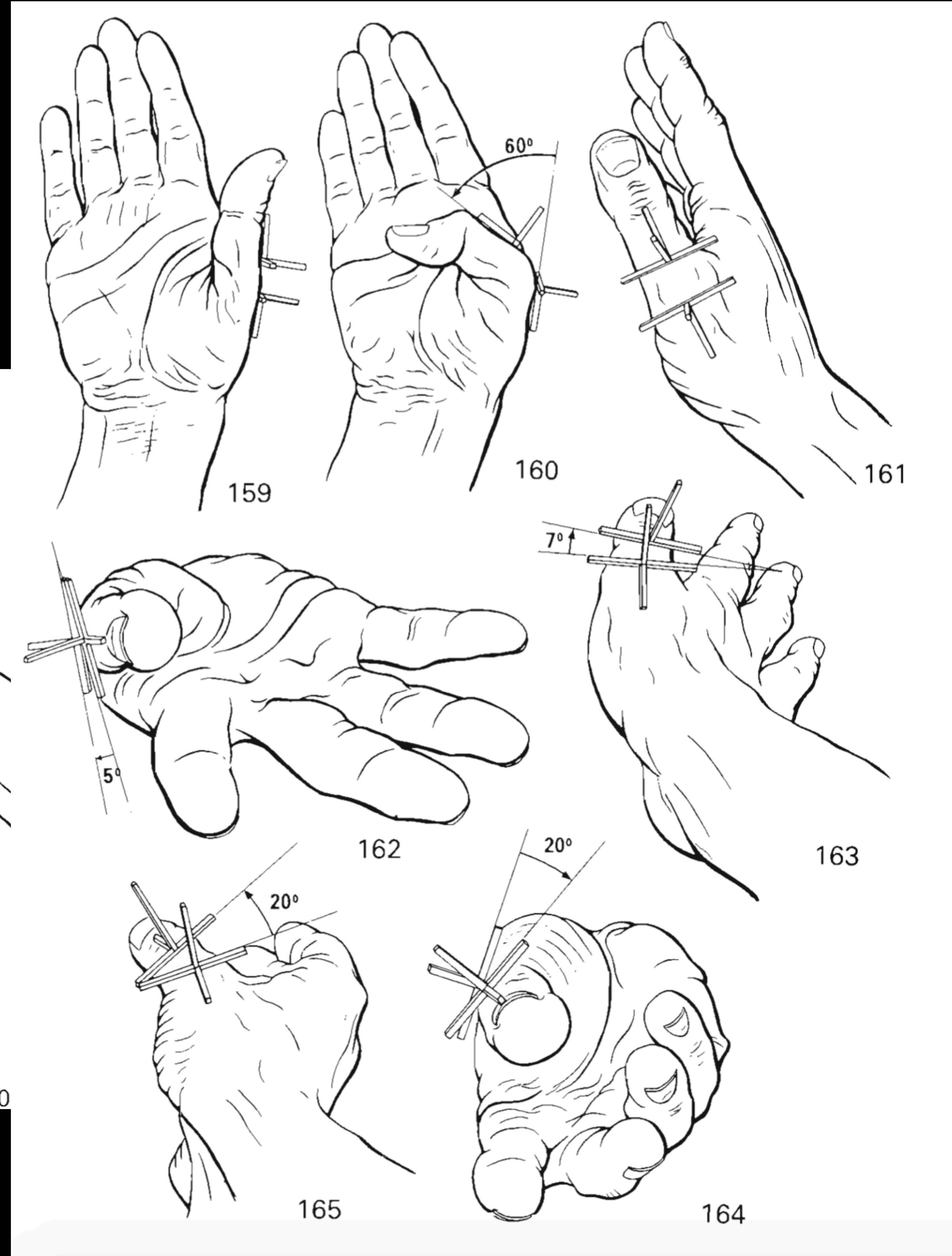
143



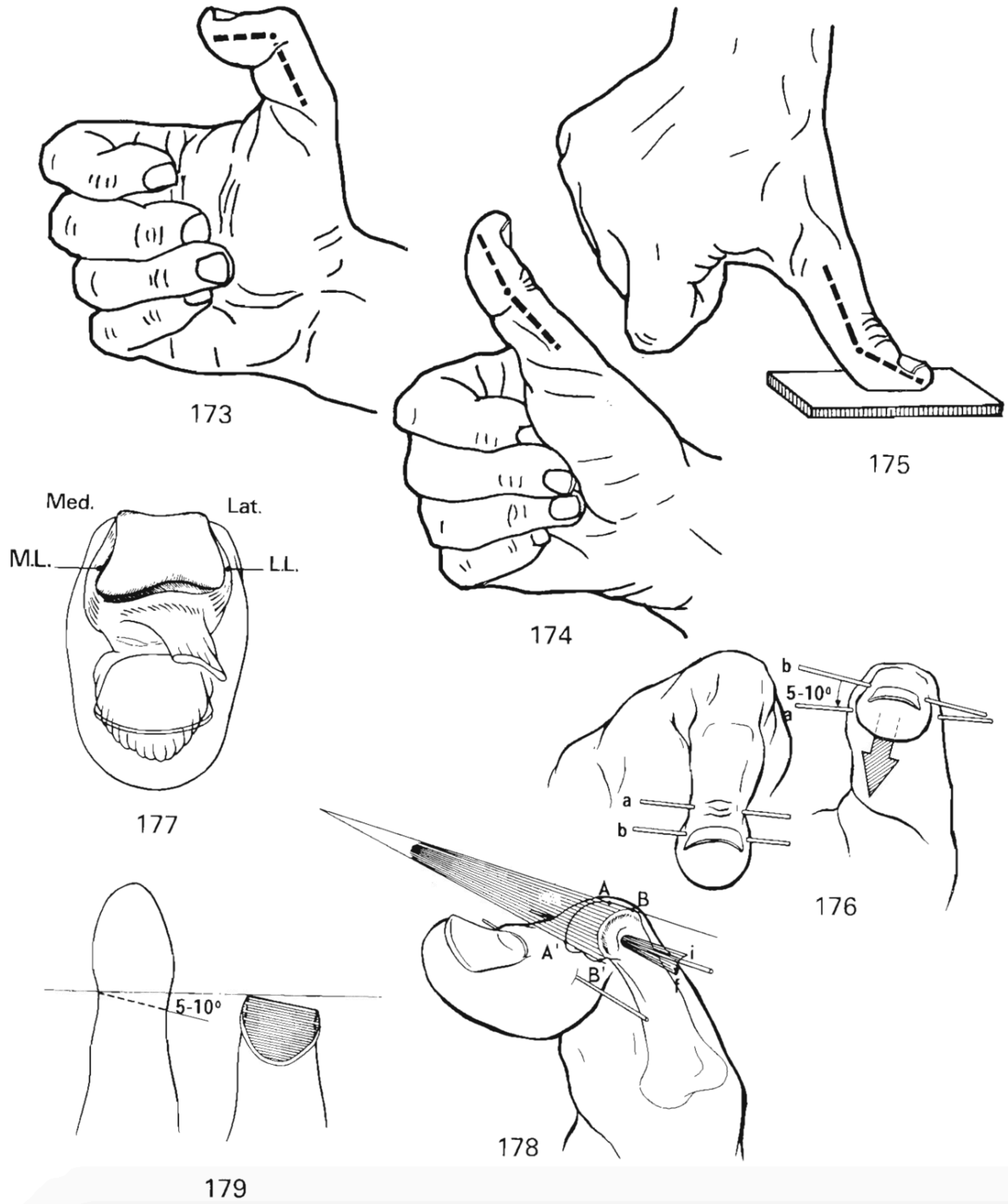
144

Metacarpophalangeal joint (MCP joint)

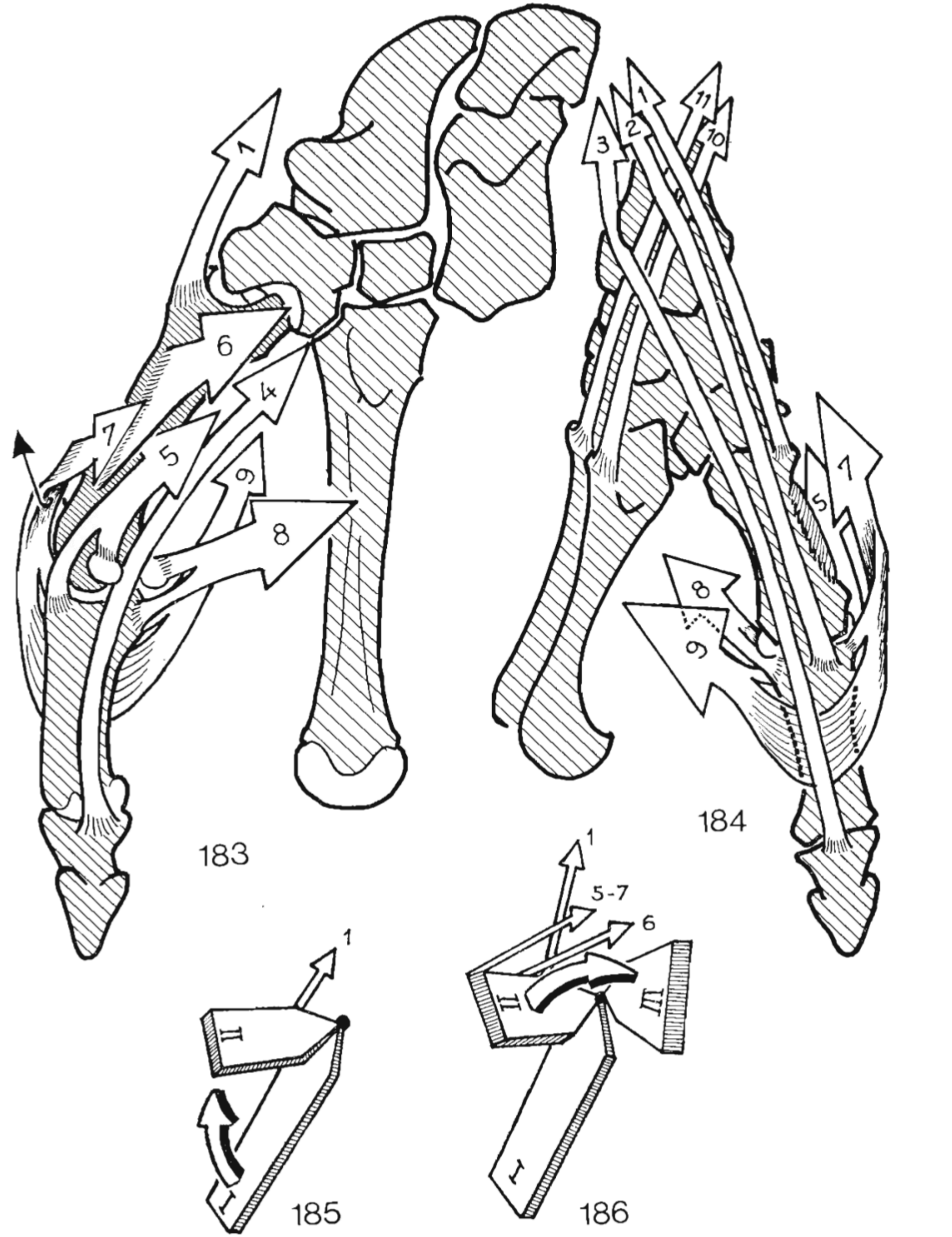


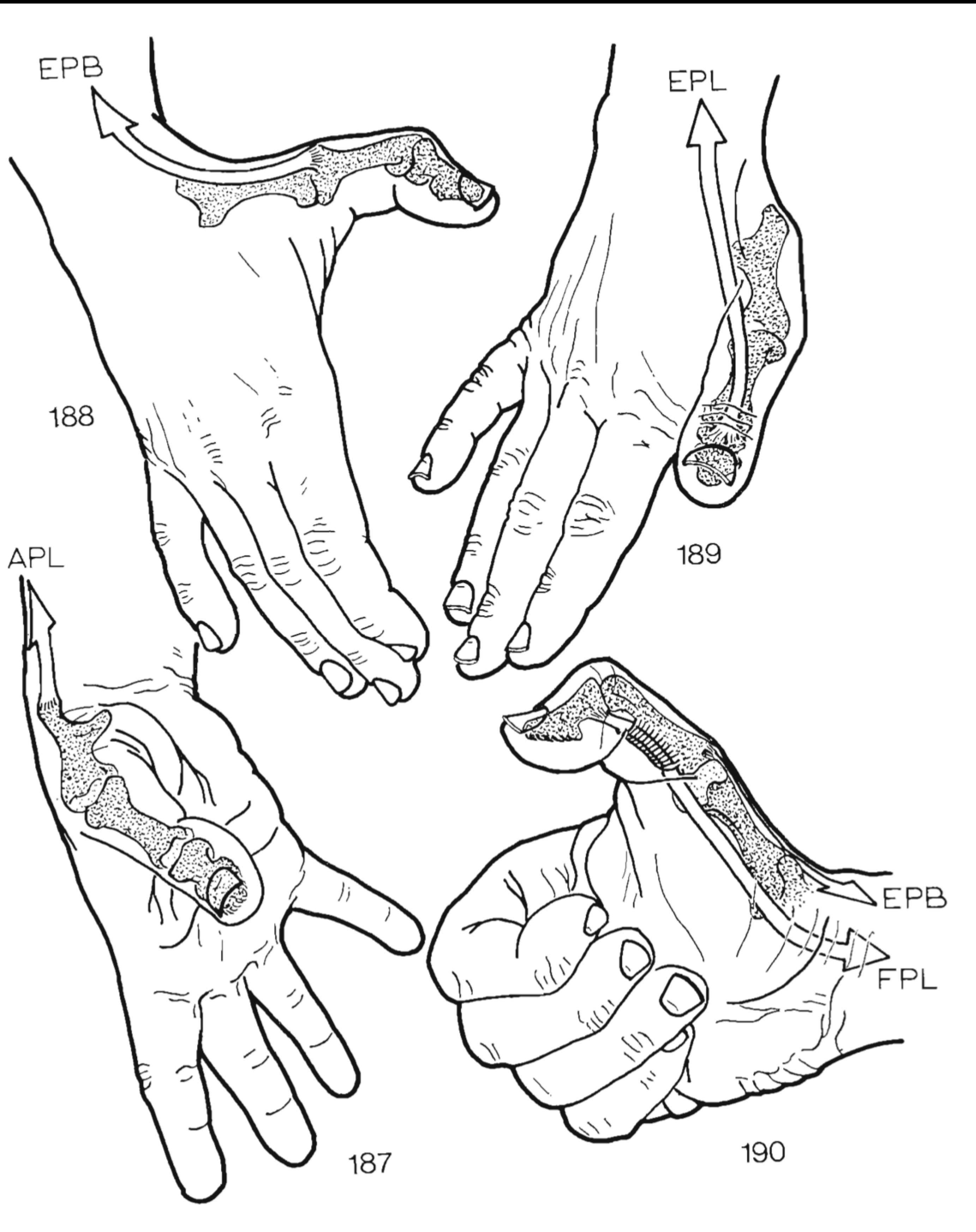


Interphalangeal joint (IP joint)

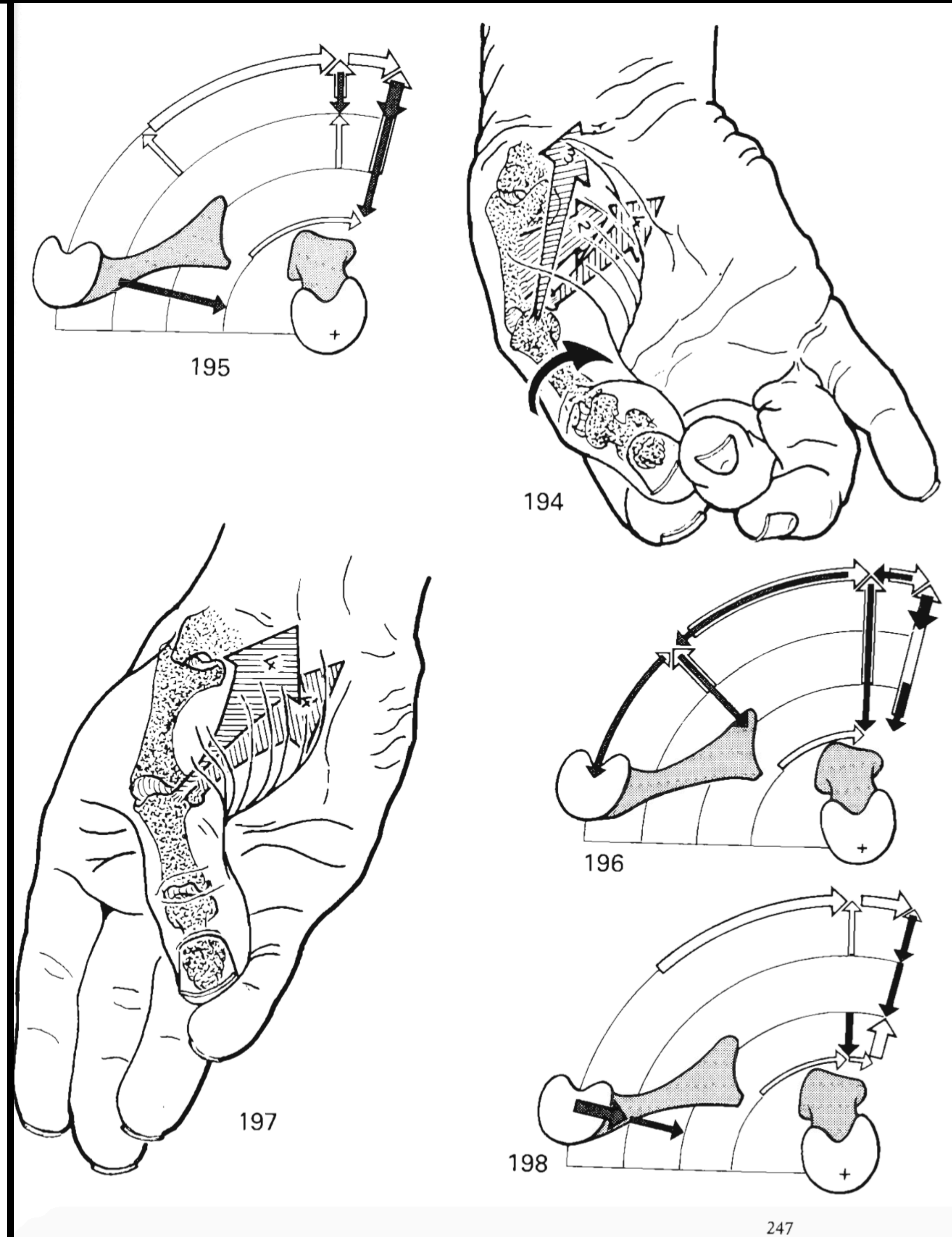


Muscles of the Thumb

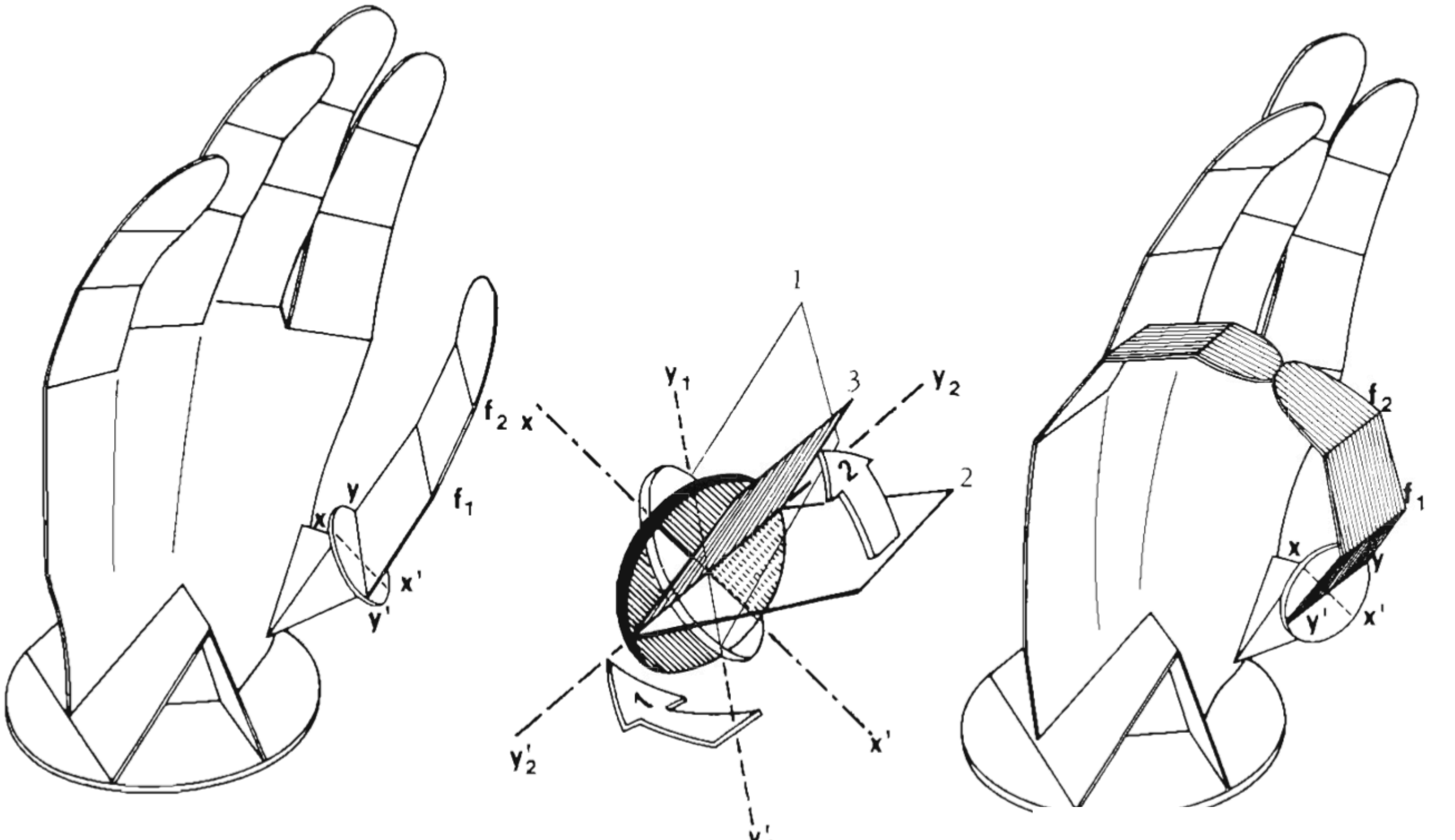




actions of extrinsic muscles

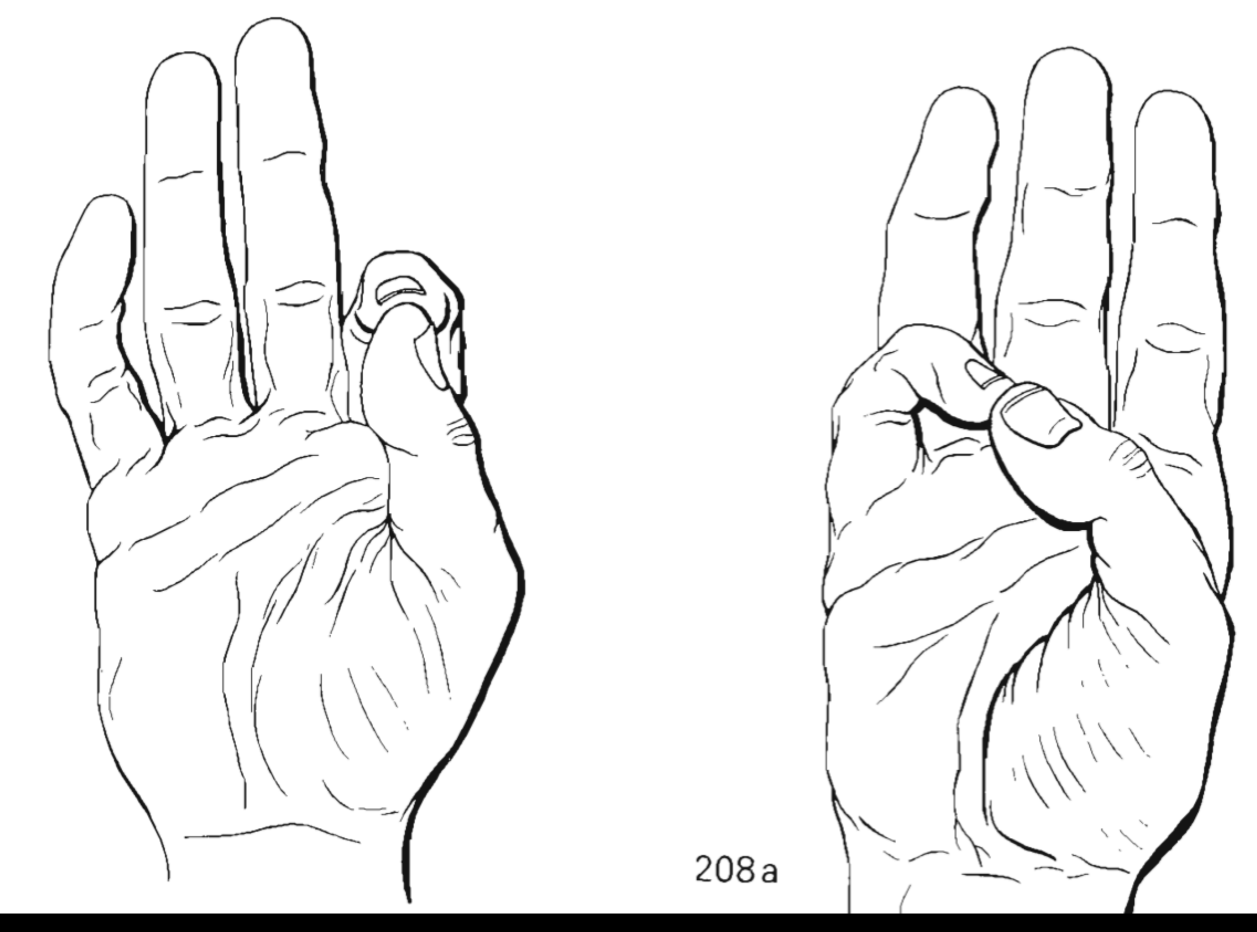


actions of intrinsic muscles



204

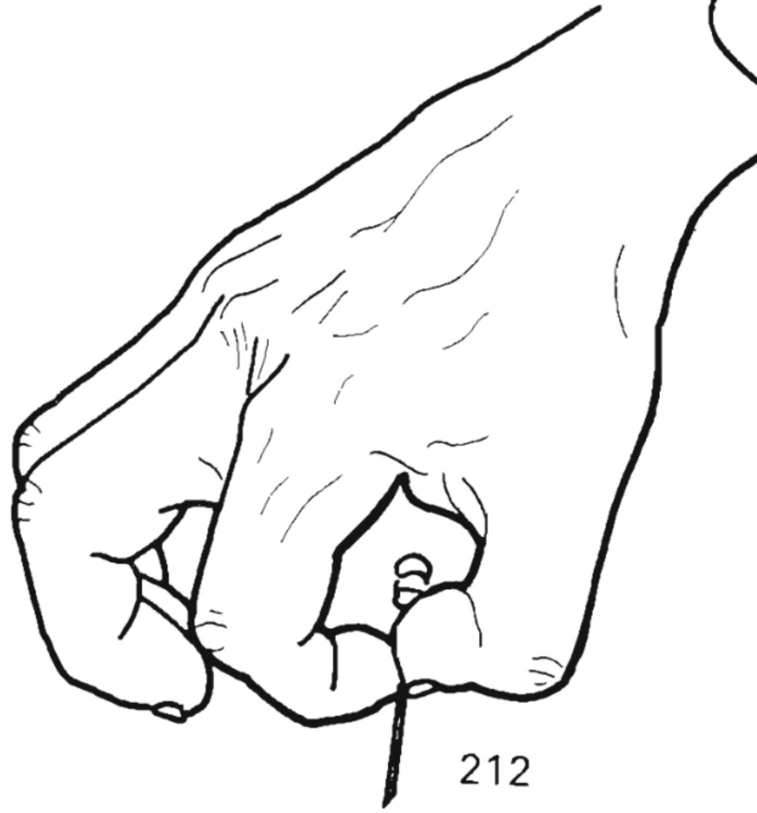
206



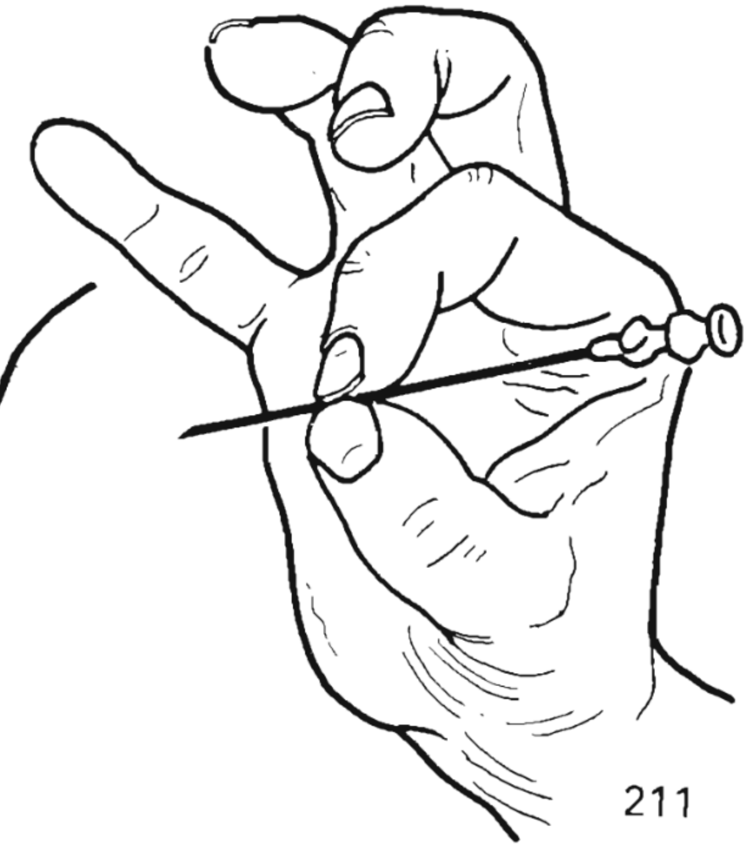
208a

THE MODES OF PREHENSION

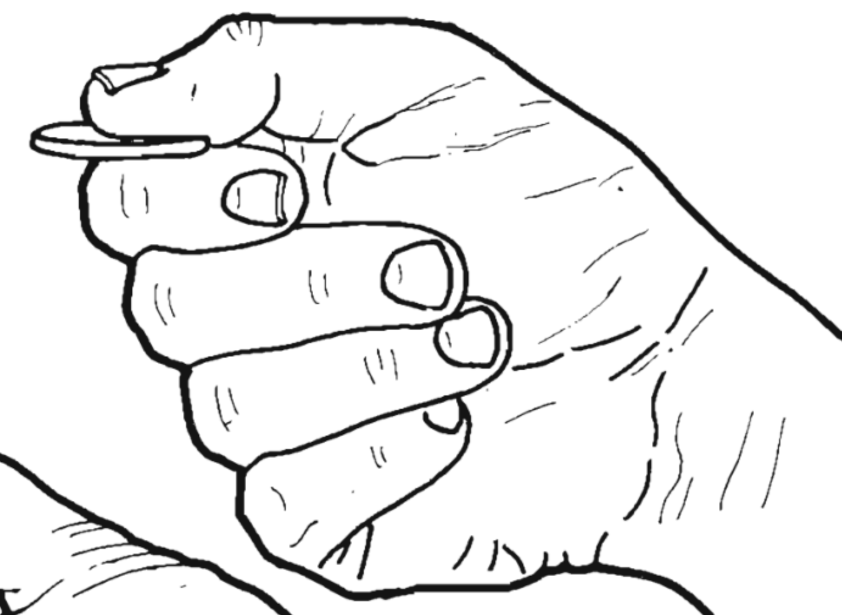
The complex anatomical and physiological organization of the hand contributes to prehension. There are many modes of prehension which fall into three broad categories: static grips, grips associated with gravity and dynamic grips (associated with actions). In addition to prehension, the hand can act as an instrument of percussion, as a means of contact and in the performance of gestures. These will be discussed sequentially.



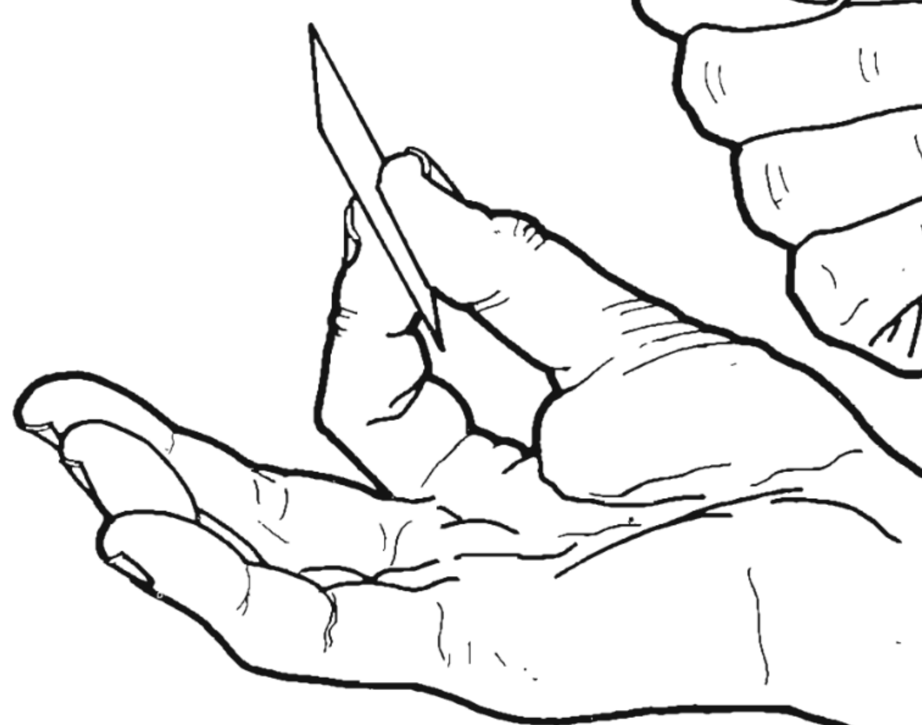
212



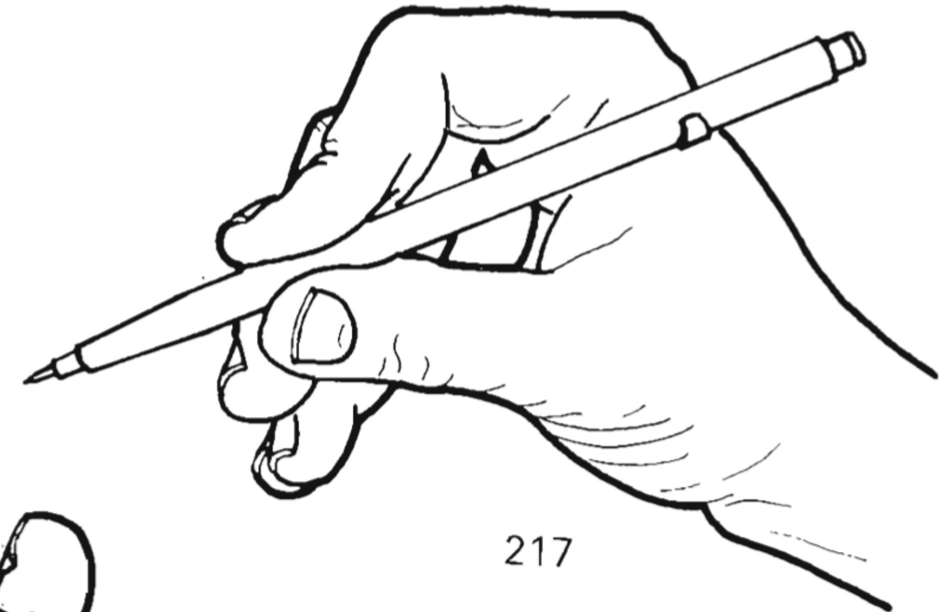
211



214



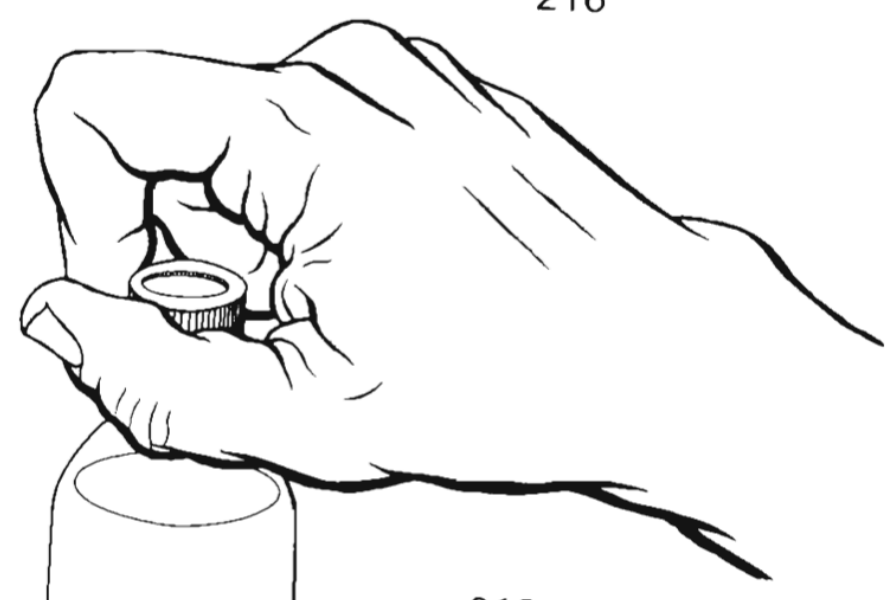
213



217

216

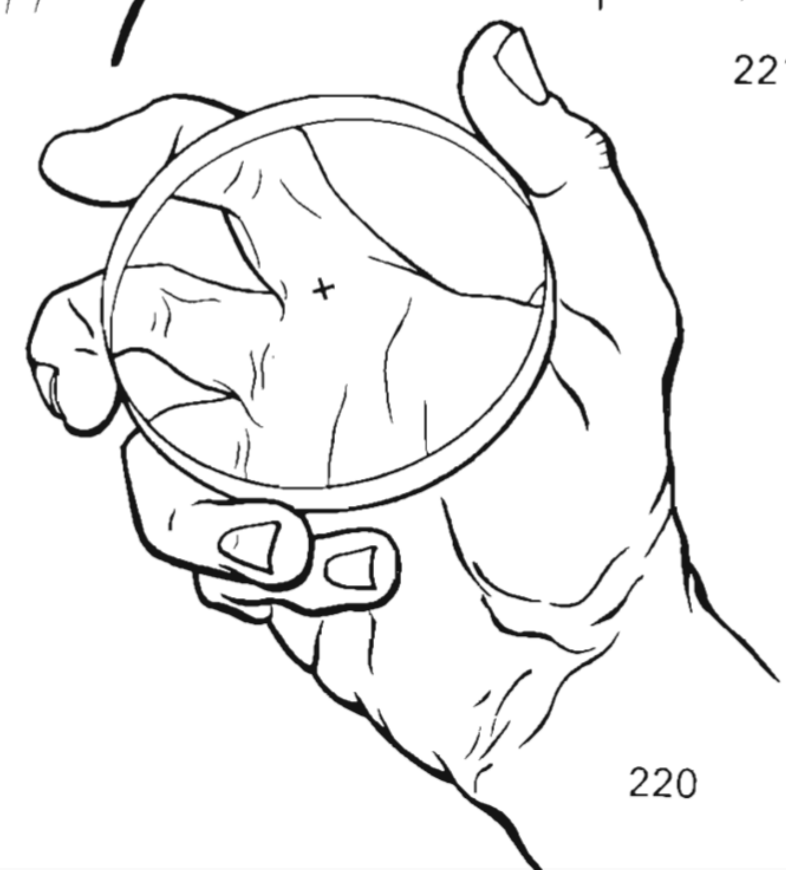
215



218

219

221

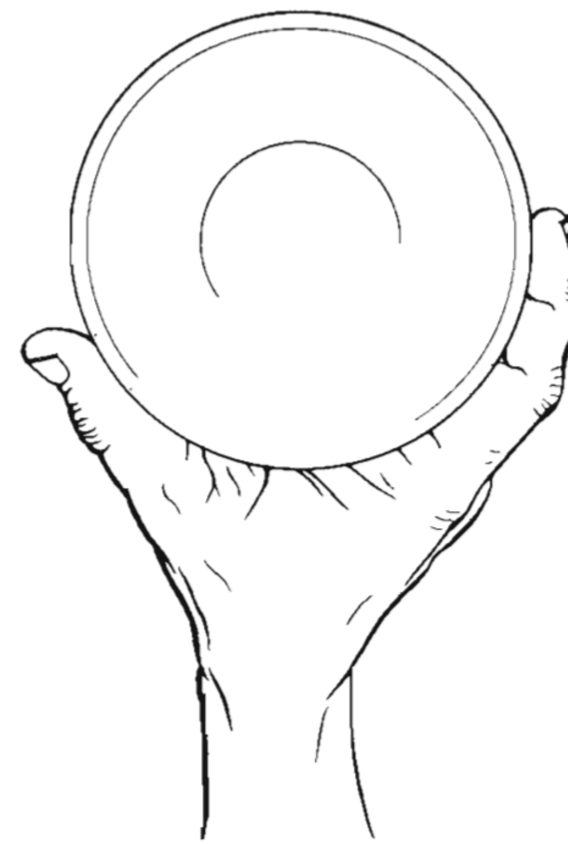


220

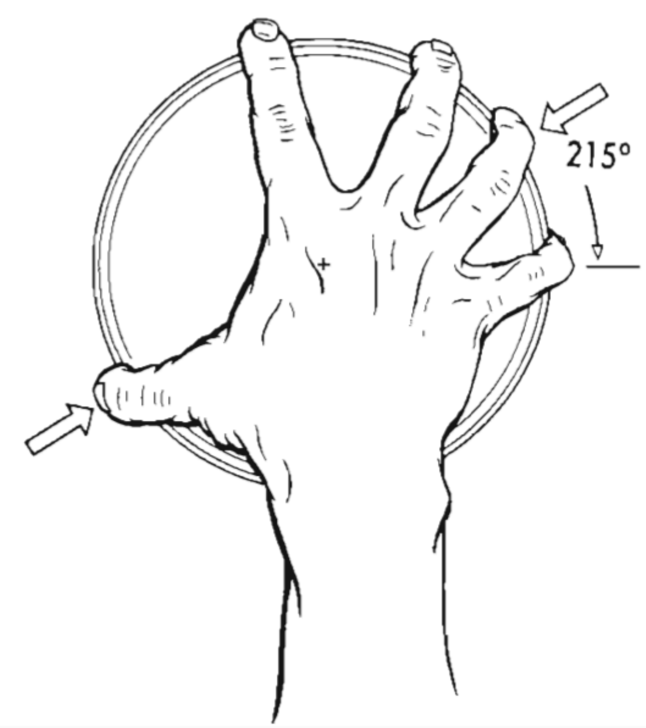
222

223

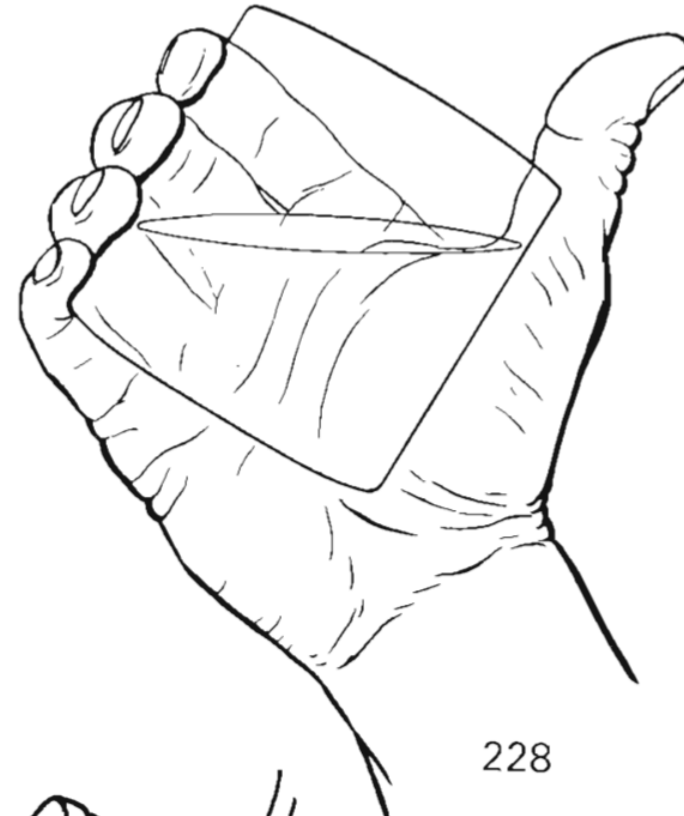
225



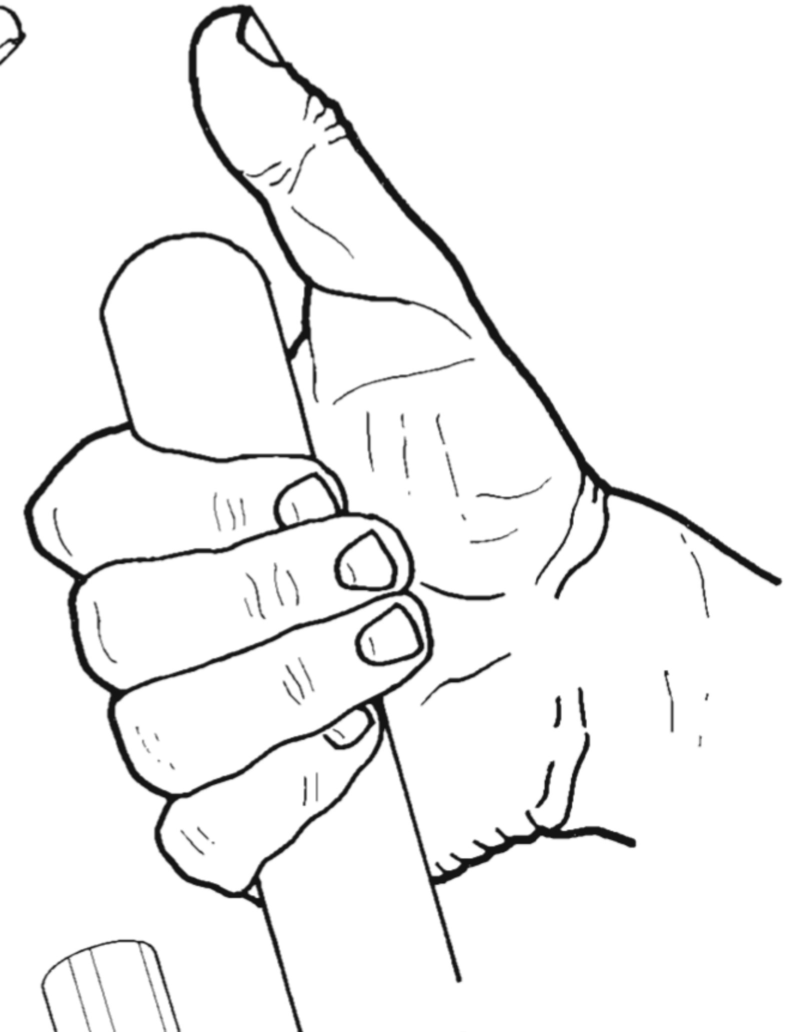
224



226



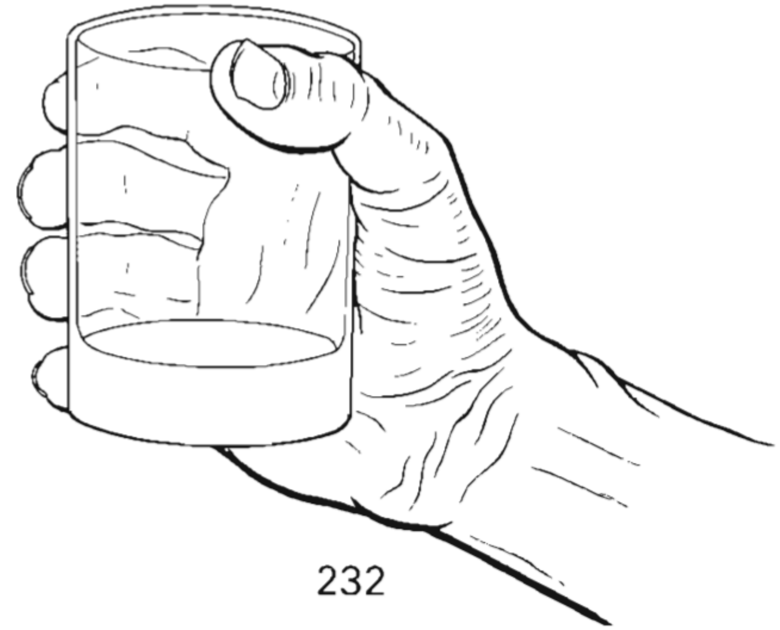
228



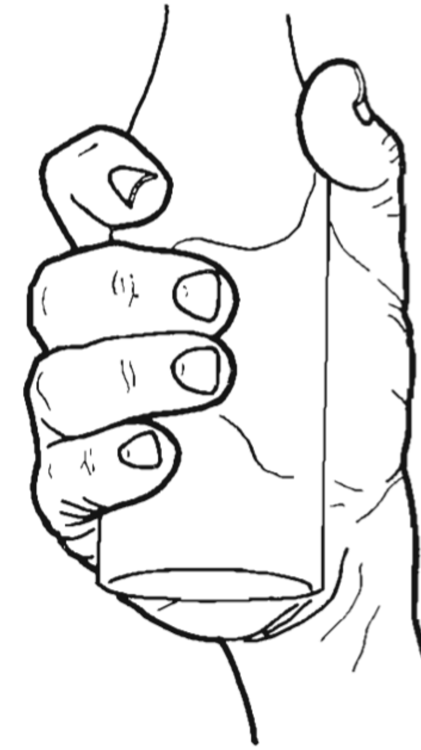
227

230

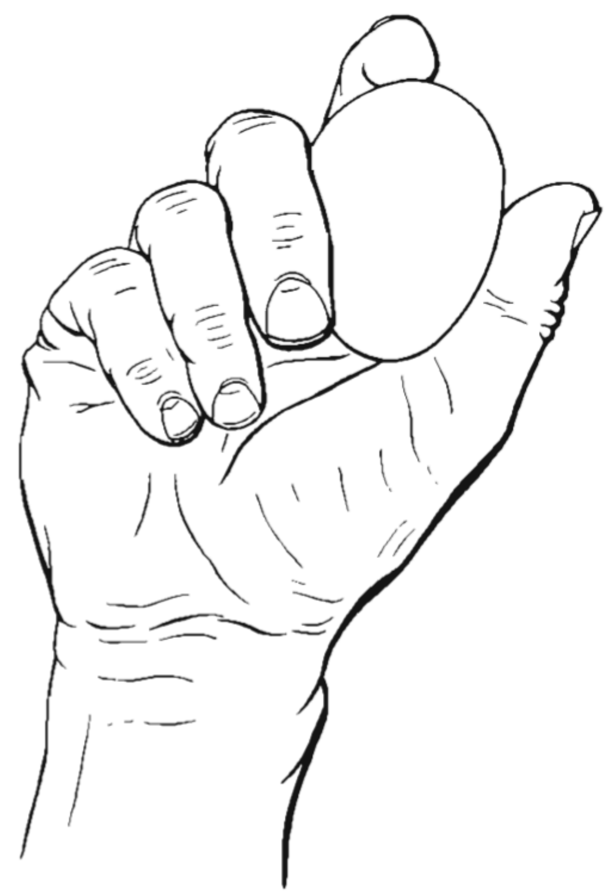
229



232



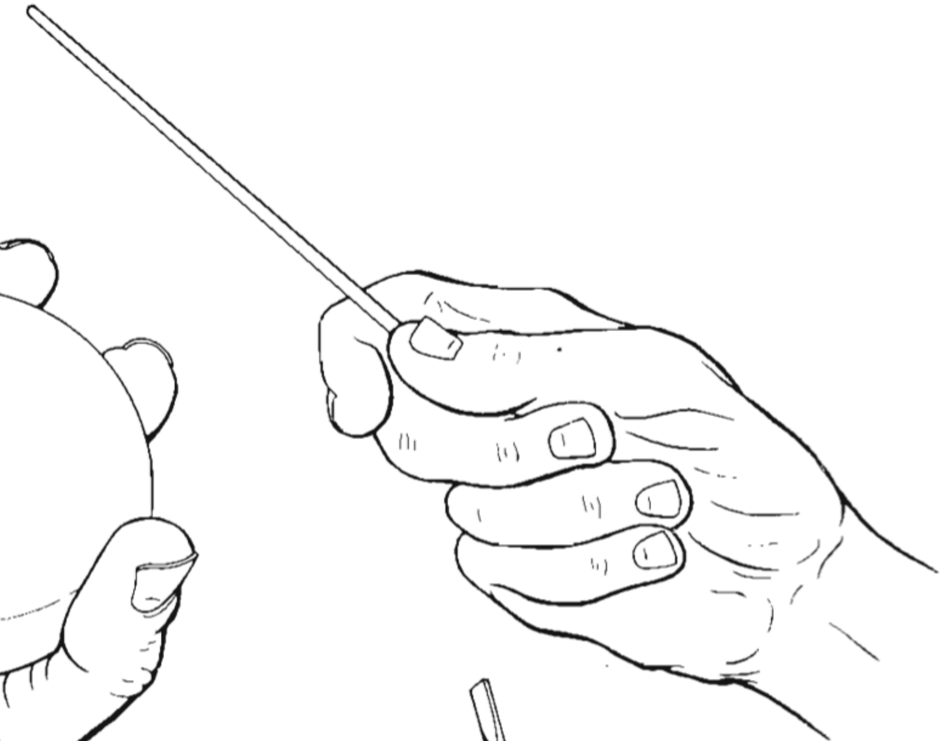
231



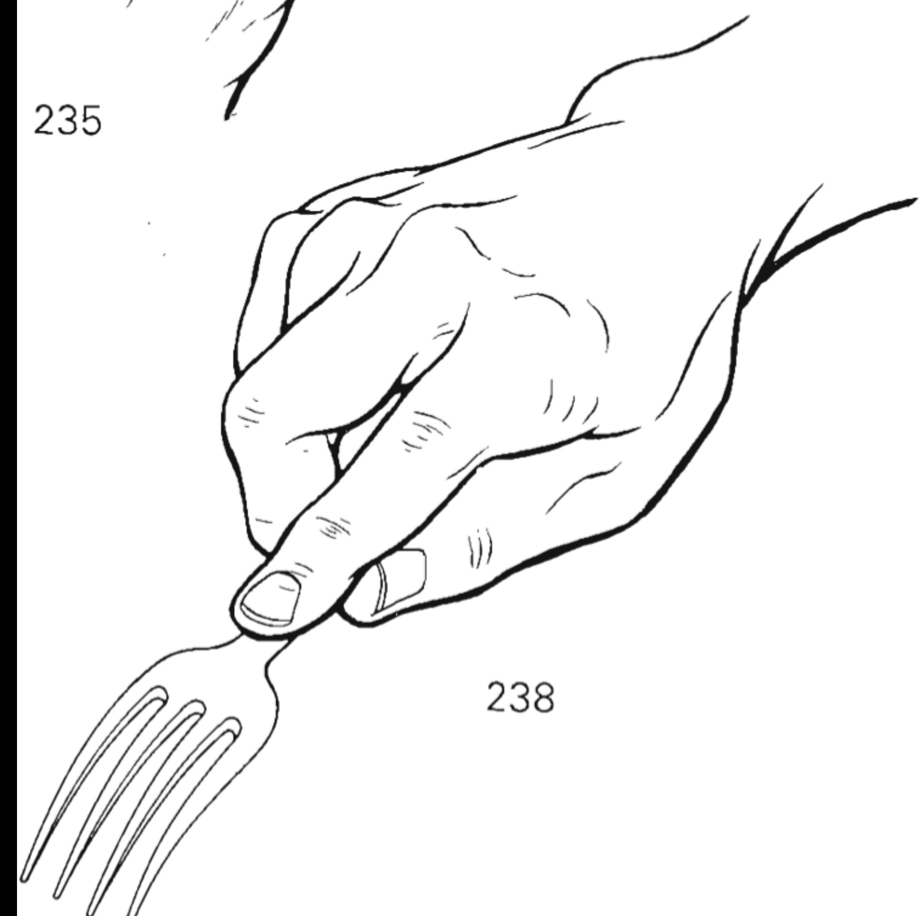
233

234

235

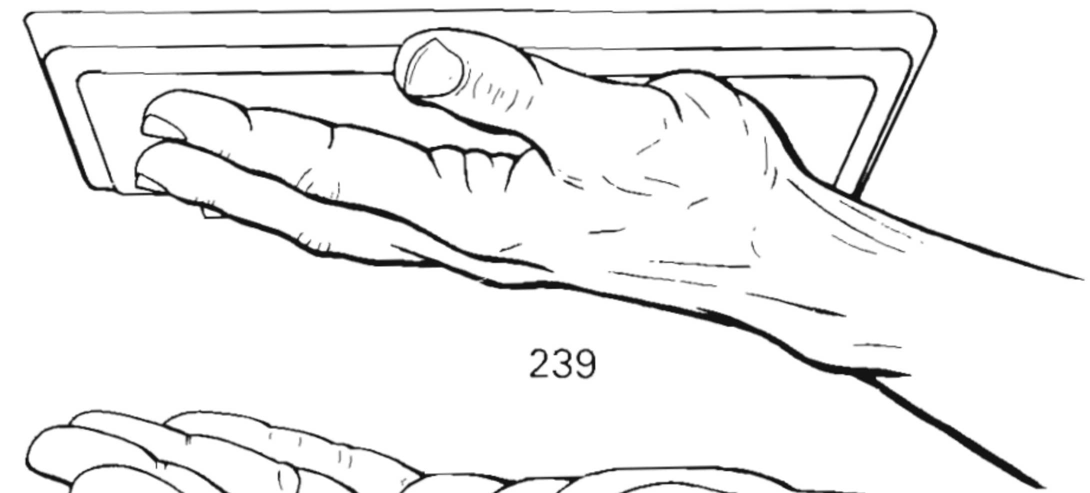


236



238

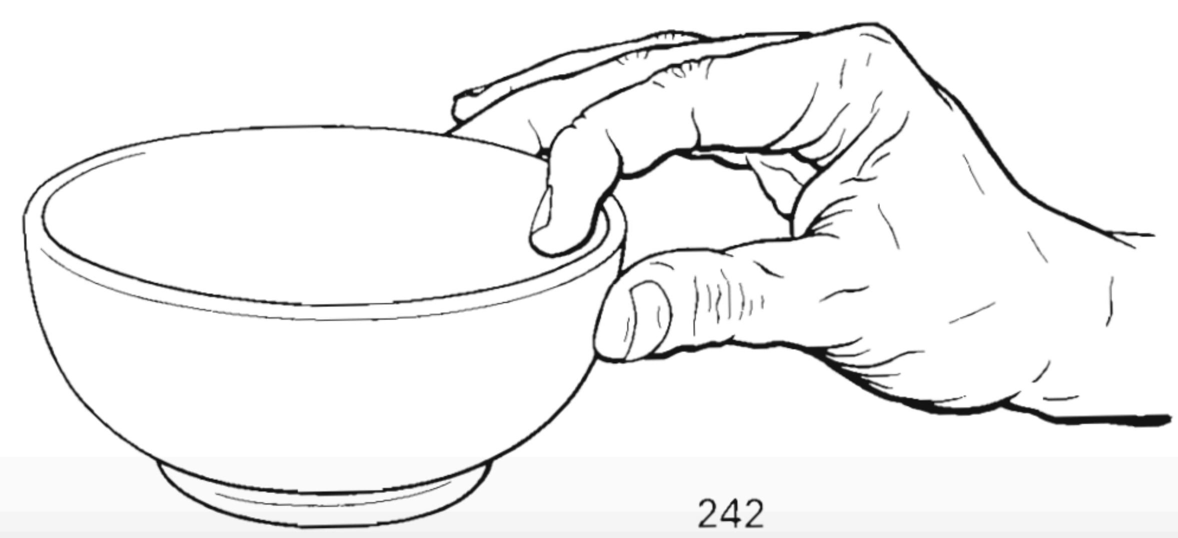
237



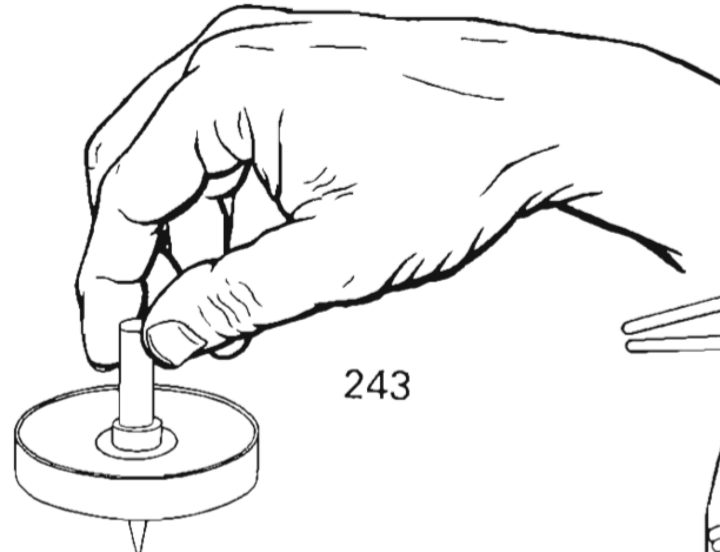
239

240

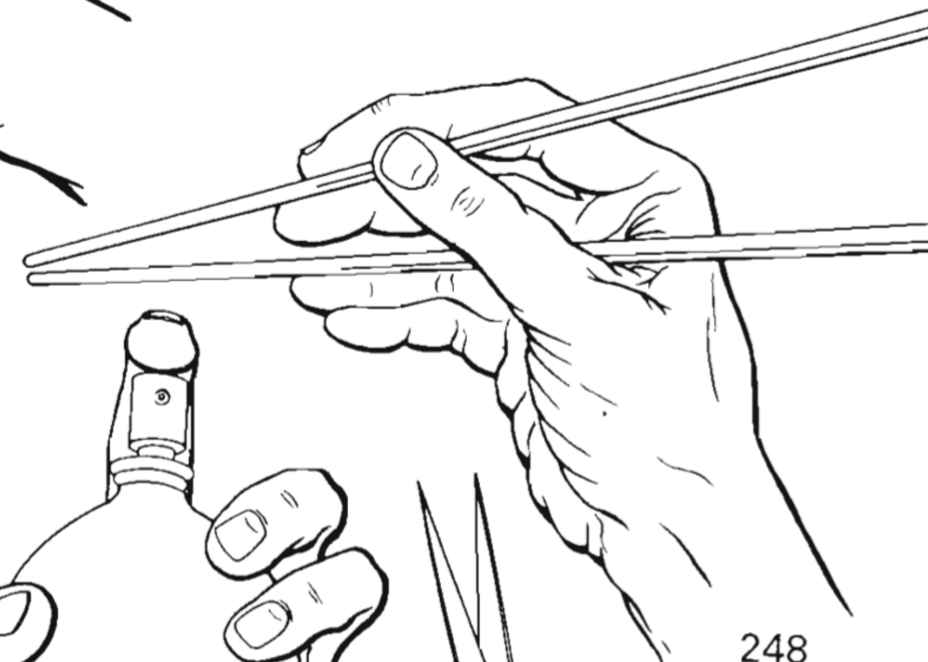
241



242



243



248

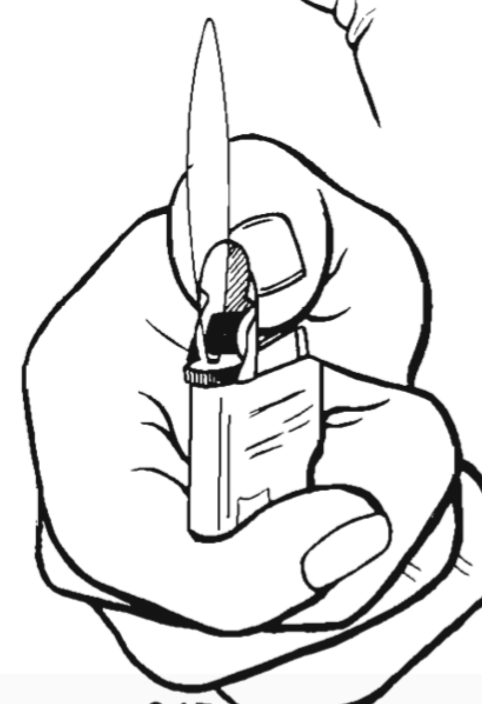
246

249

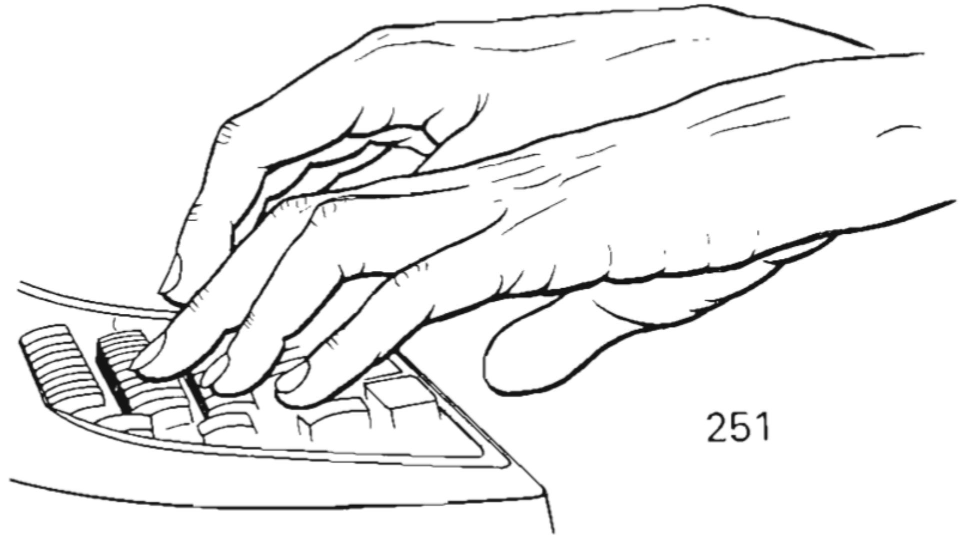
247

250

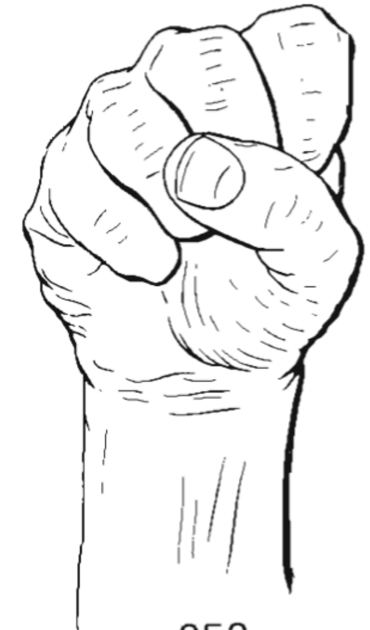
244



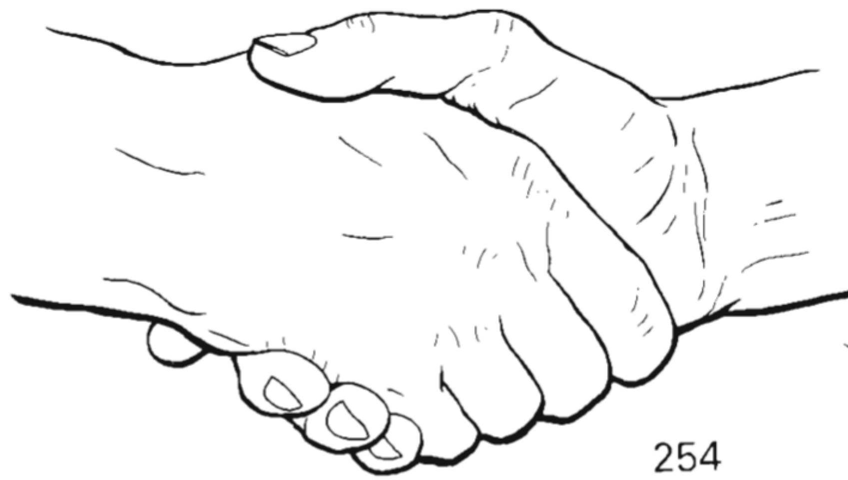
245



251

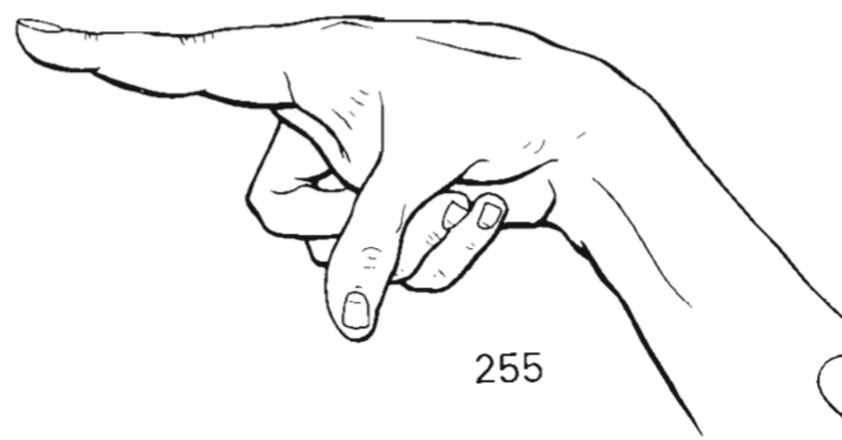


252



254

253



255

256

Finger	Anatomical Name	Relative Tension [a]	Joints/DOF	| Moment Arm | [b]
Index [c]	Flexor Digitorum Superficialis	2.0	MCP flex.	11.9
			MCP add.	1.7
			PIP flex.	6.2
	Flexor Digitorum Profundus	2.7	MCP flex.	11.1
			MCP add.	1.1
			PIP flex.	7.9
			DIP flex.	4.1
	Extensor Digitorum Communis	1.0	MCP ext.	8.6
			MCP abd.	0.2
			PIP ext.	2.8
			DIP ext.	2.2
	Extensor Indicis	1.0	MCP ext.	9
			MCP add.	1.3
			PIP ext.	2.6
			DIP ext.	1.9
	Lumbrical I	0.2	MCP flex.	9.3
			MCP abd.	4.8
			PIP ext.	1.8
			DIP ext.	0.7
	Palmar Interosseus I	1.3	MCP flex.	6.6
			MCP add.	5.8
			PIP ext.	2.6
			DIP ext.	1.6
	Dorsal Interosseus I	3.2	MCP flex.	3.7
			MCP abd.	6.1
Middle [d]	Flexor Digitorum Superficialis	3.4	MCP flex.	11.9
			MCP add.	1.7
			PIP flex.	6.2
	Flexor Digitorum Profundus	3.4	MCP flex.	11.1
			MCP add.	6
			PIP flex.	7.9
			DIP flex.	4.1
	Extenxor Digitorum	1.9	MCP ext.	8.6
			MCP abd.	0.2
			PIP ext.	2.8
			DIP ext.	2.2
	Lumbrical II	0.2	MCP flex.	5
			MCP abd.	4.8
			PIP ext.	1.8
			DIP ext.	0.7
	Dorsal Interosseus II	2.5	MCP flex.	3.7
			MCP add.	6.1
			PIP ext.	2.6
			DIP ext.	1.6
	Dorsal Interosseus III	2.0	MCP flex.	3.7
			MCP add.	6.1
			PIP ext.	2.6
			DIP ext.	1.6
Ring [d]	Flexor Digitorum Superficialis	2.0	MCP flex.	11.9
			MCP add.	1.7
			PIP flex.	6.2
	Flexor Digitorum Profundus	3.0	MCP flex.	11.1
			MCP add.	6.0
			PIP flex.	7.9
			DIP flex.	4.1
	Extensor Digitorum	1.7	MCP ext.	8.6
			MCP abd.	0.2
			PIP ext.	2.8
			DIP ext.	2.2
	Lumbrical III	0.1	MCP flex.	5
			MCP abd.	4.8
			PIP ext.	1.8
			DIP ext.	0.7
	Palmar Interosseus II	1.2	MCP flex.	6.6
			MCP add.	5.8
			DIP ext.	2.6
			PIP ext.	1.6

Finger	Anatomical Name	Relative Tension	Joints/DOF	| Moment Arm |
Pinky [d]	Flexor Digitorum Superficialis	0.9	MCP flex.	11.9
			MCP add.	1.7
			PIP flex.	6.2
	Flexor Digitorum Profundus	2.8	MCP flex.	11.1
			MCP add.	6
			PIP flex.	7.9
			DIP flex.	4.1
	Extensor Digitorum	0.9	MCP ext.	8.6
			MCP abd.	0.2
			PIP ext.	2.8
			DIP ext.	2.2
	Extensor Digiti Minimi	1.0	MCP ext.	8.6
			PIP ext.	2.6
			DIP ext.	1.9
	Abductor Digiti Minimi	1.4	CMC opp.	6
			MCP abd.	4
			PIP ext.	2.5
			DIP ext.	2
	Flexor Digiti Minimi Brevis	0.4	CMC opp.	6
	Opponens Digiti Minimi	2.0	CMC opp.	6
	Lumbrical IV	0.1	MCP flex.	5
			MCP abd.	4.8
			PIP ext.	1.8
			DIP ext.	0.7
	Palmar Interosseus III	1.0	MCP flex.	6.6
			MCP add.	5.8
			DIP ext.	2.6
			PIP ext.	1.6
	Dorsal Interosseus IV	1.7	MCP flex.	3.7
			MCP abd.	6.1
			PIP ext.	2.6
			DIP ext.	1.6
Thumb [e]	Flexor Pollicis Longus	2.7	CMC abd.	0.2
			CMC flex.	14.3
			MCP add.	0.1
			MCP flex.	13.6
			IP flex.	8.7
	Extensor Pollicis Longus	1.3	CMC ext.	8.1
			CMC add.	9.5
			MCP ext.	8.5
			MCP add.	4.4
			IP ext.	4.1
	Abductor Pollicis Longus	3.1	CMC ext.	7.1
			CMC abd.	10.5
	Extensor Pollicis Brevis	0.8	CMC ext.	13.0
			CMC abd.	3.2
			MCP ext.	8.6
			MCP abd.	1.4
	Abductor Pollicis Brevis	1.1	CMC flex.	3.9
			CMC abd.	16.5
			MCP abd.	11.1
			MCP flex.	2.6
	Flexor Pollicis Brevis	1.3	CMC flex.	13.4
			CMC abd.	10.5
			MCP abd.	8.7
			MCP flex.	8.8
	Opponens Pollicis	1.9	CMC flex.	12.9
			CMC abd.	4.8
	Adductor Pollicis(t)	3.0	CMC flex.	36.9
			CMC add.	20.6
			MCP flex.	9.7
			MCP add.	6.0
	Adductor Pollicis(o)	3.0	CMC flex.	27
			CMC add.	17
			MCP flex.	8.2
			MCP add.	4.0

TABLE III

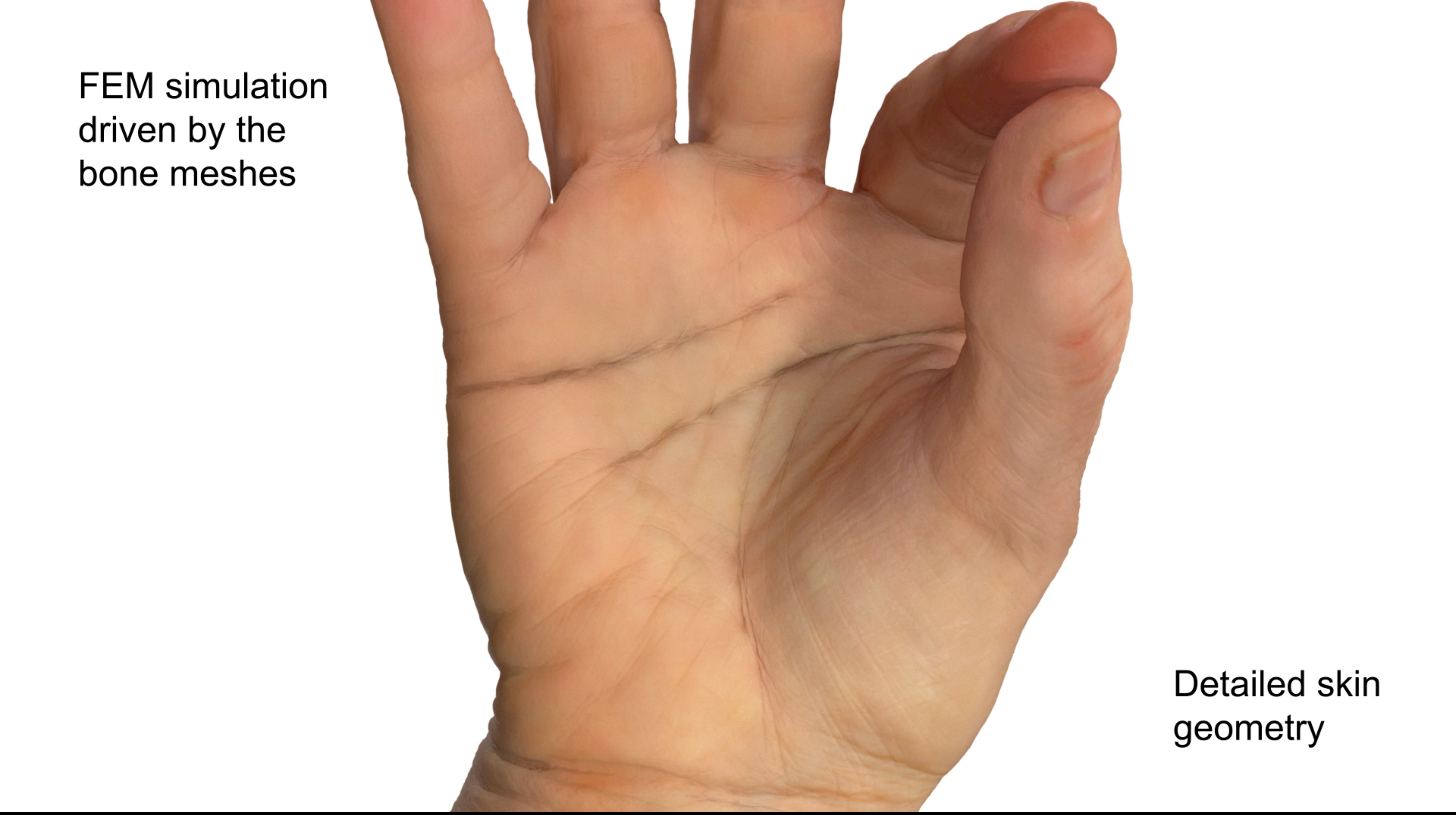
TENDON DATA

Y. Li, J. L. Fu, and N. S. Pollard, 2007. Data Driven Grasp Synthesis using Shape Matching and Task-Based Pruning, IEEE Transactions on Visualization and Computer Graphics, 2007.

Finger	Anatomical Name	Relative Tension [a]	Joints/DOF	| Moment Arm | [b]
Index [c]	Flexor Digitorum Superficialis	2.0	MCP flex.	11.9
			MCP add.	1.7
			PIP flex.	6.2
	Flexor Digitorum Profundus	2.7	MCP flex.	11.1
			MCP add.	1.1
			PIP flex.	7.9
			DIP flex.	4.1
	Extensor Digitorum Communis	1.0	MCP ext.	8.6
			MCP abd.	0.2
			PIP ext.	2.8
			DIP ext.	2.2
	Extensor Indicis	1.0	MCP ext.	9
			MCP add.	1.3
			PIP ext.	2.6
			DIP ext.	1.9
	Lumbrical I	0.2	MCP flex.	9.3
			MCP abd.	4.8
			PIP ext.	1.8
			DIP ext.	0.7
	Palmar Interosseus I	1.3	MCP flex.	6.6
			MCP add.	5.8
			PIP ext.	2.6
			DIP ext.	1.6
	Dorsal Interosseus I	3.2	MCP flex.	3.7
			MCP abd.	6.1
Middle [d]	Flexor Digitorum Superficialis	3.4	MCP flex.	11.9
			MCP add.	1.7
			PIP flex.	6.2
	Flexor Digitorum Profundus	3.4	MCP flex.	11.1
			MCP add.	6
			PIP flex.	7.9
			DIP flex.	4.1
	Extenxor Digitorum	1.9	MCP ext.	8.6
			MCP abd.	0.2
			PIP ext.	2.8
			DIP ext.	2.2
	Lumbrical II	0.2	MCP flex.	5
			MCP abd.	4.8

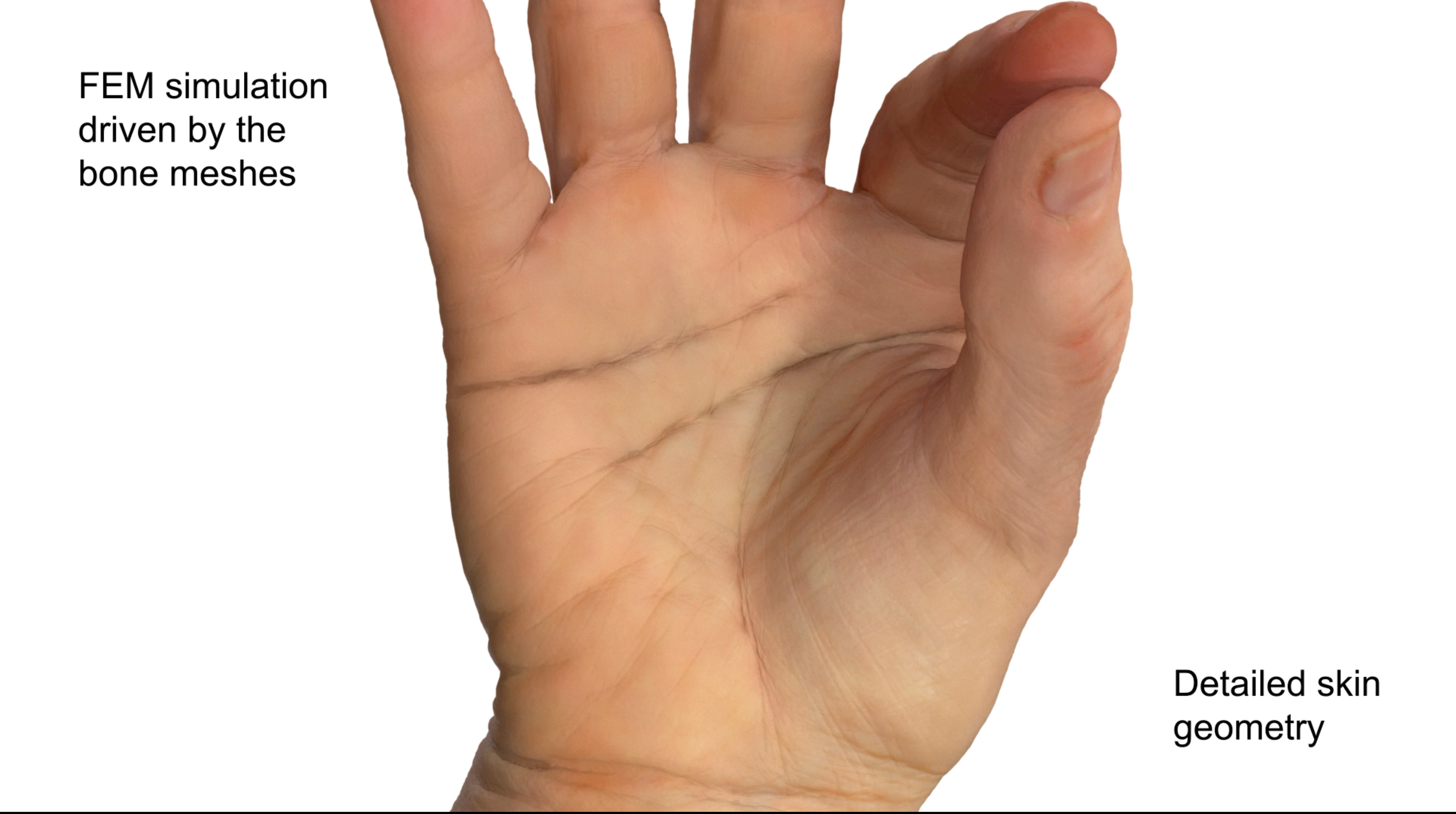
Finger	Anatomical Name	Relative Tension	Joints/DOF	| Moment Arm
Pinky [d]	Flexor Digitorum Superficialis	0.9	MCP flex.	11.9
			MCP add.	1.7
			PIP flex.	6.2
	Flexor Digitorum Profundus	2.8	MCP flex.	11.1
			MCP add.	6
			PIP flex.	7.9
			DIP flex.	4.1
	Extensor Digitorum	0.9	MCP ext.	8.6
			MCP abd.	0.2
			PIP ext.	2.8
			DIP ext.	2.2
	Extensor Digiti Minimi	1.0	MCP ext.	8.6
			PIP ext.	2.6
			DIP ext.	1.9
	Abductor Digiti Minimi	1.4	CMC opp.	6
			MCP abd.	4
			PIP ext.	2.5
			DIP ext.	2
	Flexor Digiti Minimi Brevis	0.4	CMC opp.	6
	Opponens Digiti Minimi	2.0	CMC opp.	6
	Lumbrical IV	0.1	MCP flex.	5
			MCP abd.	4.8
			PIP ext.	1.8
			DIP ext.	0.7
	Palmar Interosseus III	1.0	MCP flex.	6.6
			MCP add.	5.8
			DIP ext.	2.6
			PIP ext.	1.6
	Dorsal Interosseus IV	1.7	MCP flex.	3.7
			MCP abd.	6.1
			PIP ext.	2.6
			DIP ext.	1.6
Thumb [e]	Flexor Pollicis Longus	2.7	CMC abd.	0.2
			CMC flex.	14.3
			MCP add.	0.1
			MCP flex.	13.6
			IP flex.	8.7
	Extensor Pollicis Longus	1.3	CMC ext.	8.1

Y. Li, J. L. Fu, and N. S. Pollard, 2007. Data Driven Grasp Synthesis using Shape Matching and Task-Based Pruning, IEEE Transactions on Visualization and Computer Graphics, 2007.



Wang, Bohan, George Matcuk, and Jernej Barbič. "Hand modeling and simulation using stabilized magnetic resonance imaging." ACM Transactions on Graphics (TOG) 2019

https://viterbi-web.usc.edu/~jbarbic/hand-mri/WangMatcukBarbic-SIGGRAPH2019.mp4



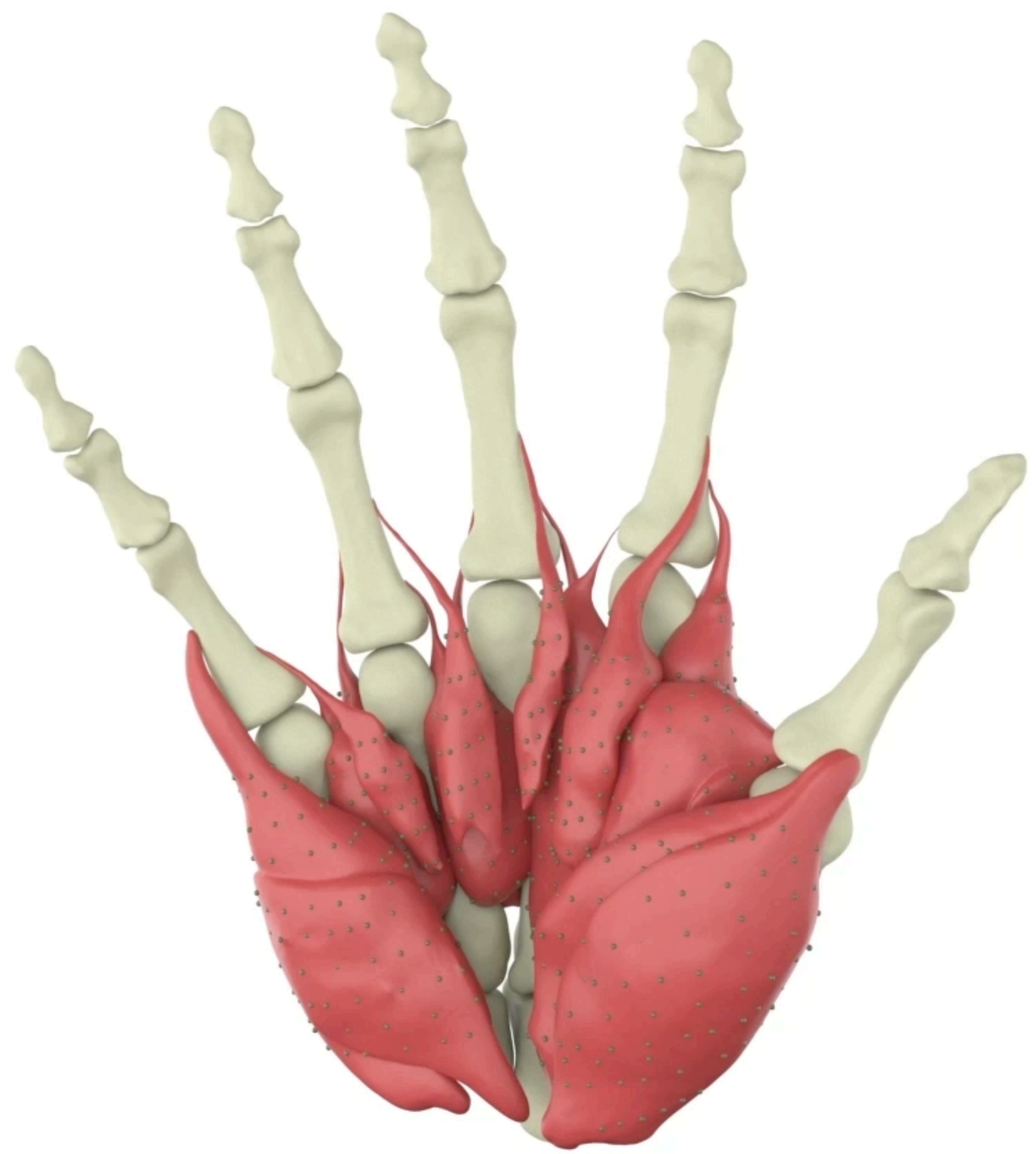
Wang, Bohan, George Matcuk, and Jernej Barbič. "Hand modeling and simulation using stabilized magnetic resonance imaging." ACM Transactions on Graphics (TOG) 2019

https://viterbi-web.usc.edu/~jbarbic/hand-mri/WangMatcukBarbic-SIGGRAPH2019.mp4

Hand muscles

Dark green: ICP markers from MRI scan

Template

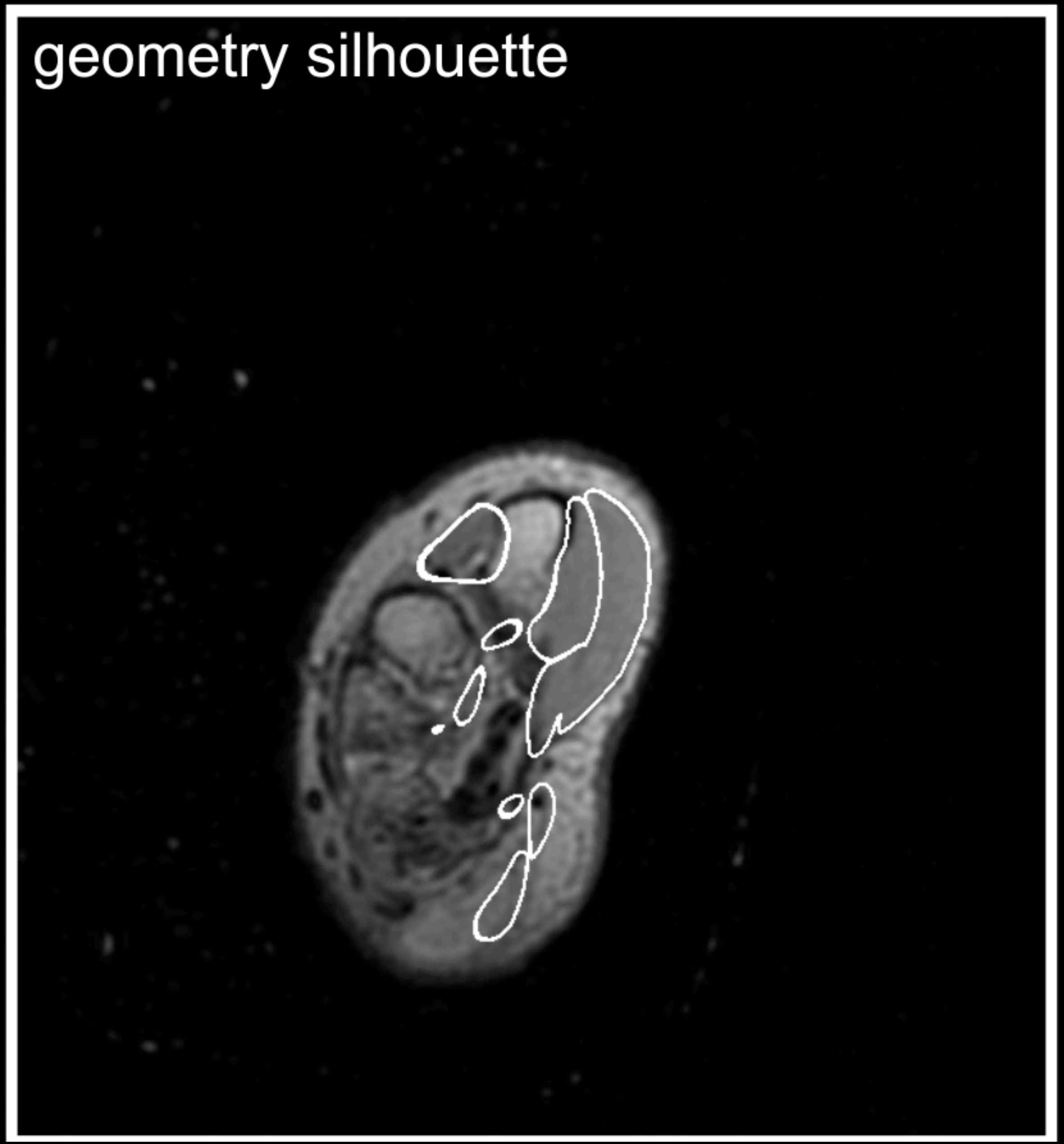


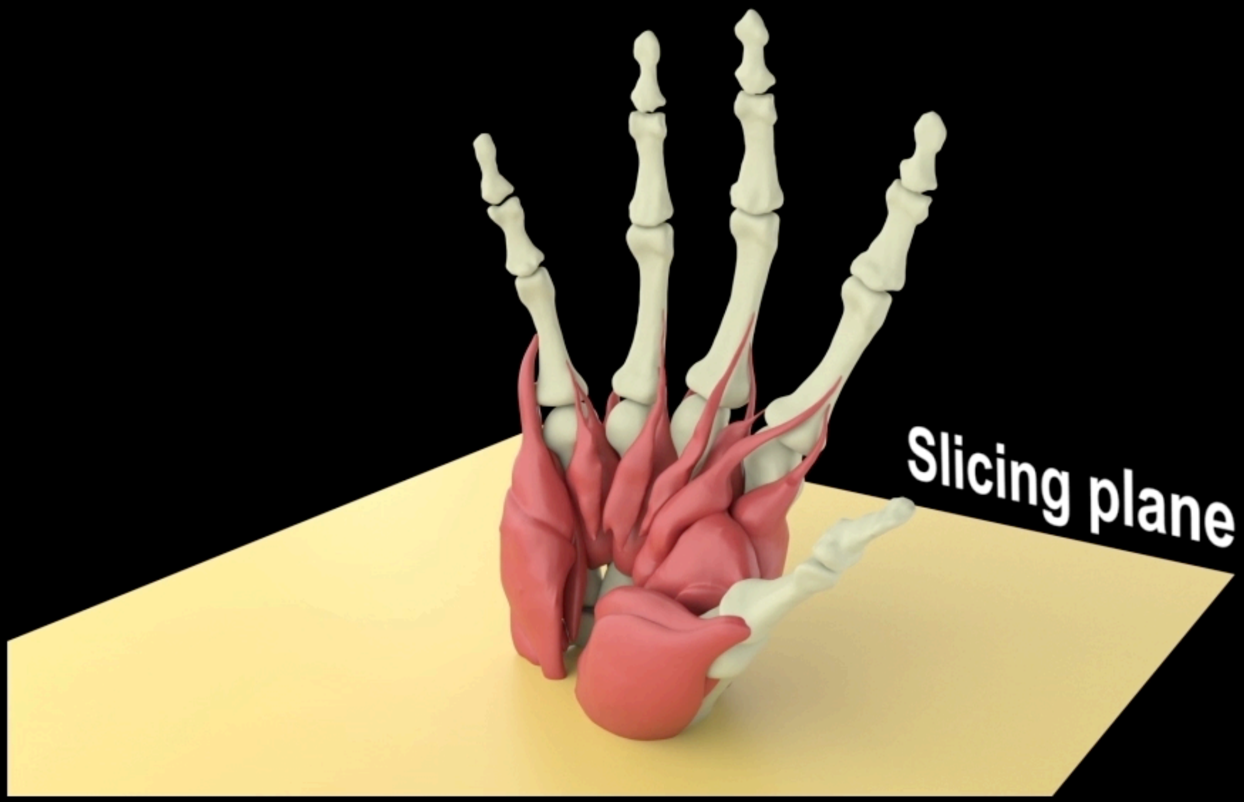
Our output

Wang, Bohan, George Matcuk, and Jernej Barbič. "Modeling of Personalized Anatomy using Plastic Strains." ACM Transactions on Graphics (TOG) 40, no. 2 (2021): 1-21.

https://viterbi-web.usc.edu/~jbarbic/plasticDefo/WangMatcukBarbic-tog2020.mp4

MRI slices





Wang, Bohan, George Matcuk, and Jernej Barbič. "Modeling of Personalized Anatomy using Plastic Strains." ACM Transactions on Graphics (TOG) 40, no. 2 (2021): 1-21.

https://viterbi-web.usc.edu/~jbarbic/plasticDefo/WangMatcukBarbic-tog2020.mp4

J. Anat. (2000) **197**, pp. 121–140, with 10 figures Printed in the United Kingdom

Review

Evolution of the human hand: approaches to acquiring, analysing and interpreting the anatomical evidence

MARY W. MARZKE[1] AND R. F. MARZKE[2]

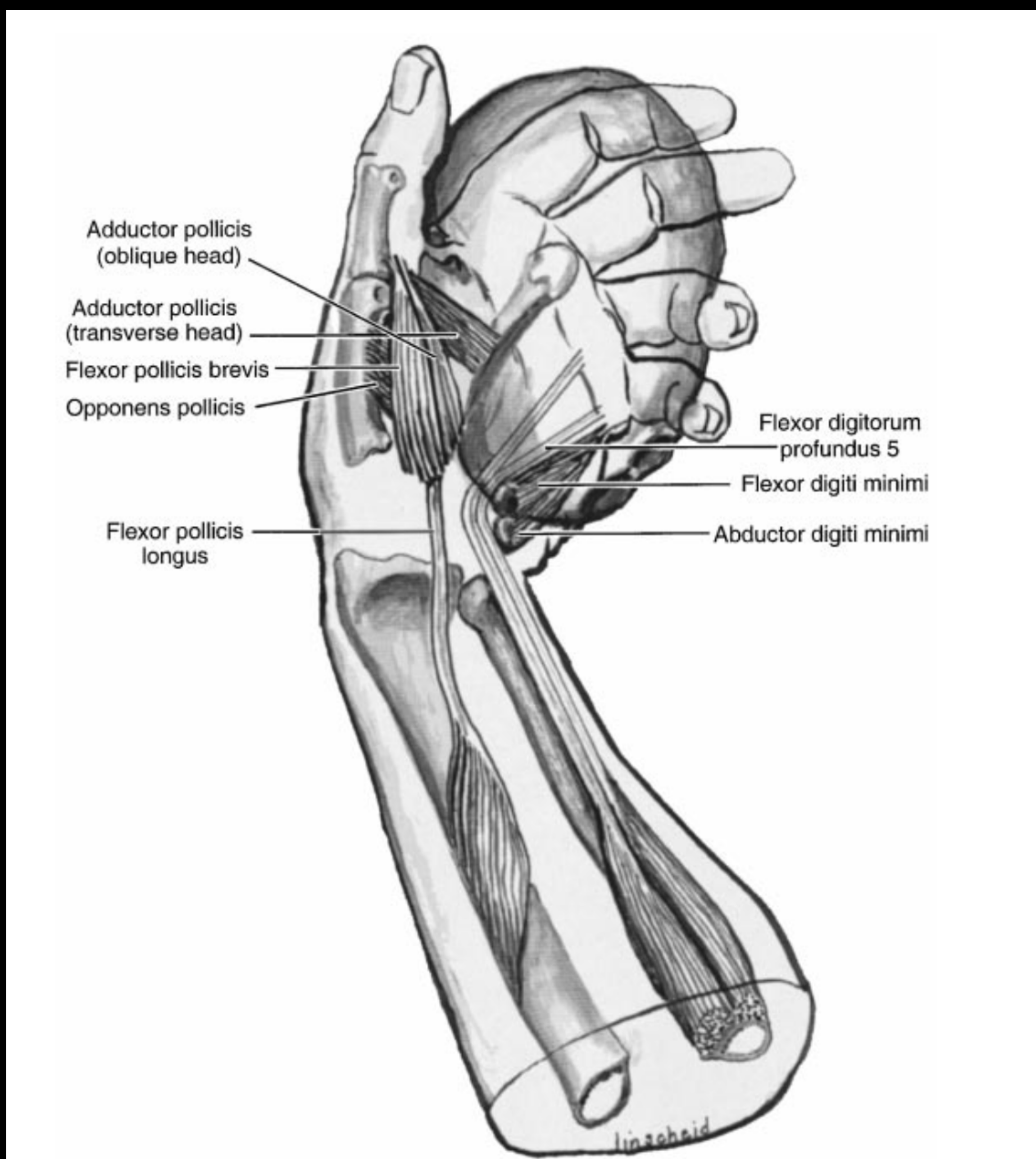


Fig. 9. Muscles strongly recruited during hard hammer percussion manufacture of Oldowan-type tools.

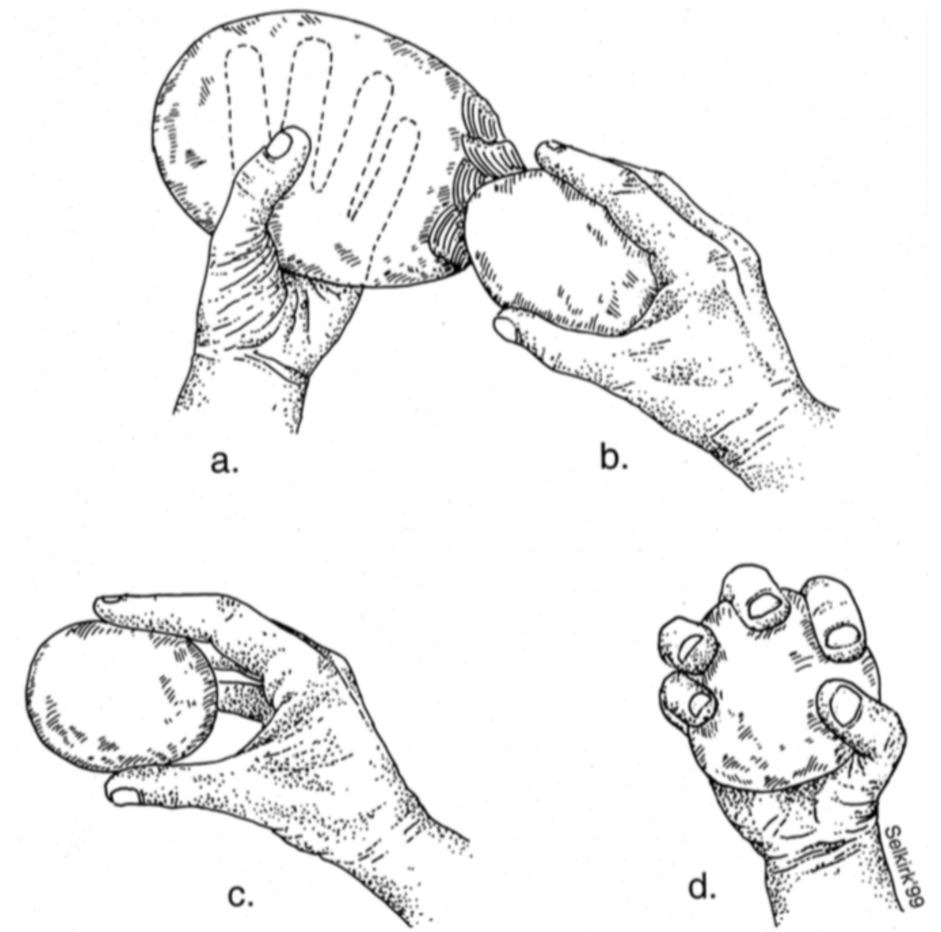
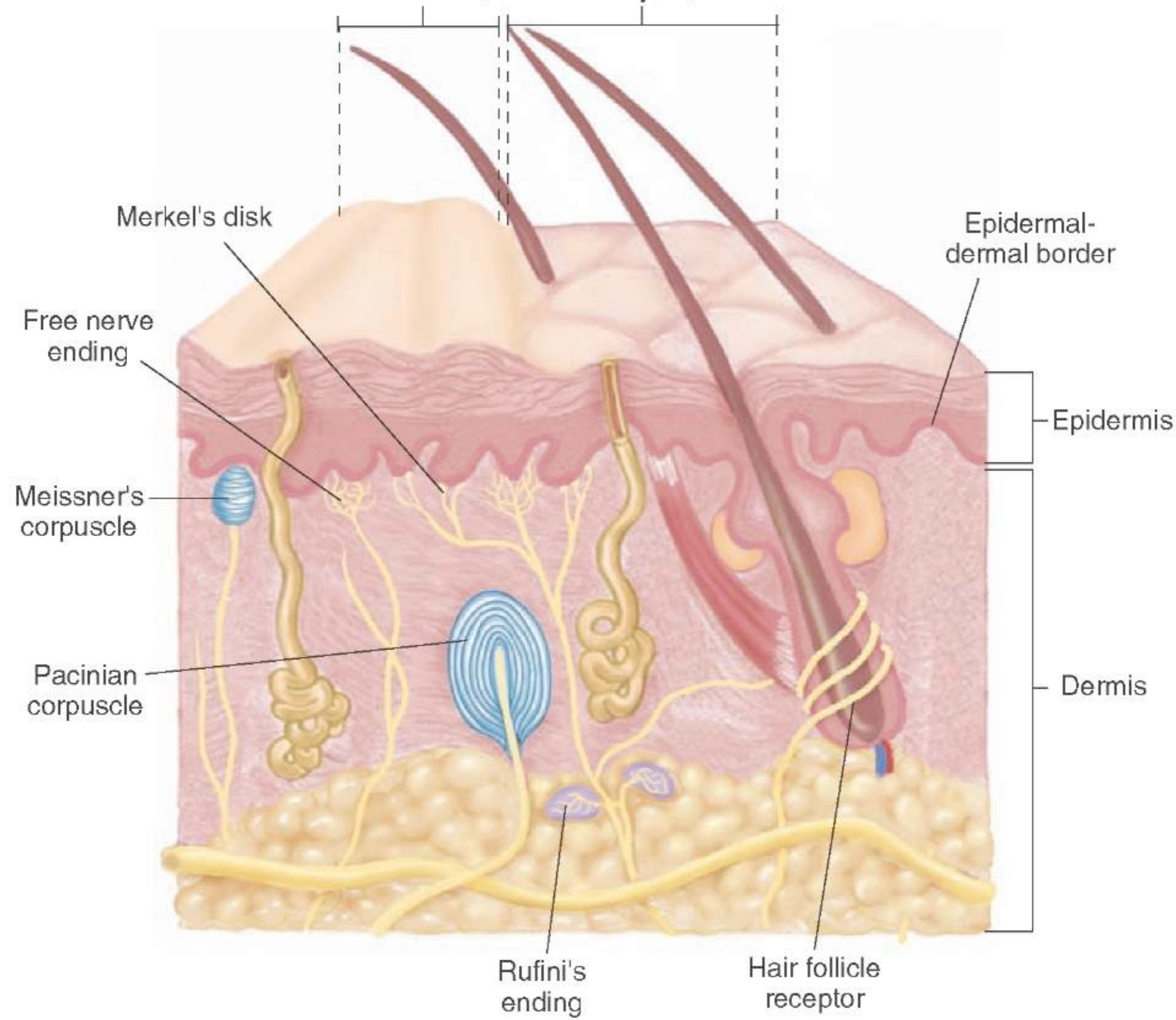


Fig. 6. Contrasts between: (*a*) a firm precision cradle grip of a stone core; (*b*) a 3-jaw chuck precision pinch grip of a hammerstone; (*c*) a delicate precision grip by the tips of the thumb and fingers and (*d*) a spherical power grip. The delicate precision grip would not resist displacement of the core by a hammerstone during the removal of flakes. The spherical power grip encloses the stone, exposing the fingers to damage by the hammerstone. The firm precision cradle and 3-jaw chuck grips resist displacement of the core, but allow exposure of the working edge of the core for safe flake removal.

Sensing



Merkel's disk
Epidermal-
dermal border
Free nerve
ending
Epidermis
Meissner's
corpuscle
Pacinian
corpuscle
Dermis
Rufini's
ending
Hair follicle
receptor

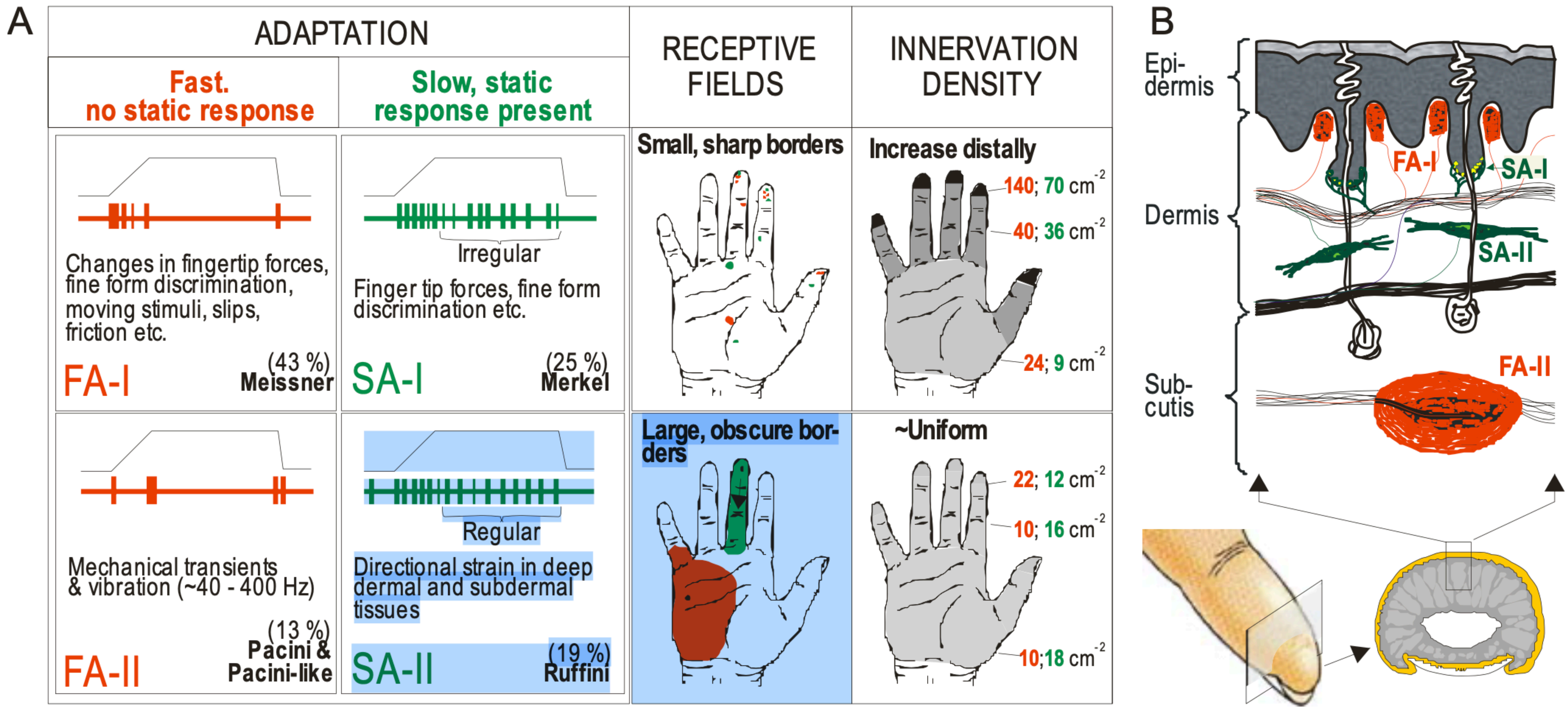
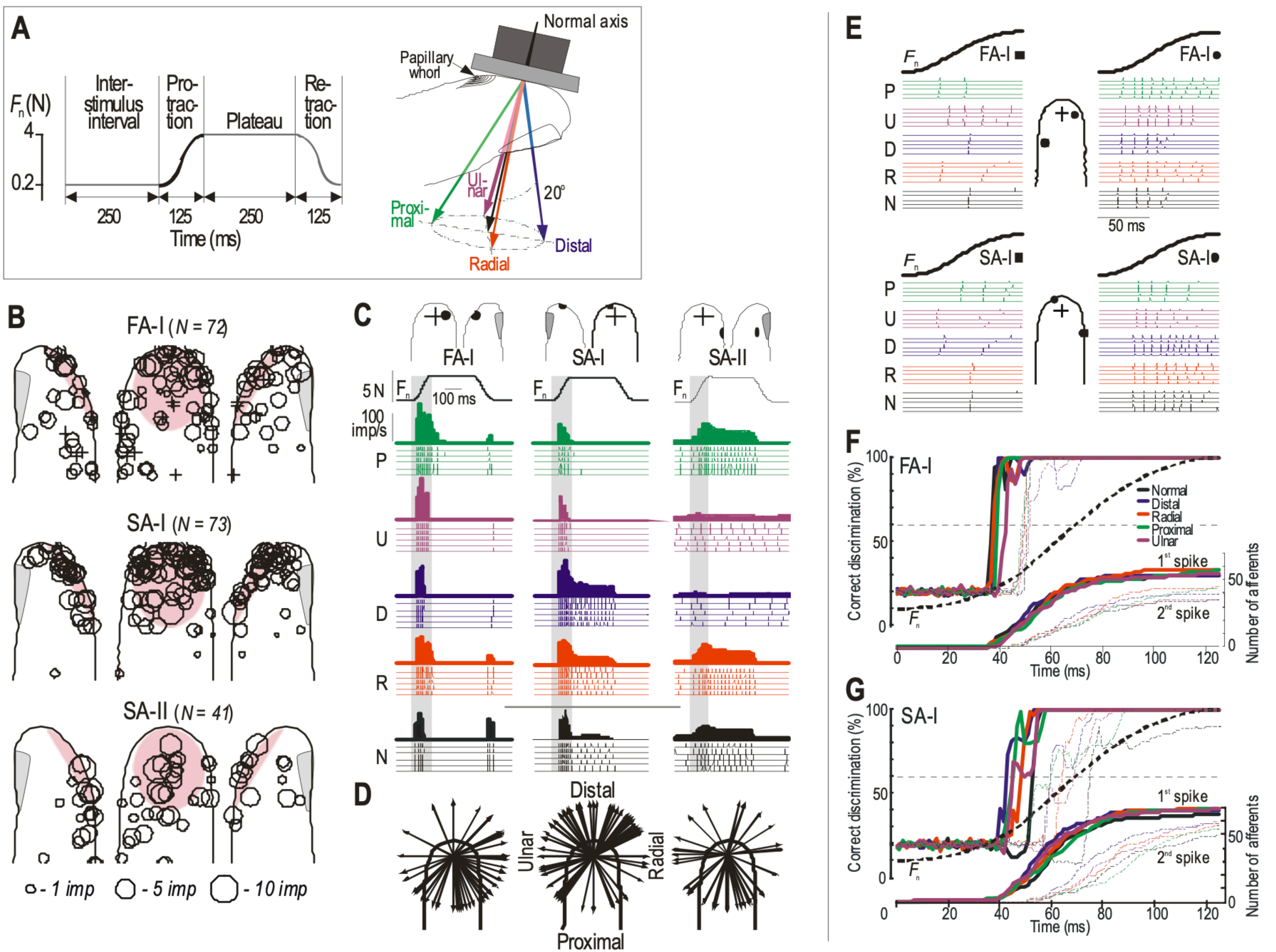
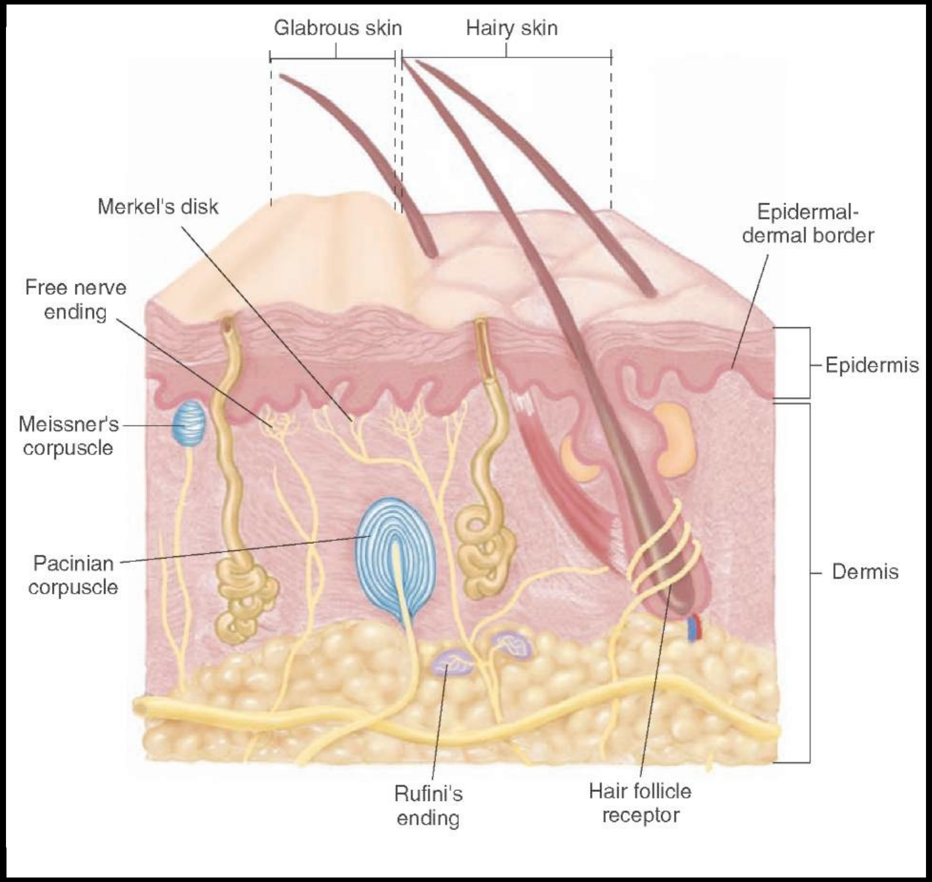


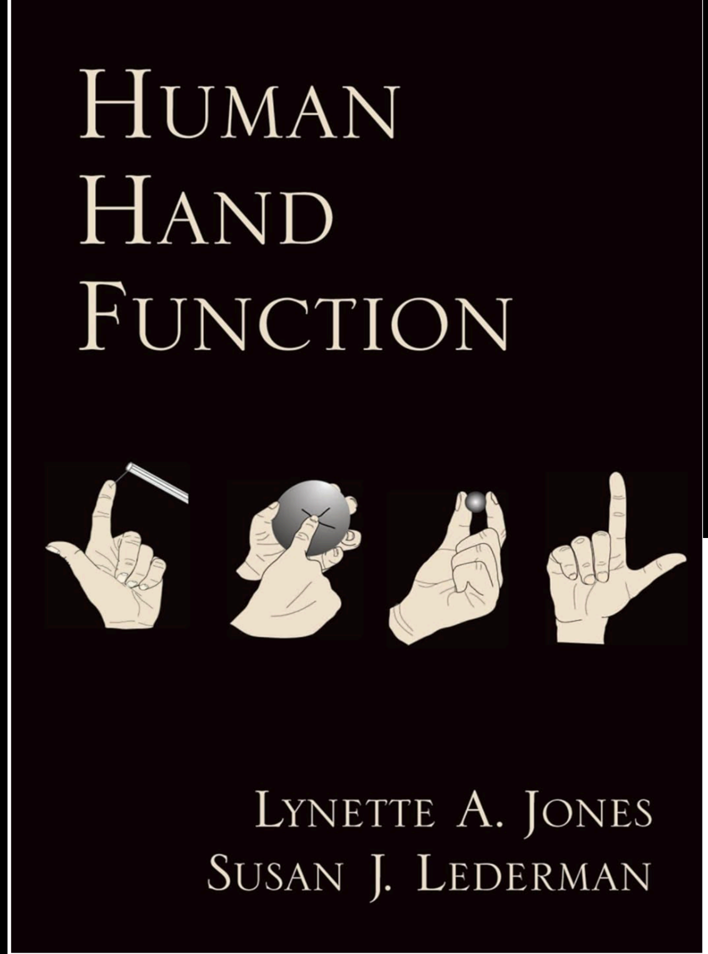
Figure 2. Types of tactile (mechanoreceptive) sensors in the glabrous skin of the inside of the human hand. A. Graphs schematically show the impulse discharge (lower traces) to perpendicular ramp indentations of the skin (upper traces) for each sensor type. Two types (FA-I and FA-II) show fast adaptation to maintained tissue deformation, i.e. they only respond to deformation changes. These afferents was originally termed RA (rapidly adapting) and PC (Pacinian). Two types adapt slowly (SA-I and SA-II). That is, they show an ongoing response related to the strength of maintained tissue deformation. The type I sensors (FA-I and SA-I) have small and well-defined cutaneous receptive fields (typically 10 mm²) when defined by light pointed stimuli (patches in the drawing of the hand represents the fields of 15 different sensors). The density of these sensors increases stepwise in the proximo-distal direction of the hand, with one step from the palm to the main parts of the digits and one at the border between the proximal to the distal half of the distal phalanx (see the right-most drawing of the hand where the numbers afferents per sq. cm skin area is indicated for the fingertips, fingers and palm, respectively). In contrast, the FA-II and SA-II sensors show lower and about uniform densities over the hand and their receptive fields are larger and less well defined. The FA-IIs are especially responsive to mechanical transients that propagate though the tissues, whereas the SA-IIs sense strain in the dermal and subdermal fibrous tissues, often with a remote origin. The relative frequency of occurrence in the glabrous skin and the probable morphological correlate are indicated for each type of sensor. B. Diagrammatic vertical section of a fingertip showing the organized nerve terminals corresponding to the four types of tactile sensors. (Compiled from data reviewed in Johansson, R.S. and Vallbo, Å.B. 1983 and in Vallbo, Å.B. and Johansson, R.S. 1984.


A
Fn (N)
4
0.2
Inter-stimulus interval
Pro-trac-tion
Plateau
Re-trac-tion
250
125
250
125
Time (ms)
Normal axis
Papillary whorl
Ul-nar
20°
Proxi-mal
Distal
Radial
B
FA-I (N = 72)
SA-I (N = 73)
SA-II (N = 41)
- 1 imp
- 5 imp
- 10 imp
C
FA-I
SA-I
SA-II
5 N
Fn
100 ms
100 imp/s
P
U
D
R
N
D
Distal
Ulnar
Radial
Proximal
E
FA-I
SA-I
50 ms
F
FA-I
Correct discrimination (%)
Normal
Distal
Radial
Proximal
Ulnar
1st spike
2nd spike
Number of afferents
Time (ms)
G
SA-I

Design Issues - Sensing

nerve endings	temperature, pain
Meissner corpuscles	velocity, light touch
Merkel discs	pressure, low freq
Ruffini corpuscles	pressure, skin stretch
Pacinian corpuscles	acceleration, high freq
Golgi tendon organs	tendon stretch
Proprioceptors	position





Contact Area

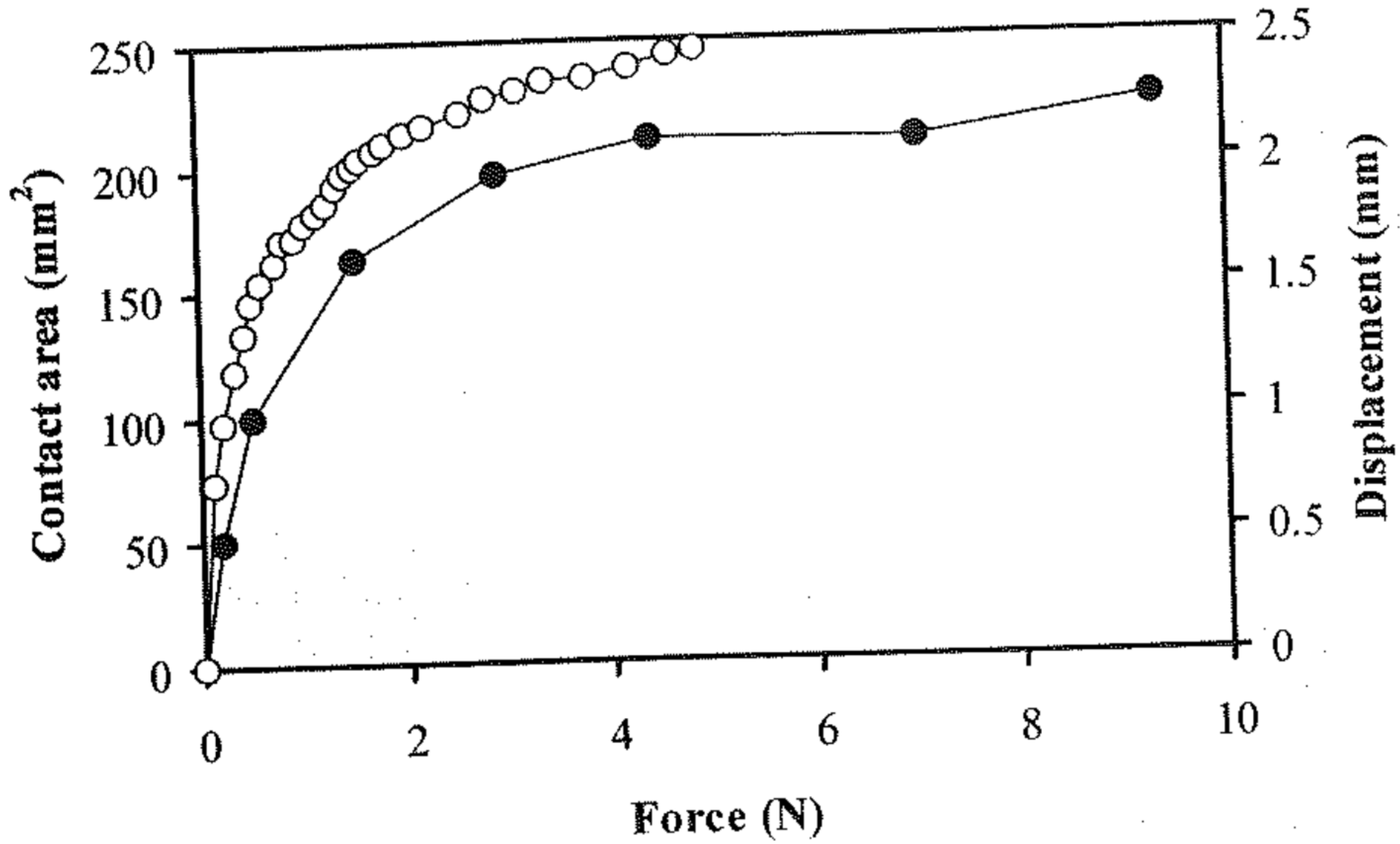


Figure 2.10. Relation between the force applied at the fingertip and the area of contact on the tip of the index finger during grasping (filled circles) and between finger force and the displacement of the index fingertip pulp during contact with a rigid surface (open circles). The force-contact area data are from Westling & Johansson, 1987, and come from a single participant, and the force-pulp displacement data are from Serina et al., 1998, and are also from a single participant. Redrawn from Serina et al., 1998, with the permission of the authors and Elsevier.

Design Issues – Control

It has been observed that muscle coordination patterns switch from position control to isometric force control ~65 ms before contact

For humans, forces modulated by sensor feedback w/in 70ms

Typists may have 100-200ms interval between keystrokes

Pianists may have 80-100ms interval between notes

Typical latencies in a robotic hand/arm system may be 40ms

A hand moving at a typical reaching speed of 1m/s will move 4cm in 40ms