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Functional Anatomy and Biomechanics of the Hand

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Introduction

Anatomy of the hand and dynamics are intimately interconnected. Right from the structure and mobility of the skin in the surface, to the articular surfaces of the joints at the depth, each structure plays an important role in the function of the hand.

Coordination between various structures is necessary for converting a muscle contraction into a movement and then into a function. Signals from the brain are transmitted through the nerves to the muscles; the tendons move through pulleys across fulcrums, and the joints ultimately move to perform. Not to forget the opposing groups resisting it so that the movement becomes controlled and the hand does not collapse. Even the skin plays a vital role in the grip. Sensory feedback is necessary so that appropriate pressure is applied. These series of actions are required even for performing a simple task such as picking up a glass of water and taking it to the mouth. Without the sensory feedback, there is a possibility to crush the glass not knowing the amount of pressure required. Even ipsilateral cerebellum is activated when complex manipulation of objects is done in hand.[1]

The brain, the skin, and even the nails have a role to play, and the dynamics are dependent on their anatomical structure and biomechanics.

Motor function is considered by many as the main function of the hand, but the sensory component is very important. We use the hand to touch an object to assess its physical characters before using it. We touch to feel the texture of an object; touch to see whether the liquid is hot or cold to consume. Use it to comfort persons by caressing them and to express anger or gesture to convey the emotions. The hand is used to guide in darkness and to cup ears to listen intensively. Occasionally, it is used to touch and smell, for example, a perfume or to touch and taste before consuming it. Thus, this is found to be substituting or helping other sensory organs.

In this chapter, the author will dwell on the functional anatomy of the hand as an organ in general and also of specific structures.

Indian classical dances depict various emotions with hand gestures called Mudras. Most of the bronze idols seen in temples and in old Chola period give importance to the position of the hands and fingers. An artistic exaggeration of the hyperextended metacarpophalangeal (MCP) joints in those idols is noticed (**Fig. 1.1**). But in real life, the muscle balance of the fingers and thumb plays a key role in the activities of daily living (ADLs) and preventing deformities.

Fig. 1.1 Ancient bronze idols depicting exaggerated metacarpophalangeal extension as beauty.

The Basic Anatomical Arrangement of the Hand Influencing the Dynamics

Anatomically, the hand comprises eight carpal bones articulating with five metacarpals and three phalanges in each finger and two in the thumb. In between them, they have the carpometacarpal (CMC), MCP, and interphalangeal (IP) joints. The carpals take part in wrist movement as a whole in dorsi and palmar flexion and in radial and ulnar deviations. The ligaments of CMC joints do not allow any great movements in them except in the thumb and little finger. The CMC joint of the thumb is a saddle type and allows a wide range of movements. The CMC joint of the little finger allows approximately 10 to 15 degrees of flexion and medial rotation. The MCP joints move mainly in two planes: flexion and extension occurs around the transverse axis and abduction and adduction through the anteroposterior (AP) axis. When the MCP joint is flexed and the grip is tightened, minimal rotation is noticed in the index finger also. The thumb is normaly kept away from the palm for approximately 1.5” to 2” and is rotated through 90-degree plane.

It is also noticed that the transverse axis of the fingers is parallel to the AP axis of the thumb and vice versa (**Fig. 1.2**).

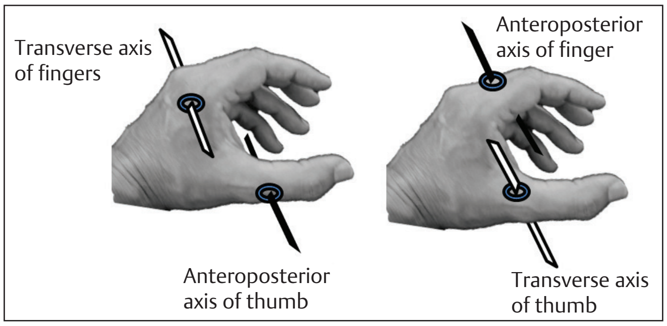

Fig. 1.2 Axis of fingers and thumb are at right angles.

Landsmeer’s Concept

The metacarpal along with proximal and middle phalanges can be considered as a chain of biarticular bitendinous mechanism as described by Landsmeer. If the proximal phalanx is considered as the middle bone in this chain, then both the flexors and extensor are not inserted in it but enclose it and get inserted distally as flexor digitorum sublimis (FDS) insertion and central slip into the middle phalanx. This middle bone of the chain is called intercalated bone by Landsmeer (**Fig. 1.3**).

Therefore, both the flexor and extensor have no control over the proximal phalanx, which will be unstable in any position of the joints. The chain falls into an unstable "zigzag" position depending on the moment arm (MA). MA is the distance between the tendons and the transverse axis, as shown by arrows in **Fig. 1.3**. Let us assume the MA at the first bone on the extensor side as IE and on the flexor side as IF, and MA at the second bone on the extensor side as IIE and on the flexor side as IIF. If the ratio of IE/IF is greater than the ratio of IIE/IIF, then the second bone will tilt toward the extensor side, the first joint will hyperextend, and the second joint will flex. If it is the other way around, then the first joint will flex and the second will extend. This instability can be corrected only if the second bone is controlled by some muscular force, which in a normal hand is the intrinsic. That is why when the intrinsic are paralyzed, the finger assumes the hyperextended position at the first joint. With the intrinsic muscles and the balancing by retinacular ligaments, the hand assumes controlled movement without any collapse. This will be dealt in detail later in section "Tendons, Muscles, and Ligaments."

Positions of the Hand

When the hands are observed wherein the opposing groups of muscles are in a state of relaxation while a person is sleeping, it is noticed that the forearm is slightly pronated and the wrist is kept in neutral or minimal flexion and minimal ulnar deviation. The MCP joints are kept flexed as a cascade from the index through the little fingers (45–70 degrees) and the IP joints in flexion of varying levels. The thumb is abducted and is away from the plane of the palm. This position is commonly called the *resting position* (**Fig. 1.4a**).

While attempting a function, the position changes into an extension of approximately 30 degrees at wrist opening up of the MCP joints with the proximal phalanx of the index parallel to the thumb and the IP joints flexed as if to oppose the thumb pulp (**Fig. 1.4b**).This is called the functional position, and commonly the hand is dressed in this position. The intrinsic position is the one in which the wrist is extended more, the MCP joints are kept flexed approximately 60 to 75 degrees, and the IP joints are kept straight. In this position, the MCP capsule, long extensors, and the extensor expansion over finger including the lateral bands are kept relaxed. This is the ideal position for splinting in tendon transfers or in repair of extensors (**Fig. 1.4c**).

If there is a change in position of the proximal joint, then, due to the length of the tendons being constant, the distal joint has to change its position accordingly to compensate for the changed position of the proximal joint dynamically.

If this is visualized in a clinical situation, wherein there is infection of the hand or there is trauma, the hand goes into position of ease to relax the flexors. The wrist goes into flexion, the MCP joint goes into compensatory extension, and the IP joints into more flexion. This leads to the MCP joint capsular contracture, and if left uncorrected, the IP joints also go into flexion contracture (**Fig. 1.4d**). It will be described in detail later in this chapter.

When the hand is opened and closed sequentially from the extended position of the hand to full flexion, it is seen that the fingers are abducted initially, and as the hand is closed, the fingers go from a neutral position of function to full flexion and at that time the fingers get adducted. Then, when the hand is opened, it is extended in the same adducted position until the hand is open and slowly the fingers abduct to assume the resting position, as you see in **Fig. 1.5**.

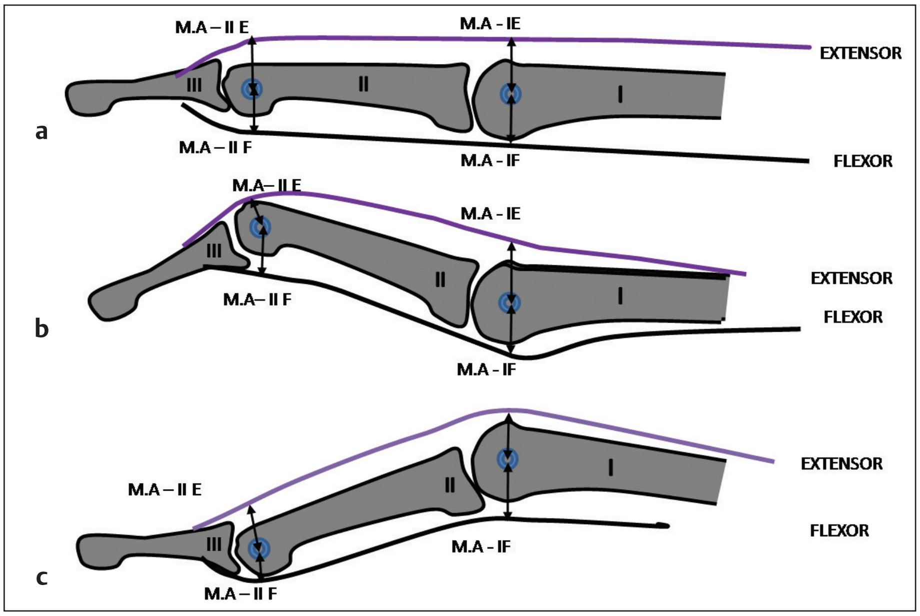

Fig. 1.3 **(a–c)** Biarticular bitendinous model with central intercalated bone without muscle attachment.

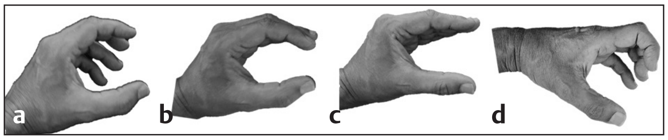

Fig. 1.4 **(a–d)** Positions of the hand.

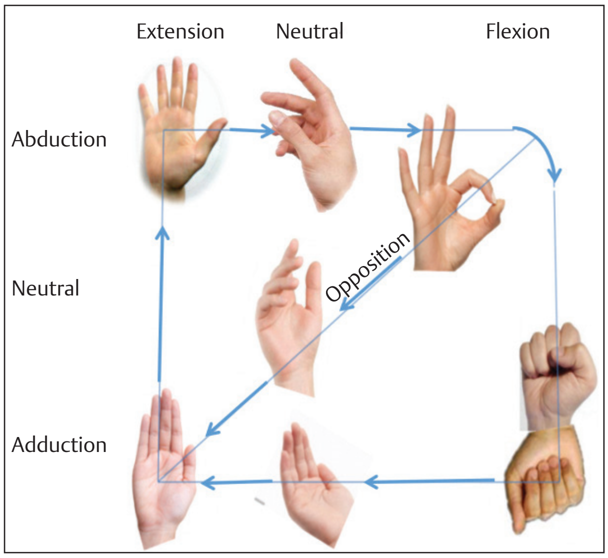

Fig. 1.5 Sequence of opening and closing the hand and opposition.

Similar sequence occurs in opposition also. Abduction, neutral, and adduction sequences go with extension, neutral, and flexion sequences.

This sequence occurs within the hand, which is the functional intrinsic space. For having full function, not only a person must be capable of going through the entire range within this intrinsic space but also the shoulder, elbow, and wrist must go through their entire range to carry the hand all around. These are the functional spaces.

Functional Spaces of the Hand

From the stable trunk, the upper limb moves at various levels at joints. Many levers and pivots form a system on which they move. The scapula glides and rotates on the chest moving the entire upper limb forward, backward upward, or downward. At every level of this gliding range, the shoulder can circumduct in a large more or less spherelike space.

Within this large external space, the elbow at the middle of the limb flexes the upper limb and reduces the range (**Fig. 1.6**).

The hand at wrist flexes within this space to reduce the space further. Therefore, from fully flexed to fully extended position, the range of upper limb carries the hand to various places around the body. This forms the extrinsic or external space.

The hand opens and closes fully forming the intrinsic or internal space (**Fig. 1.7**).

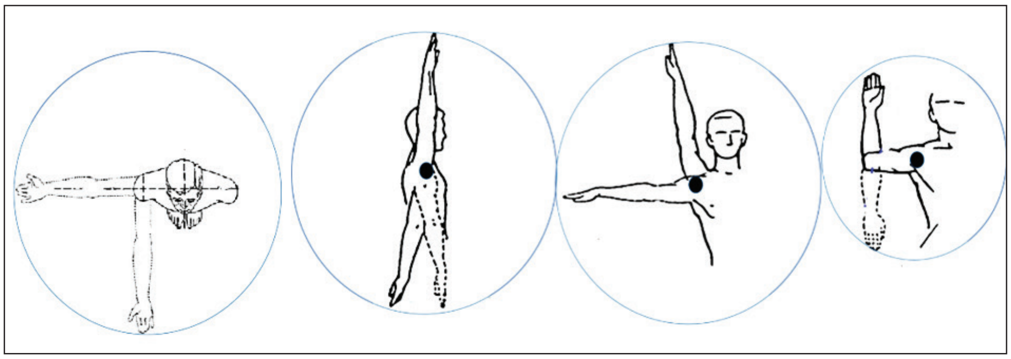

Fig. 1.6 Extrinsic space.

Fig. 1.7 Intrinsic space.

The internal space of the hand is maintained as a modified cup with expanding and collapsing side walls comprising the fingers and thumb that can open up more space or collapse to close the gaps. Both the hands can be brought together to form even a big bowl. This facilitates accommodating various size objects within the hands.

This concavity of the cupping of the hand is maintained by the arches, the fascia, and ligaments.

Full function is possible only if both the external and internal spaces are capable of opening and closing completely. For example, when there is stiffness of shoulder, there is restriction to full abduction, and therefore the external space cannot be opened fully. The person will not be able to reach an object at a higher level. Similarly, if there is thumb web contracture, the intrinsic space cannot be opened fully, leading to less available space to accommodate objects. A larger object cannot be held with a contracted thumb web.

Restriction also can happen if the spaces cannot close fully but can open fully. For example, if there is paralysis of the flexors of the elbow, it may extend fully opening the extrinsic space, but the patient will not be able to reach his/her mouth closing the space. Similarly, if the flexors of the fingers are cut, then the fingers will open the intrinsic space to accommodate the object but cannot close to hold the object.

Arches of the Hand

There are two transverse arches, proximal and distal (**Fig. 1.8a**).

The proximal arch is formed by the proximal and distal rows of carpal bones forming the carpal tunnel. It is maintained by the flexor retinaculum and intercarpal ligaments. They keep the flexor tendons in line with the center of the palm from where the tendons deviate to the corresponding fingers. The distal arch is formed by the heads of metacarpals, varies in shape, depending on the positions of the fingers, and alters dynamically in various positions of grasp.

Every ray of the finger and thumb forms the longitudinal arches. They are formed by the phalanges and their corresponding metacarpals. The thumb ray is the most mobile and then the little and ring fingers; the index and middle fingers are more or less stable.

An oblique arch formed by the thumb ray and the fingers can also be described. This is again dynamically altered by the movements of thenar and hypothenar muscles (**Fig. 1.8b**). The oblique arch of the thumb with the index finger is important for precision grip (**Fig. 1.9a**), whereas that with the little finger tightens the grip (**Fig. 1.9b**).

Activities and Disabilities

Activities can be ADLs, self-care, or economic and social activities. Anatomical loss or loss of function of a component of the hand will lead to impairment.

Impairment leads to functional limitation, which, in turn, leads to disability. Therefore, a proper understanding of the anatomy and function or dynamics is essential to prevent disability in a person.

It is not that only the major joints or nerves are important. Even the nail and tip of a finger play a role in the day-to-day activities of everyone's life. The nail comes in handy, for example, while picking up a pin, and the pulp helps to tear pieces of paper, not to mention the role of all these while playing a guitar or violin.

The joint must move through a range of motion for functional activity. This, in turn, requires muscle strength and excursion of the muscle tendon units. The muscles require proper innervations. Even when all these are intact, the higher function is required for coordination. Picking up a book from a top shelf and keeping it on the table may look like a simple activity but requires the movements at almost all joints of the upper limb, from the shoulder to the IP joints of the fingers and thumb. It also requires absolute coordination among all of them.

Prehensile and Nonprehensile Functions

Prehensile means the object is wholly or partly seized within the hand and is manipulated like a ball, a pencil, a key, or a handle hooked in hand (**Fig. 1.10**).

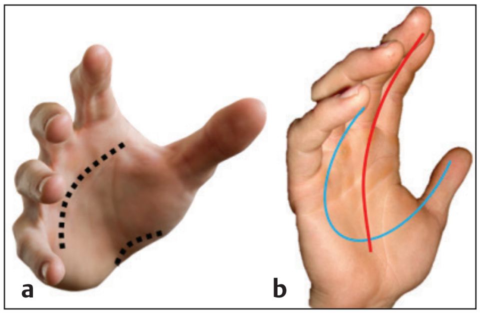

Fig. 1.8 (a,b) Arches of hand.

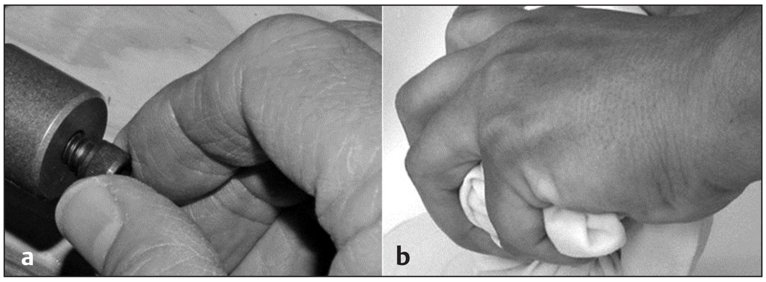

Fig. 1.9 (a,b) The oblique arches formed with the thumb by the fingers.

Fig. 1.10 Prehensile functions of the hand.

Fig. 1.11 Nonprehensile functions of the hand.

On the other hand, nonprehensile functions are those in which the hand or fingers are used as a whole or partly without seizing or holding the object as an object is pushed with the hand, such as, dribbling in basketball, using finger in a touch screen, or using a key board (**Fig. 1.11**).

When an object, such as a ball, is taken and thrown, the hand space is actually opened to accommodate the ball, and close the space and grasp it. Then the muscle forces are used in the wrist elbow and shoulder to throw it by releasing it from the hand by opening the intrinsic space again. The prehensile functions of the hand are responsible for holding the object in the hand for performing activities and the muscle power for throwing it. They convert the motor forces into functions and, in turn, into activities.

Grasping an object involves the primary motor cortex sending signals to the muscles. But manipulating the grasped object to perform activities requires the cerebellum and also somatosensory feedback. Milner et al[1] in their study of functional magnetic resonance imaging found that if the hand performs a complex manipulation of a grasped object, then ipsilateral cerebellum gets activated, and suggested that a role for cerebellum apart from the primary motor cortex. Depending on the complexity of dynamics involved, they speculated that areas that include secondary somatosensory cortex, Brodmann area 40, and insula integrate tactile and proprioceptive information in the context of controlling and orientation of the object and provide appropriate feedback to primary motor cortex.

These are described as the grasp, pinch, and hook functions. Abductors and adductors of the fingers also perform functions such as holding a syringe or a cigarette between the fingers (**Fig. 1.12**), which was described as syringing function by Srinivasan.

Fig. 1.12 Syringing function as described by Srinivasan.

If the components of the hand that take part in performing a prehensile function are viewed, it is realized that all the fingers and thumb take part in grasp, all the fingers without the thumb take part in hook, and the thumb with the middle and/or index finger take part in pinch.

In the proximodistal axis, the flexors and extensors get inserted at different levels. The insertion of the wrist flexors and extensors to the carpal and metacarpal bones stabilizes the wrist proximally, and on this stable base, the distal joints flex and extend. The extensors of the fingers exert opposing force to control the flexion of the fingers gradually (**Fig. 1.13**). With these muscle forces acting on the various joints, many patterns of grasp are possible. These are influenced by the size and shape of the objects.

While trying to define the mechanics for constructing the robotic hand, Zheng et al[2] during the IEEE International Conference on Robotics and Automation 2011 workshop

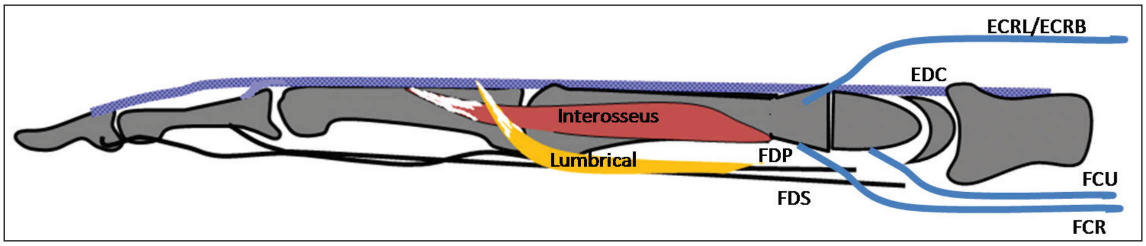

Fig. 1.13 Depiction of various muscle forces acting on a finger ray. ECRB, extensor carpi radialis brevis; EDC, extensor digitorum communis; ECRL, extensor carpi radialis longus; FCR, flexor carpi radialis; FDP, flexor digitorum profundus; FCU, flexor carpi ulnaris; FDS, flexor digitorum sublimis.

presented on *Grasp Type and Frequency in Daily Household and Machine Shop Tasks*. They presented a treelike taxonomy of 16 possible patterns of grasp, depending on size and shape of objects.

Grasp

Grasps can be divided into power grasp and precision grasp. Power grasp can be cylindrical (prismatic) as in holding a hammer or circular, which can be spherical or discoid as in holding a ball or a disk. Precision grasp is like holding a paper cup or an egg where force is not required.

Apart from the shape of the object held the intention of the action also determines the type of grasp whether powerful or refined. It may be a mixture of, both firmly and loosely held grasp as in conoid grasp. Huei-Ming Chai[3],of National Taiwan University, in her web article on hand, Kinesiology describes the conoid grasp clearly. The apex of the cone is held firmly at the ulnar side of the hand , and the radial side fingers and palm gradually opening up like a cone and holding it loosely around (**Fig. 1.14**).

Cylindrical Grasp

When a cylindrical object is held, all the fingers wrap over it and the thumb also flexes but mostly in line with the palm. Almost all joints of the fingers and thumb tighten. As the fingers tighten over the object, the CMC joints of ring and little fingers also flex, and there is some rotation at the MCP joints as well around the stable midmetacarpal. This exaggerates the curvature of the distal metacarpal arch (**Fig. 1.15**).

The power for this grip requires the power of both the flexors, and therefore repairing both the tendons during the primary repair becomes essential, especially in manual laborers.

As the grip tightens to perform the function as in tightening with a spanner or a screw driver, it is noticed that the ulnar flexion at wrist adds strength to the performance. In the same way, radial extension of the wrist helps in loosening the screw. This radiodorsal to volar ulnar axis is important, and most of the tools are designed to accommodate this. It can be seen that the motor bike handle is designed in such a way as to rotate down or up the throttle handle in this axis.

Spherical Grasp

In spherical grasp, the fingers and thumb assume a radially equally spaced position as in holding a ball. The thumb assumes a more opposing function with the remaining fingers. The fingers flex less than that in cylindrical grasp.

Pinch

Pinch can also be classified as power pinch and precision pinch, depending on activity. Power pinch is as in holding a key wherein force is required to turn the key in a lock (lateral pinch). For this, there must be enough power in first dorsal interosseous and the adductor pollicis apart from the flexors.

Precision pinch is as we hold the pin (tip pinch) or a thread while passing it through a needle (pulp to pulp). Holding a pen or pencil requires the same pulp-to-pulp pinch but some power is required to grip it.

Combination of Various Grasps

For performing ADLs, various combinations are required. Author personally feels that for many attitudes of grasp and

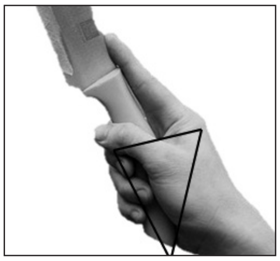

Fig. 1.14 Conoid grasp.

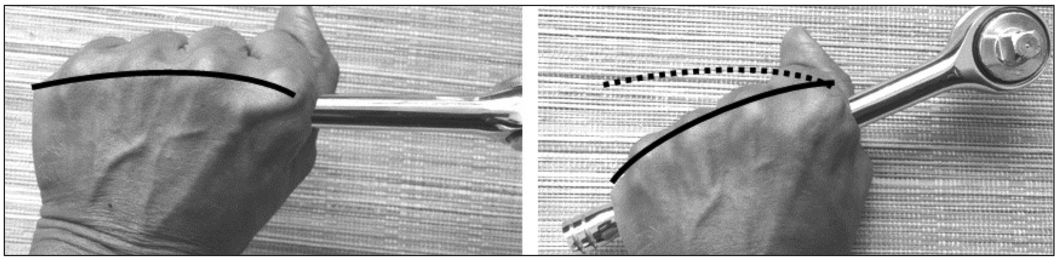

Fig. 1.15 Distal metacarpal arch on normal grasp and on tightening the grasp.

pinch in daily activities, there is some amount of overlap, and that both power and precision may be required to perform a simple ADL, such as wearing a belt (**Fig. 1.16**). The right hand requires power and grasp and the left hand requires a precision pinch.

Thumb Opposition

For all the activities of grasp and pinch, the thumb has to move from its position in line with the palm to a position opposing the fingers (**Fig. 1.17**).

Author considers this as an arc initiated by radially innervated muscles going through median and ultimately the ulnar innervated, with abduction, opposition, flexion, and adduction taking place sequentially.

When the thumb moving from the palmar plane to oppose the fingers is observed carefully, it is noticed that extensor pollicis longus, abductor pollicis longus (APL) and extensor pollicis brievis (radial innervation), abductor pollicis brevis, opponens pollicis brevis (median innervated), flexor pollicis brevis (median/ulnar innervated), and, finally, adductor pollicis brevis (ulnar innervated) come into play, as you can see in **Fig. 1.17**. Each group of muscles sequentially contract as the previous group relax.

Fig. 1.16 Grasp and pinch in a single activity.

Ulnar innervated first dorsal interosseous also may come into play if the thumb performs pinch with the index finger.

This range of arc gets reduced in various palsies: the dorsal side of arc in radial palsy, the abduction part of arc in median palsy, and the flexion adductor side of arc in ulnar palsy (**Fig. 1.18**).

Further detailed description of anatomy and dynamics of each component of the hand are dealt in subsequent sections.

Skin, Fascia, and Retinaculum Cutis

Skin

The skin of the hand is special in nature. The dorsal skin being loosely attached to deeper structures with areolar tissue is traversed by veins and lymphatic. Because of this loosely attached nature, edema of the hand manifests more on the dorsum. It is also a cause for avulsion in trauma. This skin allows full flexion of the fingers and hand at wrist. It is capable of being stretched to the maximum, allowing the fingers to tightly make a fist, with the wrist totally flexed. At the same time, it will be noticed that the skin in this position cannot be pinched, showing the skin is just adequate for the fullest extent of movement, and nothing extra is available to reconstruct in case of loss (**Fig. 1.19**).

The dorsal skin is thin with hair present to a varying extent but mainly on ulnar side and the dorsum of the fingers. The unique thing about the hair is the direction being almost always ulnar ward.

Unlike the dorsal skin, the palmar skin is thick. It has no hair and has a large number of eccrine glands. The population of these sweat glands is almost 3,000 per square inch of skin. Even though the palmar skin is not smooth and has plenty of ridges, the absence of hair merits it being called "glabrous skin." Unlike other areas, the skin of the palm is thick, approximately 0.8 to 1.4 mm, to handle pressure from objects and is tethered to deeper structures with

Fig. 1.17 Stages of opposition from normal thumb position.

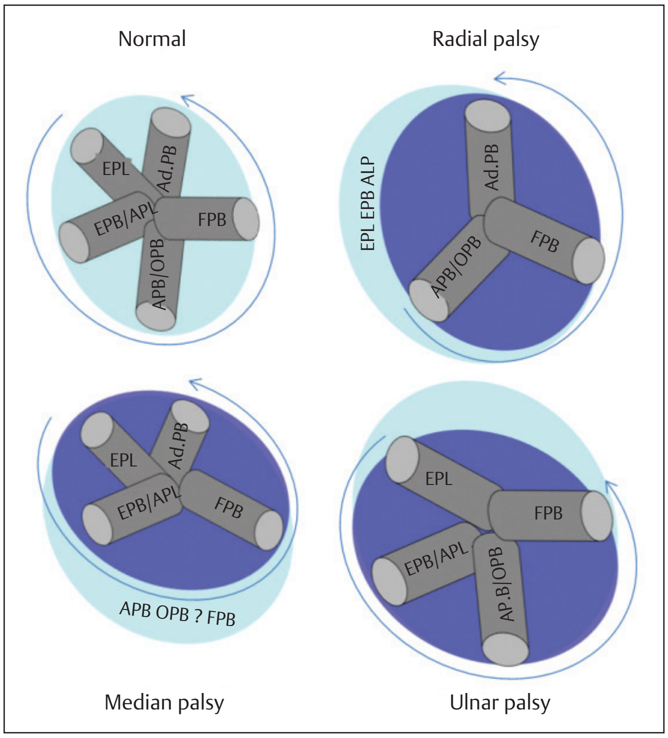

Fig. 1.18 Roles of all three nerves in the opposition sequence. APL, abductor pollicis longus; APB, abductor pollicis brevis; EPB, extensor pollicis brevis; EPL, extensor pollicis longus; FPB, flexor pollicis brevis; OPB, opponens pollicis brevis.

Fig. 1.19 This demonstrates that the skin on the dorsum is just adequate for full flexion.

fibrous tissues. This anchorage prevents bagging of skin on flexion and the objects can be manipulated with good grip and precision. Imagine opening a bottle's lid if the skin of palm is like the dorsum. Then the skin will move over the lid without gripping it.

The skin is most firmly anchored to the deep structures at the palmar creases—this is of clinical importance when planning surgical incisions to minimize skin contractures. In contrast to the dorsal skin, the blood supply to the palmar skin is through numerous small, vertical branches from the common digital vessels traversing in between the fibrous septa. Therefore, the elevation of palmar skin flaps is limited. When palmar skin gets avulsed, the blood supply and therefore the viability of raised skin become vulnerable.

Skin creases and their relationship to the joints were studied by Bugbee and Botte[4] by keeping wires over the creases and taking X-rays (**Fig. 1.20**). They found that the distal interphalangeal (DIP) crease is proximal to the joint by nearly 7 to 7.8 mm and the proximal interphalangeal (PIP) crease by approximately 1.6 to 2.6 mm. On the other hand, the palmar digital crease is consistently distal to the MCP joint by 1.4 to 1.9 cm. Distal palm crease is proximal to the MCP joint of the little, ring, and middle fingers by 7.9, 10.3, and 6.9 mm, respectively. The distal palm crease stops short of the index finger; hence, the MCP joint of the index finger is related to proximal palm crease, which is 9.1 mm proximal to it.

The outermost keratin layer, stratum corneum, is the thickest and keeps exfoliating allowing deeper layers to come to surface. Its cells are devoid of nuclei. It is followed by stratum lucidum, granulosum, spinosum, and basal layer from superficial to deep (**Fig. 1.21**).

The skin of the palmar surface of the hand contains a high concentration of sensory nerve organs essential to the hand's normal function. The mechanoreceptors on the volar side of the hand are low threshold receptors innervated by fast-conducting "A" type of fiber with a subclassification of β type fibers having a diameter of 6 to 12 μm and a speed of 2 to 20 m/s. Meissner's corpuscles lie encapsulated between the dermal papilla just below the epidermis[5] and account for 40% of mechanoreceptors found. Pacinian corpuscles are deeper in subcutaneous plane and have lesser threshold for stimuli than Meissner's corpuscle. These help in distinguishing fine texture and account for 10 to 15% of receptors.

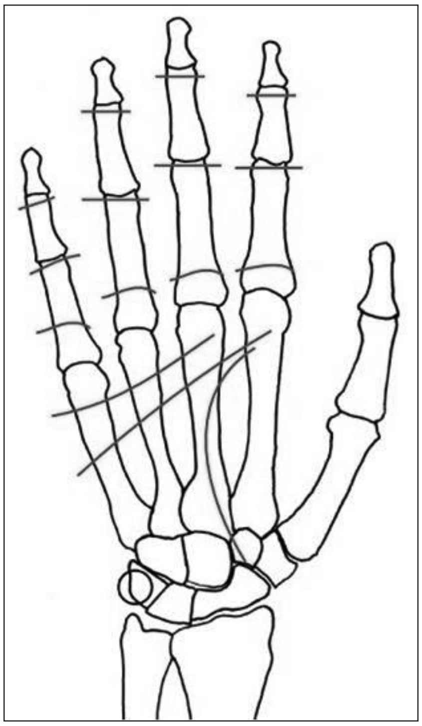

Fig. 1.20 Relationship of creases to joints in hand.

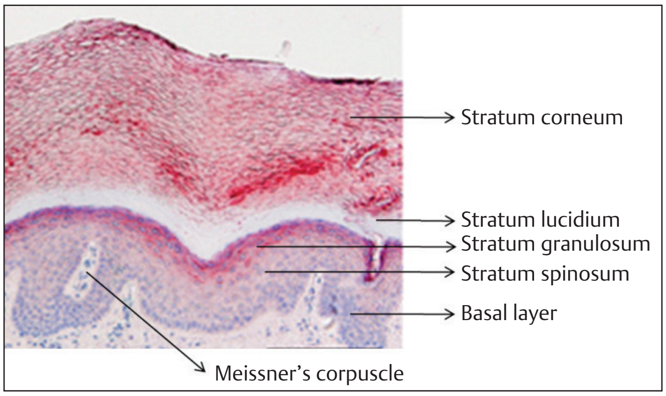

Fig. 1.21 Structure of the palmar skin.

Apart from these, Merkel's disks and Ruffini's corpuscles are also located in the skin of the hand. Merkel's disks are located in the epidermis where they are aligned with the papillae beneath the dermal ridges and are particularly dense in the fingertips and form approximately 25% of the receptors.

Ruffini's corpuscles are located deep in the skin and also in the tendons, and account for 20% of the receptors.

The sweat secretion and nervous system are intimately connected. On the one hand, it improves the tactile sensitivity, and on the other hand, if it is excessive, it interferes with activities. Excessive secretion due to anxiety or idiopathic hyperhidrosis is well known. It can even interfere with ADLs such as difficulty in operating a key board or turning a knob. Essential hyperhidrosis, a disorder of the eccrine sweat glands, is associated with sympathetic over activity.

Subcutaneous Tissue, Retaining Fascia, and Ligaments

The palmar skin closely adheres to the underlying structures with ropelike fascial condensation and is hence called by some retinaculum cutis. It divides the palm into various compartments and allows passage of linear structures passing from the forearm to the fingers like neurovascular (NV) structures and tendons. In this process, it also helps to stabilize the skin by the fibers of fascia mingling with deep layers of skin. It forms the creases of the palm and fingers. This effectively prevents bagging of skin and confines the folds to the respective segment of the hand and fingers (**Fig. 1.22**) so that the skin does not wobble when grip is tightened. Spanish anatomist Juan Valverde described this way back in 1556. The palmar fascia is also responsible for a greater extent for maintaining the hollow of the hand and the arches. Zancolli and Cozzi[6] in their 53 microdissections of cadavers have described the retinaculum cutis in great detail in their Atlas of Surgical Anatomy of the Hand.

The various components of the fascia described by them are palmar fascia, interdigital or natatory, and dorsal paratenon connective tissue.

They fall under various subclassification: thenar, hypothenar, midpalmar, retroadductor, and digital. The arrangements of these fibers are shown in **Table 1.1**.

The midpalmar fascia is referred to as the palmar aponeurosis and is triangular in shape and quite thick. Giovanni Cannanus in 1543 described not only this fascia but also his discovery of palmaris longus tendon. Valverde felt that the fascia, especially the superficial part, is an extension of the palmaris longus tendon. The flexor carpi ulnaris (FCU) tendon also contributes to the formation of the midpalmar fascia. The tendon has both longitudinal and radially directed fibers. The longitudinal fibers continue distally, and get inserted to the pisiform bone and continue with the fascia over the abductor digiti minimi (ADM) in the hypothenar area. The radially directed fibers contribute to the palmar aponeurosis and also form the roof of Guyon's canal.

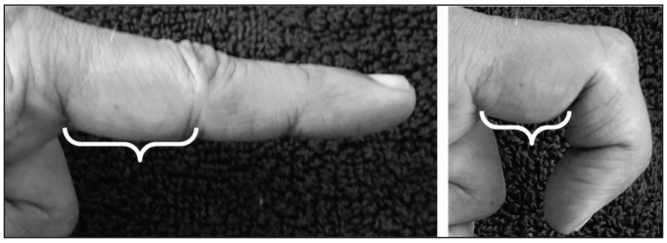

Fig. 1.22 Tetherence of the skin at crease to deeper structure.

Table 1.1 Fascia of hand

<table>
<tr><th colspan="5">Palmar fascia</th><th rowspan="6">Inter digital (or) Natatory</th><th rowspan="6">Dorsal paratenon</th></tr>
<tr><td colspan="3">Mid palmar</td><td>Thenar</td><td>Hypothenar</td></tr>
<tr><td colspan="2">Longitudinal</td><td>Transverse mid palmar</td><td colspan="2" rowspan="4"></td></tr>
<tr><td>Superficial</td><td colspan="2">Deep</td></tr>
<tr><td rowspan="2"></td><td>Proximal</td><td>Distal</td></tr>
<tr><td>Paratendinous Vertical septa</td><td>Bifurcating</td></tr>
</table>

The deep fibers also merge with the pisohamate ligament and form part of the floor of the canal (fully described under the heading Guyon's Canal; see **Fig. 1.27**).

The fibers of the midpalmar fascia distally show two different structural formations, namely, longitudinal and transverse (**Fig. 1.23**).

The longitudinal fibers are called the pretendinous bands. Superficial parts of the longitudinal fibers merge with deep dermal layers of skin and anchor them. In Dupuytren's contracture, these can be seen as bands stuck to the skin (**Fig. 1.24**). Distally, they intertwine with natatory ligaments, which are subcutaneous transverse bands.

The deeper ones of the longitudinal part go along the tendons and at distal palm crease to form paratendinous septa. These, according to Zancolli and Cozzi, divide the midpalmar compartment into many tunnels. The tunnels through which tendons pass are called tendinous tunnels, and the tunnels through which NV bundle pass are called lumbrical tunnels. These septa are proximally attached at depth to palmar interosseous fascia and distally at depth to the MCP joint assemblage, as described by Zancolli and Cozzi.[6] This palmar aponeurotic (PA) pulley is located proximal to the A1 pulley and directs the tendons to their respective fingers.

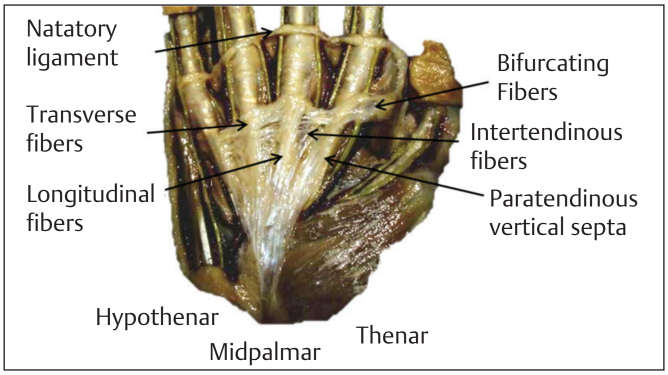

Fig. 1.23 Palmar aponeurosis.

Other longitudinal fibers can be seen running between the tendons called intertendinous fibers piercing which the perforators of vessels come to supply the skin.

Transverse fibers of the midpalmar fascia are nearly 1 cm wide and are deep to the pretendinous bands. The pretendinous bands penetrate between this to form the vertical septa. This transverse band is attached to the skin only at the ends. On the ulnar side, it is attached to distal palmar crease area, and at the radial end, it is attached to midpalmar and thenar creases.

Thenar fascia is a thin fascia covering the thenar group of muscles and is reinforced with the longitudinal and transverse fibers of the midpalmar fascia and also the natatory ligament. The fibers from the longitudinal part of the mid palmar fascia extend from the radial side of index finger to reach the thumb sesamoid bone. Those arising from the natatory ligament reach the thumb divide into two parts on either side of the flexor pollicis longus (FPL) and attach to the skin of the MCP joint crease. They form the intermuscular septum on the ulnar side.

Hypothenar fascia is like the thenar fascia, and on the ulnar side, it gets attached to the shaft of the fifth metacarpal and the pisiform bone. On the radial side, it is reinforced with fibers of the proximal midpalmar fascia.

Dorsal fibrous tissues are of two types: those running longitudinal and those that are perpendicular to the digit. The ones that are perpendicular are located over the IP joints forming the creases.

These tissues are loosely attached to skin and permit considerable movement of the skin over the tendon. They are

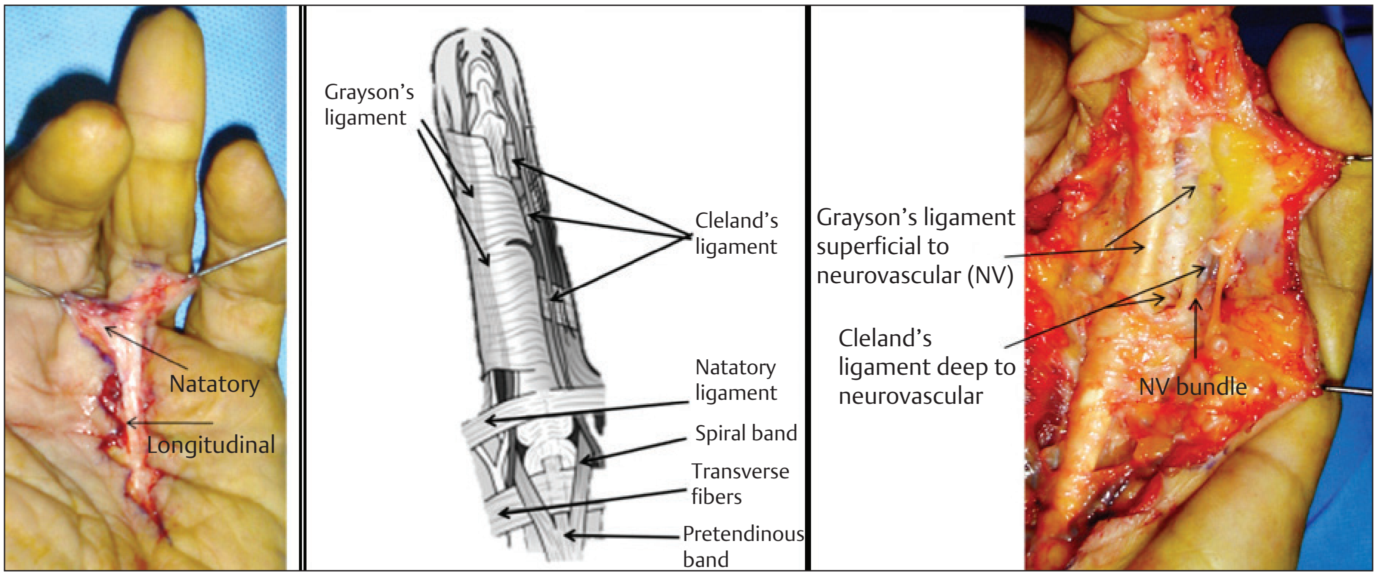

Fig. 1.24 Cutaneous ligaments in the fingers.

attached at depth to the tendon forming the paratendinous gliding plane.

Natatory ligaments are interwoven superficial fibers closely related to the dermis of the skin, forming a weblike structure connecting the fingers. They are also called superficial transverse palmar ligament.

Bourgery in 1852 described in his atlas these transverse interdigital fibers extending from the thumb, linking all the fingers. The main function of these is to restrict the spreading of the fingers. These extend on to the fingers as digital septum.

In the same plane, distally on the volar side of the fingers, microdissections show the digital septum called Grayson's ligament. Grayson described it as an extension of fascia from natatory ligament in 1941. They cover the NV bundle on the volar side. They are attached to the skin at the PIP, DIP, and the palmar digital creases (**Fig. 1.24**).

The dorsal digital septum originates from the phalangeal bone and is obliquely directed. It gets attached to skin on the laterovolar area. It is called Cleland's ligament. Between these two, the NV bundles traverse the length of digit. The arrangement of the digital septum is diagrammatically shown in **Fig. 1.24**.

Flexor Retinaculum and Carpal Tunnel

Retinaculum cutis stabilizes the skin to the deeper structures. Regulating the direction of the flexor tendons and improving the mechanical efficacy of the muscular forces is done by flexor pulleys in the fingers, aponeurotic pulley in the palm, and the flexor retinaculum at the wrist. It also protects the vital structures passing from the forearm to the palm.

The carpal tunnel is formed by the ventral surfaces of scaphoid, lunate, capitate, hamate, and trapezoid, and the intercarpal ligaments. This is covered on the volar side by the rigid flexor retinaculum.

The flexor retinaculum is almost in the same plane as the deep investing layer of the forearm fascia. The proximal part merges with the palmaris longus insertion. The midportion is very thick, and it is this portion that covers the carpal tunnel. This part is also called transverse carpal ligament. It gets attached on the radial side to the tuberosity of scaphoid and trapezium. On the ulnar side, it is attached to the pisiform and the hook of the hamate apart from triquetrum. On the radial side, the retinaculum splits to get attached to the grove in trapezium through which the tendon of flexor carpi radialis (FCR) passes (**Fig. 1.25**). This mouth of the FCR tunnel is sometime used as a pulley in tendon transfers.

Distal part of the retinaculum gives origin to the thenar and hypothenar muscles, and the aponeurosis between them is narrow (**Fig. 1.25**). It continues distally with palmar aponeurosis. FPL, FCR, and the flexors to the digit pass through the tunnel along with median nerve. The ulnar nerve remains outside along with artery.

On flexion, as the wrist gets ulnar deviated, the flexors will slide ulnar ward. This will be stopped by the flexor retinaculum and hamate. In fact, this can be called as the first flexor pulley that regulates the tendon excursions (**Fig. 1.26**).

Apart from these structures that pass through the tunnel, occasionally, arteria mediana, muscle belly of FDS, or a lumbrical muscle may be found in the carpal tunnel.

Carpal tunnel syndrome is due to the compression of the median nerve, which may be compressed at the proximal edge of retinaculum as demonstrated by Phalen's test. It may also be compressed near the hamate where the tunnel is narrowest.

When the flexor retinaculum is dissected and Guyon's canal is opened, it can be realized that they are almost just separated by a thin septum, which is continuous with the FCU insertion in the pisiform and the fibers radially reflecting from it (**Fig. 1.27**).

Guyon's Canal (Ulnar Tunnel)

Guyon's canal is a fibro-osseous compartment at the ulnar side of palmar aspect of the wrist that extends from the pisiform bone to the level of the hook of the hamate bone. This canal transmits the ulnar nerve and artery. The roof of the canal is not homogenous in its entire extent. Proximally, it is continuous with the antebrachial fascia and distally

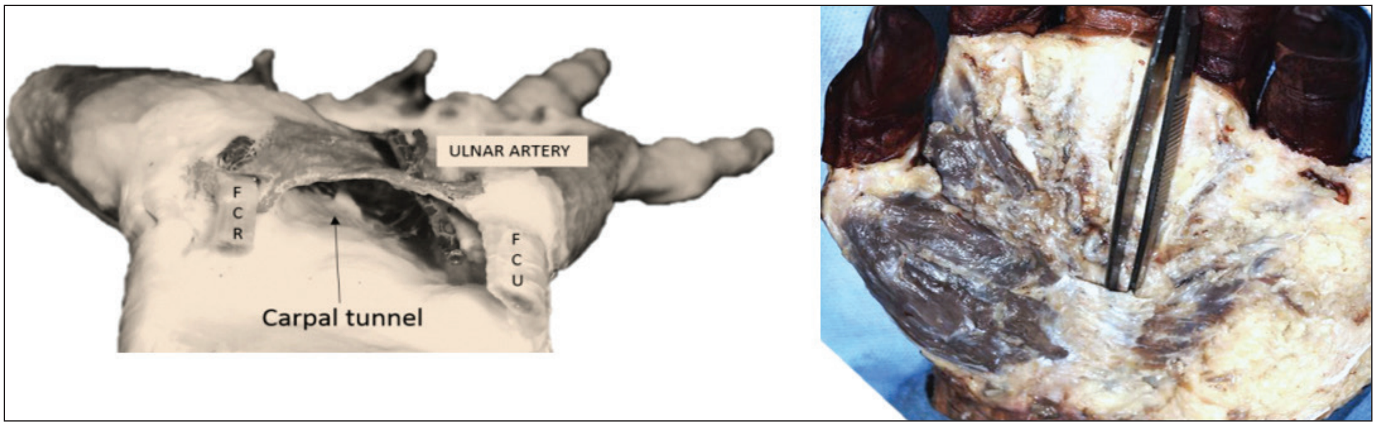

Fig. 1.25 Flexor retinaculum. FCR, flexor carpi radialis; FCU, flexor carpi ulnaris.

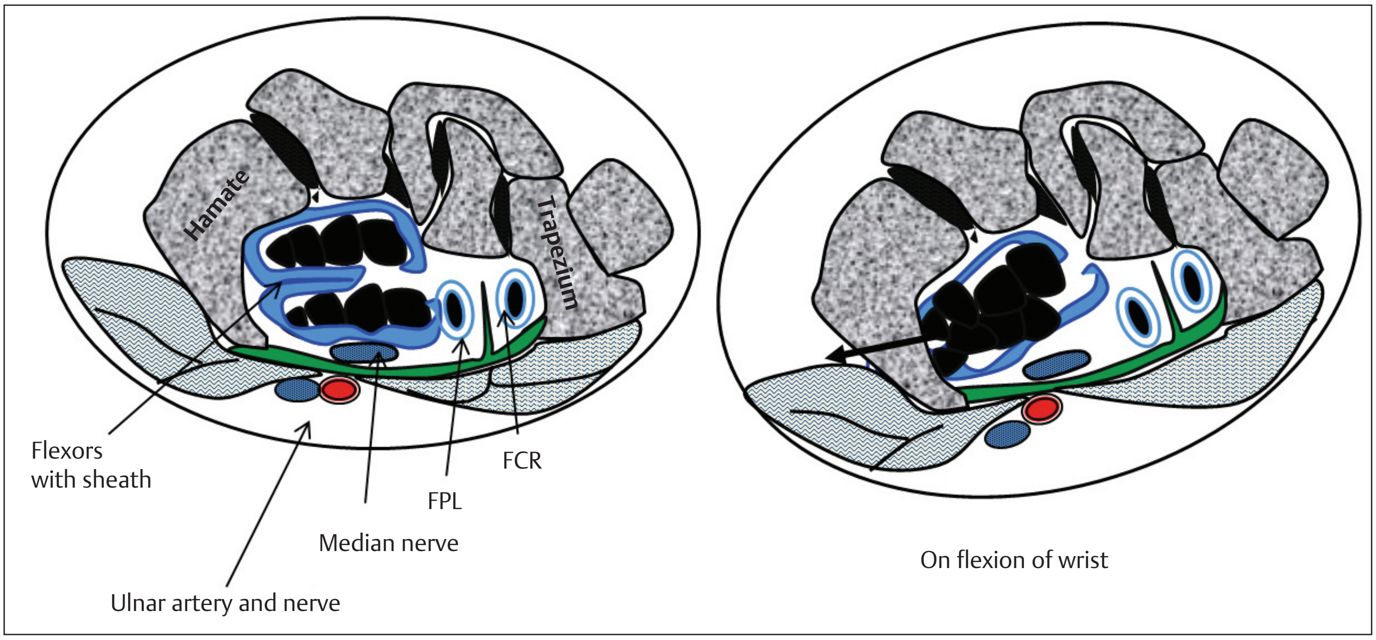

Fig. 1.26 Role of the flexor retinaculum as a pulley. FCR, flexor carpi radialis; FPL, flexor pollicis longus.

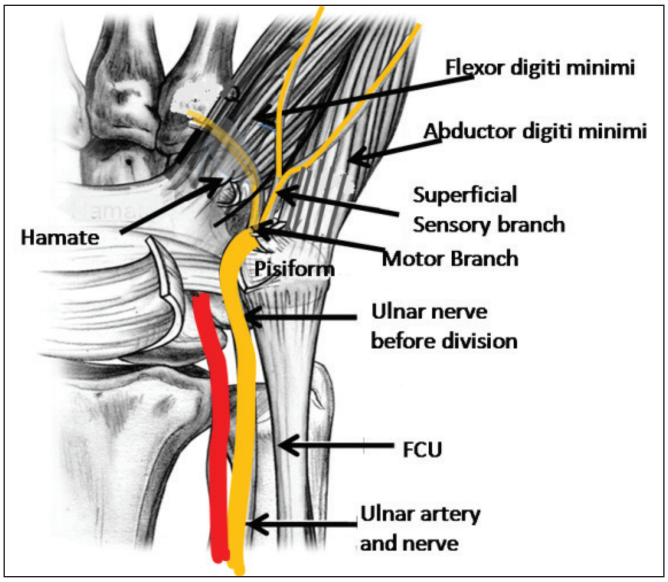

Fig. 1.27 Anatomy of Guyon's canal. FCU, flexor carpi ulnaris.

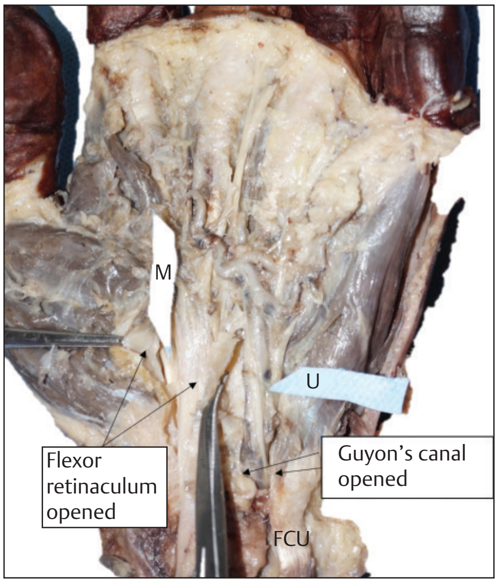

Fig. 1.28 Both carpal tunnel and Guyon's canal opened to show the nerves. FCU, flexor carpi ulnaris.

with the palmaris brevis muscle. As discussed previously, in the formation of palmar aponeurosis, the fibers of FCU gives off radially directed fibers from pisiform, which forms the roof of the canal in the midportion. This merges with the retinaculum. Author could see only a small thin septumlike structure between the two (**Fig. 1.28**).

The deeper fibers of FCU go down and merge with the pisohamate ligament, which along with the pisometacarpal ligament forms ulnar part of the floor. The transverse carpal ligament forms part of the flexor retinaculum on the radial aspect, and the flexor digiti minimi brevis distally forms the floor of the midportion.

The ulnar wall is composed of the FCU, the pisiform, and the ADM, and the radial wall is formed by the transverse carpal ligament and the hook of the hamate. The distal aspect of Guyon's canal has both a superficial and a deep exit. The superficial exit conducts the superficial sensory nerve and main trunk of the ulnar artery. This superficial distal opening is bound on the palmar side by the distal edge of the palmaris brevis muscle and the ADM. The flexor digiti minimi is on the dorsal side.

The deep or motor branch of the ulnar nerve exits through the deeper exit, the pisohamate hiatus. The hiatus is round and limited proximally by the pisiform bone, distally by the hook of the hamate bone, and dorsally by the pisohamate ligament. Palmar aspect of the hiatus is formed by attachments of ADM and the flexor digiti minimi brevis. This attachment commonly forms a tendinous arch that extends between the pisiform and the hook of the hamate.

It can be arbitrarily divided into three zones: zone I contains both the motor and sensory parts of the ulnar nerve, zone II contains the deep motor branch exiting through the deep exit, and zone III, which is parallel to zone II, contains the superficial sensory branch corresponding to the superficial exit.

Rarely the nerve can be compressed in this canal.

Nails and Tip of the Finger

"We have fingernails because we're primates," said John Hawks, a biological anthropologist. Nails have replaced in primates the claws of other mammals.

Its function may be defense against small creatures that used to inhabit the human body in primitive human beings. Nail has a more important function of protecting and supporting the broader tip of fingers in human beings. Nail is produced mainly from the germinal matrix, sterile matrix, and the dorsal roof of proximal nail fold. It grows at a rate of approximately 3 mm a month. When injured for 3 weeks, there is a delay and then the proximal part becomes thicker than a normal nail but does not migrate. After approximately 50 days, a thinner nail starts appearing and growing forward. It takes nearly 100 days before a normal-looking nail appears.

The fingertip comprises soft tissue, bone, nail, and nail-generating tissues. The nail and its germinal portion lie distal to the insertion of flexor and extensor tendons. Multiple septa arise from dermis and go down to the tip of bone. They contain rich distribution of sensory nerve endings.

Together the tip and nail have a great role to play in stereognosis. Against the resistance of nail, the pulp of the fingertip can appreciate better tactile sensation. The two-point discrimination in fingertip gets frequently doubled if the nail is not present. Since the fingertip is one of the most sensitive areas, it is also affected by extended exposure to mechanical vibration. It is known to be associated with vascular, sensorineural, and musculoskeletal disorders termed as "hand-arm vibration syndrome."

For picking up finer objects such as a pin, nails are required. Even for functions such as peeling a thin film or sticking a paper, nails are required.

In tip pinch, the resistance offered by nails can sometime be a reason for hyperextension at DIP.

Flexor Tendon Systems

Flexor muscles, tendons, their sheath, vincula, and the pulleys form the flexor system. The flexors in harmony with extensors are responsible for the movements of the hand as an organ. Flexor system has a role not only in flexion but also in extension, and the extensors have a similar role in flexion. The fact that the flexors and extensors are connected to each other by the sagittal band, transverse and oblique retinacular ligaments, and the interossei and lumbricals makes this possible.

Flexor Digitorum Sublimis

FDS arises as two bundles: humeroulnar and radial. The humeroulnar head arises from the medial epicondyle, medial collateral ligament of elbow joint, and coronoid process. The radial hand arises from the radius just distal to tuberosity. Between these two heads, the median nerve and ulnar artery pass into the distal forearm. The muscle cannot be considered as a single muscle to each finger. If at all, the middle finger part of muscle can be considered separate. The middle and ring finger tendons lie superficial, and the index and little finger tendons lie deep with an intermediate tendon present in the center of muscle mass, as shown in the figure with muscle spread out (**Fig. 1.29**). Distally, they separate into four tendons and reach their destination.

Flexor Digitorum Profundus

Flexor digitorum profundus (FDP) arises as a single mass from the upper three-fourth of the medial and anterior surface of the ulna and interosseous membrane. Near the musculotendinous junction, it forms two bundles: the radial bundle separately forms the index FDP, and the ulnar bundle forms interdigitating slips covered by a single paratenon for the middle, ring, and little fingers[7] (**Fig. 1.30**). These tendons from the forearm are directed to the palm through the carpal tunnel. This maintains the tendons in the center of the wrist and in all movements of the wrist. In fact, this is the first pulley. Hook of the hamate on the distoulnar side and the tuberosity of scaphoid on the proximoradial side are important to maintain the tendons without drifting on dorsoradial and voloulnar movements of the wrist as described earlier in carpal tunnel.

The Pulley System

After coming out of the carpal tunnel, the individual tendons diverge to each finger being directed by the PA pulleys. The PA pulleys keep the tendons close to bones by the pretendinous fibers, and the vertical septal fibers prevent their lateral drift.

The distal edge of the PA pulleys is located proximal to the A1 pulley, and the proximal edge is proximal to the

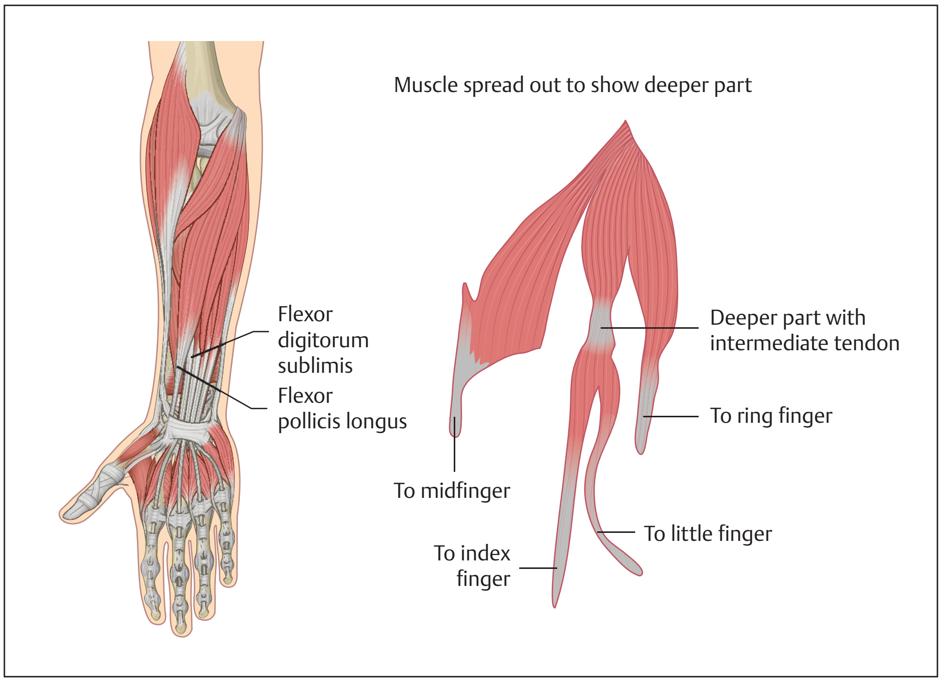

Fig. 1.29 Flexor digitorum sublimis muscle in forearm.

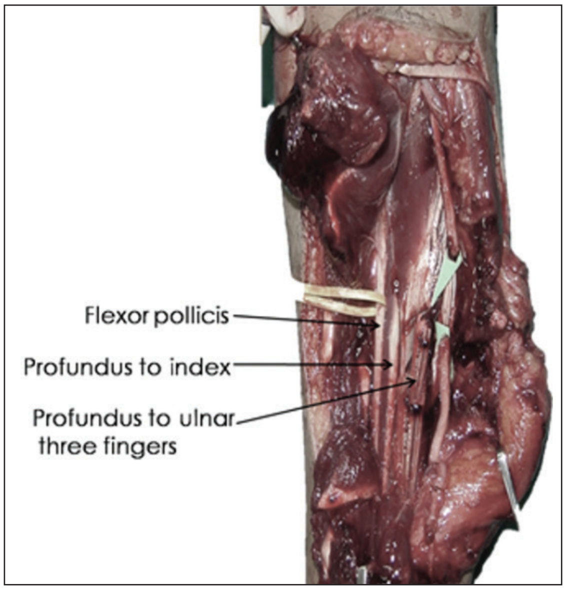

Fig. 1.30 Flexor digitorum profundus in forearm.

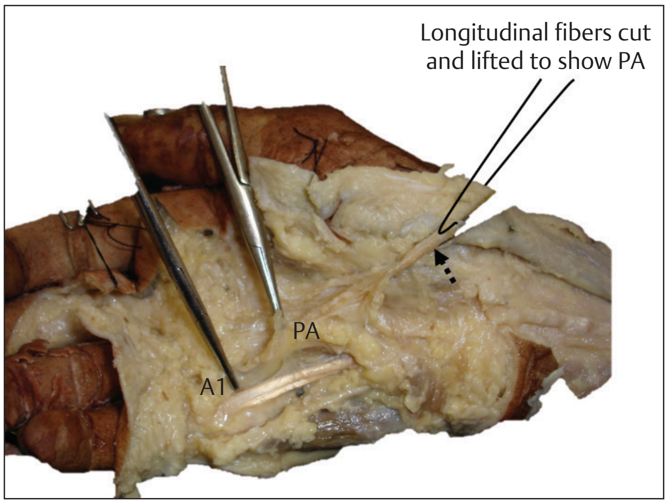

Fig. 1.31 Palmar aponeurotic (PA) pulley and the A1 pulley.

synovial sheath end. In **Fig. 1.31**, the longitudinal fibers of aponeurosis have been cut distally and reflected to show the PA pulley and the A1 pulley. Only when the palmar aponeurosis pulley was sectioned in combination with either or both of the proximal annular pulleys (A1, A2), there was a significant decrease in excursion efficiency and not when it was sectioned alone.[8,9] The lumbricals are attached to FDP on the radial side and they pass volar to the MCP joint and get attached to the lateral band of the extensor linking the flexors to the extensors.

At the MCP joint level (A1 pulley), the FDS starts to split to allow the FDP to pass through and become superficial. The two slips reunite behind and again separate to get inserted into the middle phalanx. This entire formation is called Camper's chiasma (**Fig. 1.32**). The FDP continues distally and gets inserted into the distal phalanx base. It has been demonstrated that when FDS is divided under the A2 pulley, the excursion of FDP is reduced.[10] Likewise, presence of the FDP in the digital sheath is essential for optimal FDS excursion efficiency.[11]

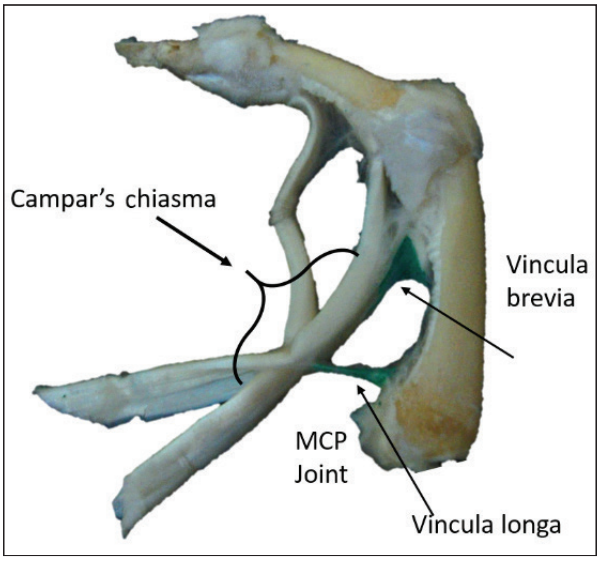

Fig. 1.32 Camper's chiasma. MCP, metacarpophalangeal.

There are two vincula for each tendon: a shorter one near insertion and a longer proximally (**Fig. 1.32**).

When the tendon gets divided and if vincula are intact, they can also act dynamically and flex the joint, which may give a false clinical picture.

The tendons are covered with three different layers of sheath, namely, membranous, retinacular, and connective tissue. The outermost layer is the connective tissue cover that goes into the gaps between the pulleys.

The innermost layer is the membranous synovium that has visceral and parietal layers. It goes around each tendon, and the lubricant fluid present is responsible for smooth gliding. It also provides nutrition for the tendon. Distally, the synovium extends up to the insertion of FDP in all the fingers and FPL in the thumb.

Proximally, it extends into the middle three fingers up to approximately 10 to 14 mm to the distal edge of the metacarpal head. In the little finger and thumb, they extend proximally through the carpal tunnel into the forearm (**Fig. 1.33**).

The retinacular layer is the toughest and forms the pulley system. It forms the important fulcrum and is responsible for distributing the flexor forces. There are five annular and three cruciate pulleys. The annular ones keep the tendons in close contact with the bones. On the other hand, the cruciate ones are over the joints, allowing movements of tendon away from joint under them. The A1, A3, and A5 pulleys are over the MCP, PIP, and DIP joints, respectively. A2 and A4 are the strongest, longest, and the most important ones. They are over the shafts of the proximal and middle phalanges. C1, C2, and C3 are after A2, A3, and A4 (**Fig. 1.34**).

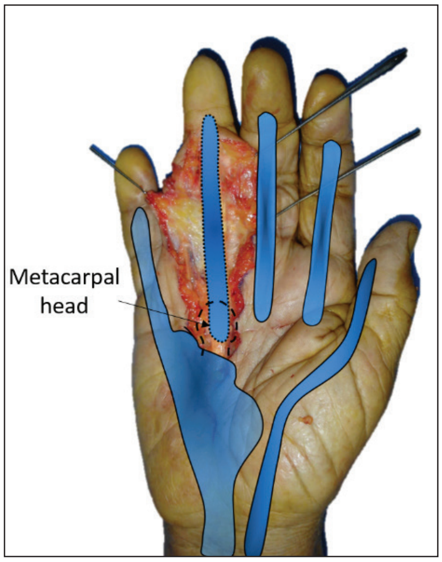

Fig. 1.33 Synovial sheath.

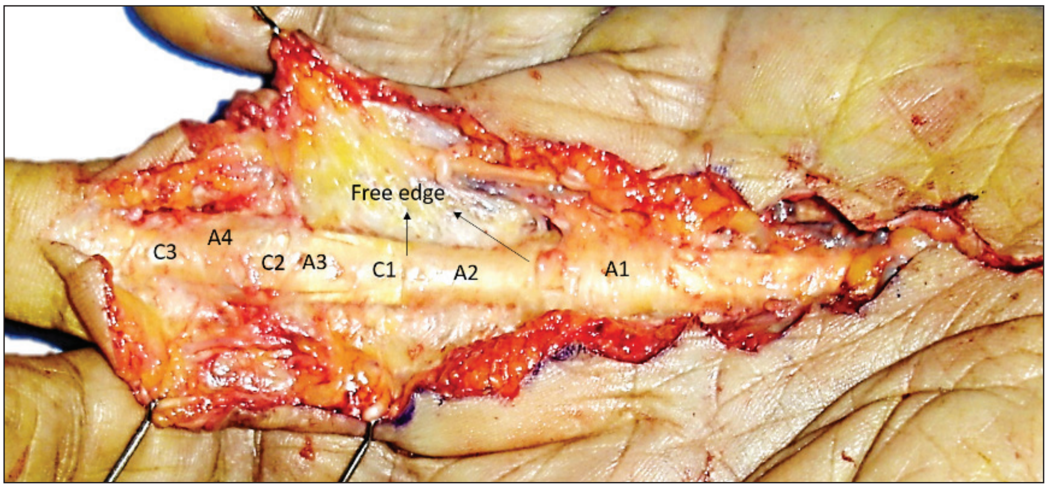

Fig. 1.34 Flexor pulleys of the hand.

A1 is located over the MCP joint and the base of the proximal phalanx. It forms a total fibrous ring with the volar plate. Traction on it will flex the MCP joint. This is used in the Lasso procedure wherein the tendon slip is tunneled through the A1 pulley.

A2 is located over the proximal part of the phalanx. It is the longest, strongest, and thickest of all pulleys. It is attached to the lateral ridge of the phalanx. There are oblique fibers that overlie the annular fibers. The edges are free. It occupies nearly 40% of the length of the phalanx and measures approximately 17 mm. The A3 pulley is over the PIP joint. It is attached to the volar plate of PIP and the assembly consisting of C1, collateral ligament, and transverse retinacular ligament, as seen in **Fig. 1.34** (see also **Fig. 1.54**).

It is thin and only approximately 3 to 4 mm in length. Together with C1 and C2, it acts on the PIP joint. In fact, the C1 and C2 pulleys are more important than A3. Sectioning of A3 does not produce any reduction in the range of motion. Next to the A2 pulley, A4 is the most important. It is found on the diaphysis of the middle phalanx just distal to base of the middle phalanx confining to zone II. It covers 45% of the shaft length and is approximately 8 mm in length; therefore, compared with A2, it is less thick. The A5 pulley is over DIP and may even be absent.

The cruciate pulleys are like lattice and can expand and collapse to accommodate the movements.

Extensive work has been done by Eduardo Zancolli on the biomechanics of the hand, especially the role of pulleys. He did microdissections and demonstrated the role of pulleys by removing them one after the other and studying the excursion. Excursion of the flexor tendons is constant and is equal to the fully stretched muscle to the fully flexed position (**Fig. 1.35**). It is approximately 45 mm for the middle finger at the metacarpal level. This available excursion must be distributed among all the three joints, enabling them to absorb the force required to flex to their full range. The range gets distributed as shown in **Fig. 1.36**. To attain the maximum flexion of 85 to 90 degrees at the MCP joint, 23 mm of excursion is required. PIP requires 17 mm of excursion to attain approximately 110 degrees of flexion, and DIP requires approximately 4.5 to mm of excursion to attain 60 degrees of flexion. When the percentage contribution of the total range at each joint is looked at, Zancolli mentions that the MCP flexion is approximately 51%, PIP is approximately 38%, and, finally, DIP is only 11%. This amounts to approximately 240 degrees of combined flexion range.

Moment Arm, Lever Arm, and Role of Pulleys

Moment arm (MA) is the perpendicular distance from the axis of the joint to the line of force. Lever arm is the length of the lever on which force is applied. If the lever arm and MA are smaller, more movement can be achieved with less excursion. This can be easily seen in the example of the manual boom barriers that are commonly seen.

When force is applied on the shorter side of the boom barrier (heavy weight), it moves a short distance, but the boom barrier moves for a great height. On the other hand, if the longer side of the boom barrier is looked at, it will be noticed that the shorter side with the weight can be lifted with very little force, but the excursion of the boom barrier is more and the distance to which the weight is lifted is short (**Fig. 1.37a**).

The pulley system can be looked in the same way. The pulleys keep the tendons in close proximity to the joint, so the MA and the lever arm are smaller. This helps to keep the tendon excursion at any given joint to the minimum. As already discussed, the excursion of the flexor tendon is constant, so if excursion at one joint is minimal, then the remaining available excursion is used for moving the distal joints. But the effort required to initiate the movement is more. On the other hand, if the A2 pulley is divided and not reconstructed, then the lever arm becomes more and can easily move the adjacent PIP joint with little effort, but the tendon has to move more to produce the same amount of flexion (**Fig. 1.37b**). This results in less available excursion to move the distal joint, ultimately resulting in lag in flexion at DIP (**Fig. 1.37c**).

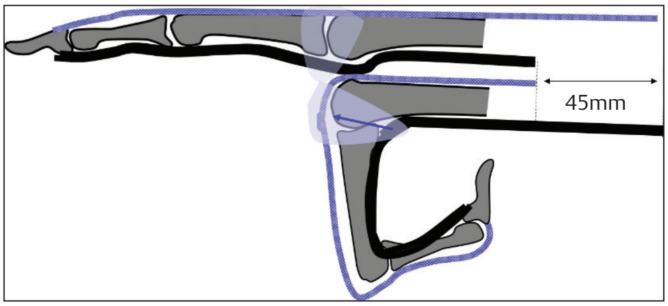

Fig. 1.35 Excursion of flexor tendons in the finger.

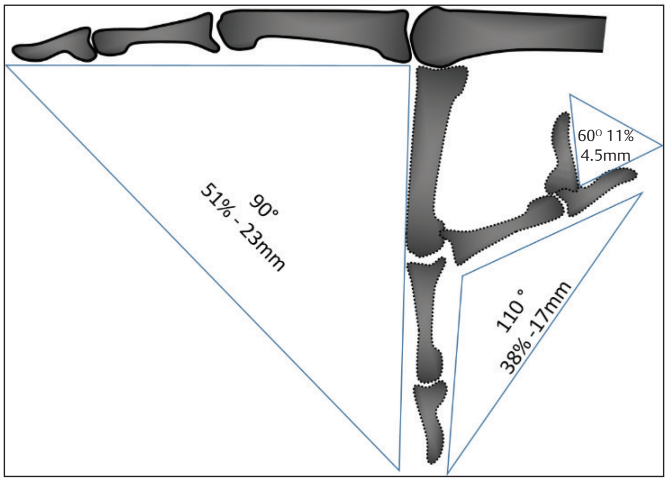

Fig. 1.36 Range of flexion at the joints.

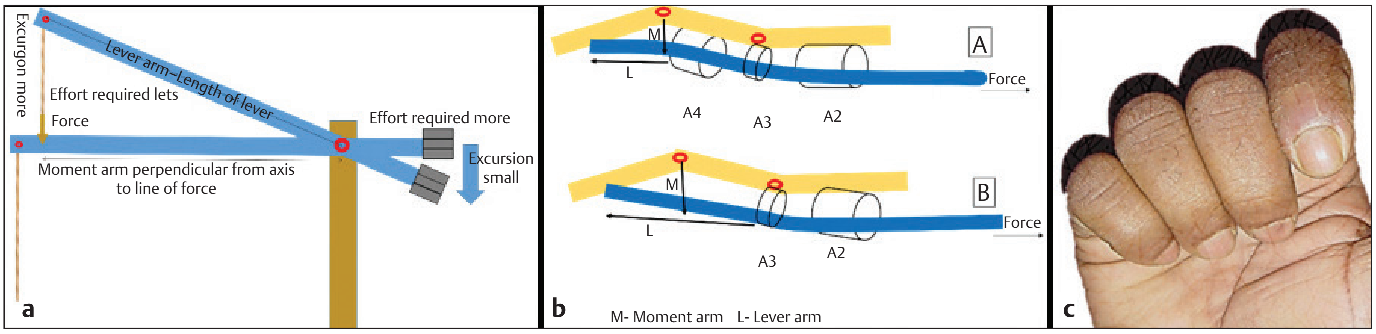

Fig. 1.37 **(a)** Boom barrier. **(b)** Role of pulley altering moment arm. **(c)** Lag of flexion.

Modification of the Moment Arm and Effort by Pulleys

A2 and C1 proximally and A4 distally play significant role. At the beginning of flexion, the volar plate folds and moves down, and A3 moves along with it volar ward, increasing the MA and lever arm. This helps in modifying the MA and reduces the effort. This may, in turn, pull A2 and A4 toward each other and reduce the bow stringing to compensate (**Fig. 1.38**).

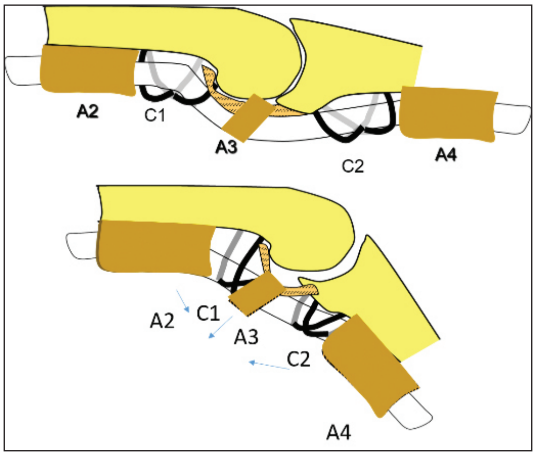

Fig. 1.38 Alteration of moment arm and lever arm by the A3, C1, and C2 pulleys.

Similar mechanism exists at the MCP joint with the A1 pulley and the volar plate.

When trigger finger release is performed, the A1 pulley is divided but does not produce any significant bow stringing. The PA and A2 pulleys keep the tendon in contact with the joint and skeleton.

Many investigators, notably Zancolli, did experiments dividing the pulleys serially to demonstrate the effect of division on the excursion of tendons and the range of motion in fresh cadavers.

Zancolli demonstrated that division of A3 alone did not produce any significant reduction of range. When A1, A3, A4, C1, and C2 were divided, even then the reduction in range was to the tune of approximately 35 degrees. When all except central part of A2 were divided, the range was 190 degrees, a reduction of 50 degrees. When all pulleys were divided, he noticed a total range of 173 degrees. This demonstrated the importance of the A2 pulley (**Fig. 1.39**) and the insignificance of the A3 pulley among all.

Extensor controls the bow stringing of the flexor tendon by the sagittal band pulling up the flexors, as it is attached to the A1 pulley and the volar plate in the region of the MCP joint (**Fig. 1.40**). Similarly, the transverse retinacular ligament controls the flexor at the PIP level.

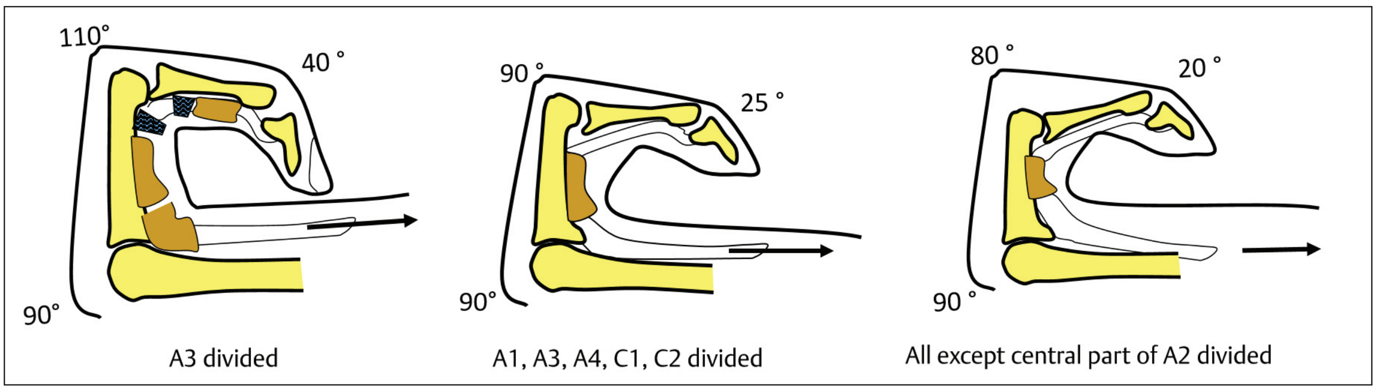

Fig. 1.39 Importance of the A2 pulley.

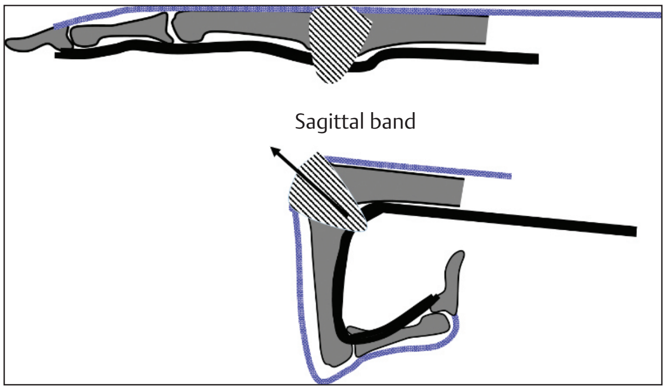

Fig. 1.40 Role of the sagittal band on flexion.

By these controlled and coordinated mechanism of pulleys, together with the extensor forces on the dorsum, the available excursion is distributed to achieve maximum range of movement at all joints.

Extensor System

Unlike the flexor tendons, the extensors exist as interwoven system and not as single tendon running along the dorsal aspect of the hand and fingers.

At the level of the distal forearm and wrist, they run as separate tendons in the compartments formed by the extensor retinaculum. The 9 extensor muscles form 12 tendons, and on the dorsum of the radius and ulna, they run through the osseofibrous compartment, as seen in **Fig. 1.41**. Except the ulnar, the remaining two tendons are in relation to the radius. Extensor digiti minimi (EDM) lies in between the ulna and radius. Extensor carpi ulnaris lies over the ulna.

Beyond the wrist, the extensors form a system comprising both tendinous and retinacular portions. On the dorsum of the hand, they become flattened and are also connected to each other by intertendinous connections. Over the shaft of the bones, they lie on the dorsum straight, and over the joints, they cover not only the dorsum but also the sides and are attached to the volar side structures such as volar plate and flexor sheath. This attachment stabilizes the tendon and prevents it from drifting.

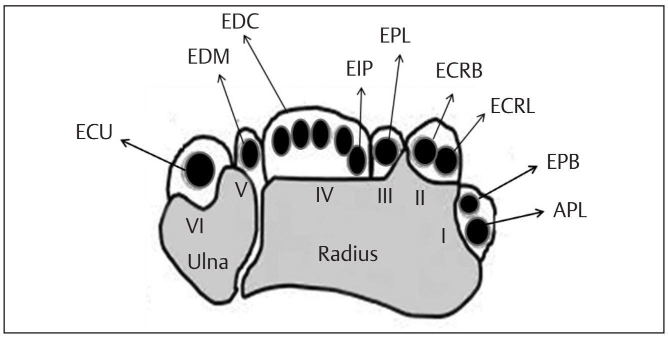

Fig. 1.41 Extensor compartment. APL, abductor pollics longus; EDC, extensor digitorum communis; EPL, extensor pollics longus; EDM, extensor digiti minimi; EIP, extensor indicis proprius; ECRB, extensor carpi radialis brevis; ECRL, extensor carpi radialis longus; ECU, extensor carpi ulnaris; EPB, extensor pollics brevis.

When the basic model is looked at (**Fig. 1.42**), it can be noticed that the tendon over the joint expands into a network attaching itself to the volar plate. The flexor sheath is also attached to the volar plate from the flexor side. This way both the extensor system and the flexor system have an indirect control over each other. There are linkages such as the sagittal band and transverse/ oblique retinacular ligaments linking these two systems of extensors and flexors with each other. This regulates the forces applied and makes the movement smooth. The proximal and distal linked extensions allow full extension with limited excursion of tendons.

Components of the Extensor System

As mentioned previously, the components of extensor system can be divided into tendinous component and retinacular component (**Fig. 1.43**).

The tendinous system is formed by the terminal tendons of both the intrinsic and extrinsic muscles. The intrinsic muscles are the interossei, lumbrical, and hypothenar muscles. The extrinsic muscles are the extensor digitorum communis (EDC) and the two proprius tendons, namely, indicis and digiti minimi proprius.

The retinacular system is formed by the retaining ligaments and intertendinous connections.

Proximally, the intertendinous bands connecting the extensors in the dorsum of the hand, interosseous hood, and sagittal band at the MCP joint form part of this system.

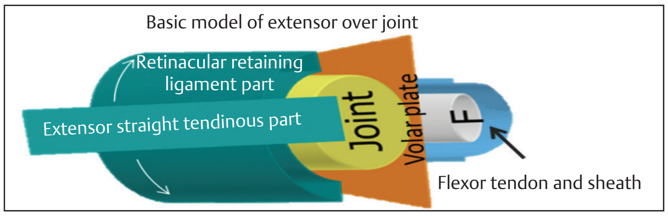

Fig. 1.42 Basic model and arrangement of extensors and flexors over a joint.

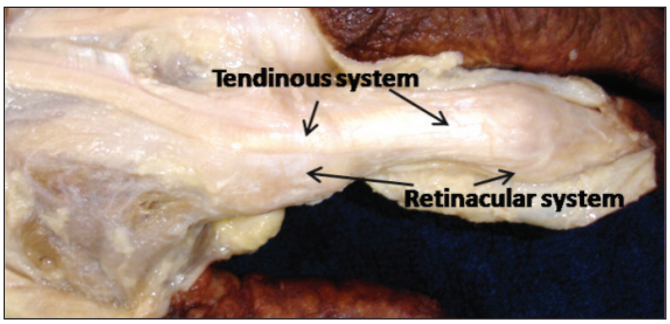

Fig. 1.43 Components of the extensor system.

Distally, the transverse retinacular ligament, oblique retinacular ligament, and triangular ligament form part of this system.

Tendinous System

The pattern of formation of the extensor system is shown in **Fig. 1.44**.

The extrinsic tendon at the proximal part of the proximal phalanx divides into a central band and two lateral bands. The terminal intrinsic tendon formed by interossei and lumbrical gives off fibers to the intrinsic hood and forms lateral band or wing tendon. They divide into medial and lateral interosseous bands. The medial interosseous fibers are also called the spiral fibers (Poirier's medial fiber).

The medial fibers join the central band to form the central slip and runs in the intercondylar groove of the proximal phalanx to get inserted at the base of the middle phalanx. It is the prime extensor of the PIP joint. The lateral fibers join the lateral band, form the conjoint lateral tendon, and proceed distally in the dorsolateral groove of the middle phalanx. This remains dorsal to the axis. Proximal to the DIP joint, lateral tendons of both sides join to form the conjoint distal tendon and get inserted into the terminal phalanx base. This tendon affects the extension of DIP. The oblique retinacular ligament passes from the volar side of PIP obliquely to get attached to the conjoint distal tendon (**Fig. 1.45a–c**).

Retinacular System

The retinacular system comprises the intertendinous and other retaining ligaments, as mentioned previously.

Juncturae Tendinum

The intertendinous bands, also known as juncturae tendinum, connect the extensor digitorum tendons of adjoining digits. The connections have lot of variations. Von Schroeder and Botte classify these into three distinct morphologic types: type 1 juncturae are filamentous within the intertendinous fascia in a transverse or oblique direction, type 2 juncturae consist of much thicker and well-defined, and type 3 juncturae consist of tendon slips from the extensor tendons in between the ring and little finger tendons. These are subclassified into "y" or "r" subtypes, depending on the shape (**Fig. 1.46**).

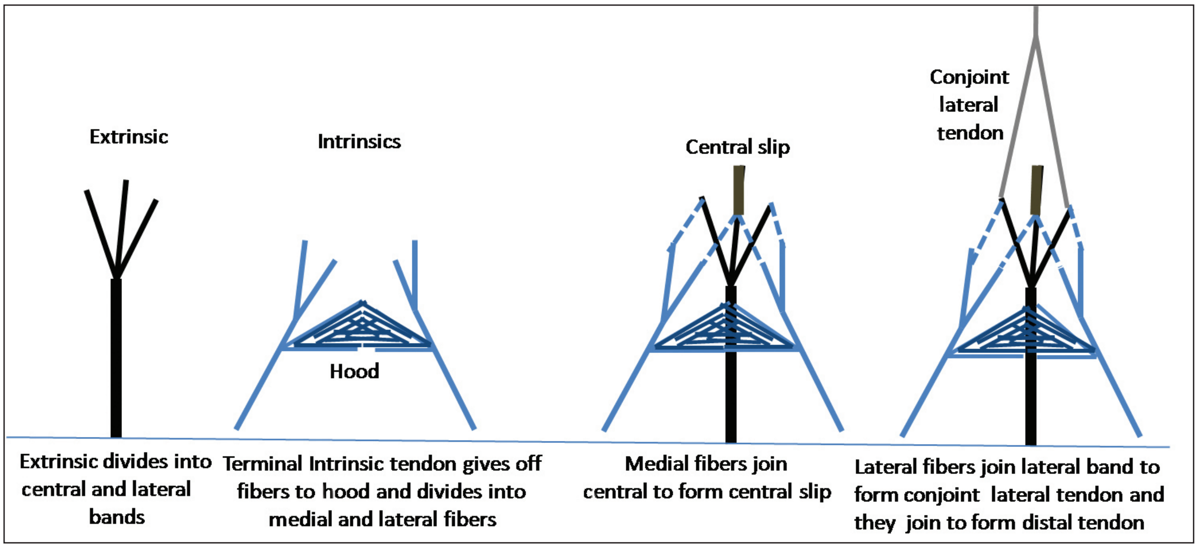

Fig. 1.44 Formation of the extensor system.

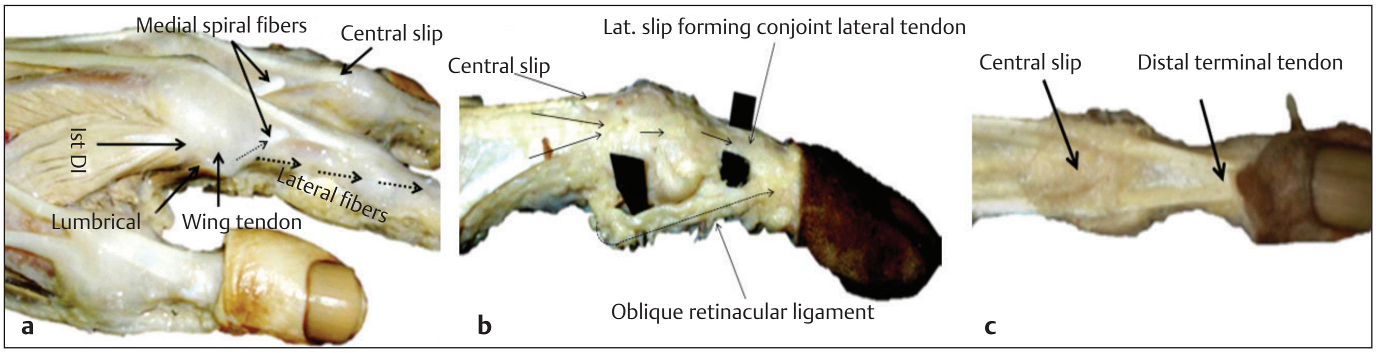

Fig. 1.45 **(a–c)** Retinacular components of the extensor system.

Interosseous Hood and Interosseous Muscle

At the MCP joint and the proximal part of the proximal phalanx, between the common extensor and intrinsic band, lies the extensor expansion. It has the sagittal band covered with the interosseous hood.

The interosseous hood originates at the intrinsic muscles, as is seen in **Fig. 1.47**. On the radial side of the fingers, the lumbricals contribute to the hood distal to the contribution from interossei. The hood covers the common extensor and joins the opposite side. The sagittal band lies deeper in the space between the central extrinsic and laterally placed wing tendon, as you see in **Fig. 1.48**, with the hood opened. The sagittal band is also attached to the volar plate.

The interosseous muscle attachments into the extensor expansion and distally into the extensor system vary as per the dissections of Zancolli. Interosseous insertion can be classified as proximal, distal, and mixed insertions.

Proximal insertion is into the interosseous hood, volar plate, and proximal phalanx base on the radial side (**Fig. 1.49a**). First dorsal interosseous muscle has only this insertion. All palmar interossei and third dorsal interosseous have distal insertions to the middle and proximal phalanges through the lateral band's medial and lateral fibers (**Fig. 1.49b**).

The second and fourth dorsal interossei and the ADM have mixed attachment.

When the hood in the center is incised through the common extensor to inspect the inside, it will be noticed that the extensor has a deeper attachment from under surface

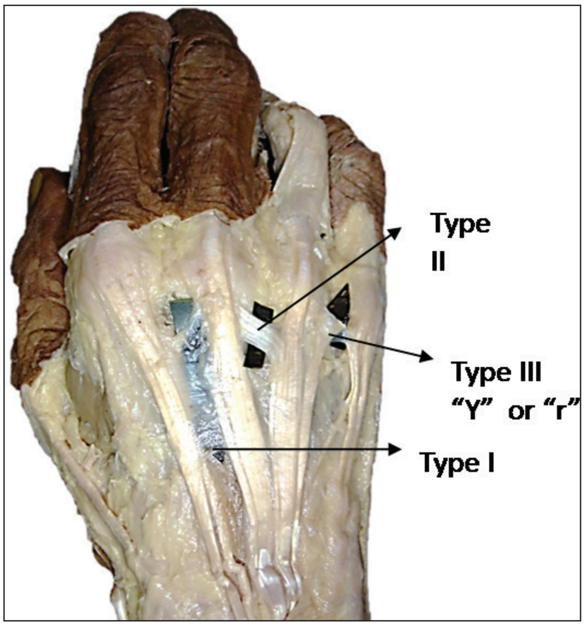

Fig. 1.46 Intertendinous ligaments on the dorsum.

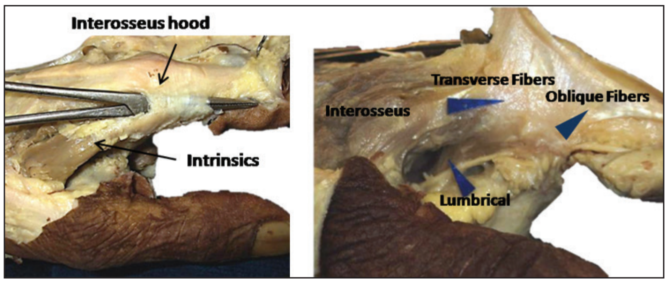

Fig. 1.47 Interosseous hood.

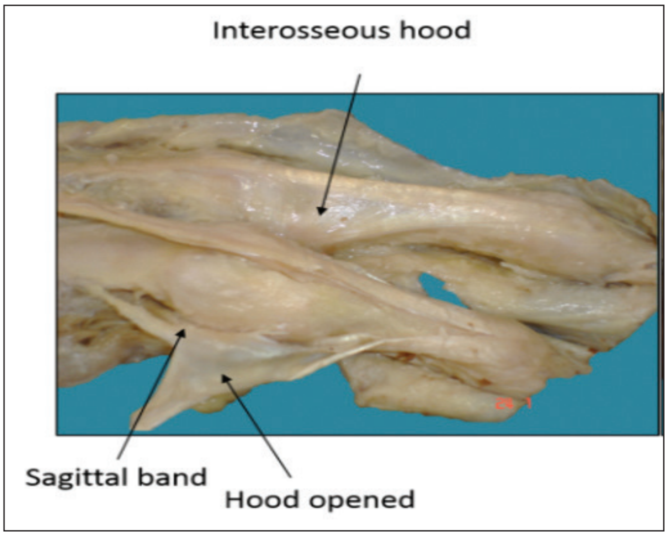

Fig. 1.48 Sagittal band.

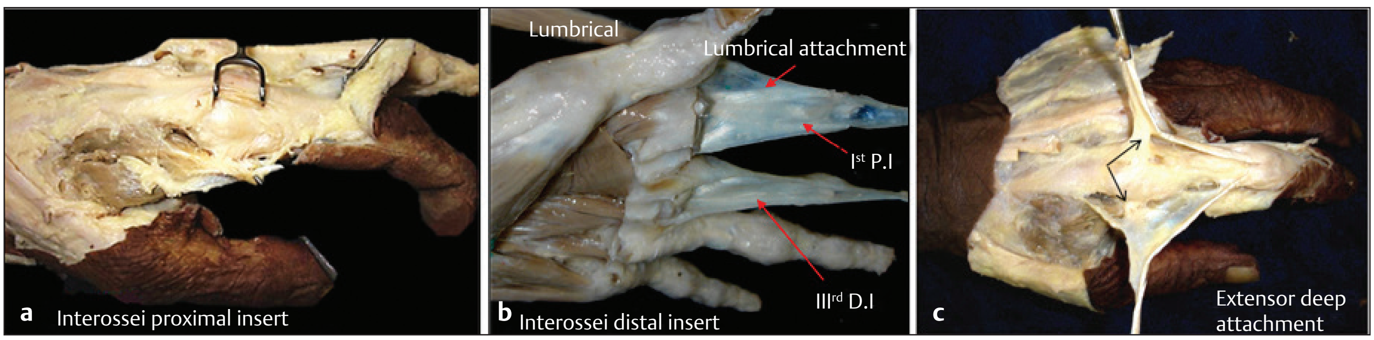

Fig. 1.49 **(a–c)** Insertion of interossei and lumbrical.

on to the MCP joint capsule and the proximal phalanx. This along with the sagittal band restricts the proximal migration of the extensors beyond a limit, which is approximately 20 mm on average (**Fig. 1.49c**).

Triangular Ligament, Transverse Retinacular Ligament, and Oblique Retinacular Ligament

At the PIP joint level, the triangular ligaments are found in between the conjoint lateral tendons stabilizing them during flexion. It prevents the lateral tendon from drifting down on flexion and maintains its dorsal relationship to the axis of the PIP joint (**Fig. 1.50a**).

The transverse retinacular ligament is almost like the sagittal band at the MCP joint (**Fig. 1.50 b**). It is attached dorsally to the conjoint lateral tendon and continues into the triangular ligament. On the volar side, the transverse retinacular ligament is attached to the volar plate of PIP and the C1 pulley like the sagittal band is attached to the volar plate of the MCP joint. At this site, Cleland's ligament from the skin passes dorsal to the digital NV bundle and gets attached to the phalanx and extensor (**Fig. 1.50c**).

The oblique retinacular ligament arises volar to the PIP joint and passes dorsal to the DIP joint. It is attached to the lateral ridge of the proximal phalanx, distal fibers of A2 pulley and is covered by lateral band. It remains volar to the PIP axis and covers the collateral ligament, but is covered by the transverse retinacular ligament. Distally, it remains on the lateral side of the shaft of the middle phalanx and goes dorsally and joins the conjoint lateral band (**Fig. 1.45b**).

Biomechanics of Extensor System

Intertendinous Connections

The intertendinous connections on the dorsum of the hand stabilize the common extensor together and with each other. When the fingers are flexed, the extensors migrate distally and the bands become more transverse, allowing the extensors to spread out over heads of the metacarpal but at the same time restricts them from slipping out.[12] These are passive stabilizers of extensor on the dorsum (**Fig. 1.51**).

Interosseous Hood

At the level of the MCP joint, the transverse fibers of interosseous hood act as active stabilizer. The interosseous muscle proximally gives off the transverse fibers to the hood, as shown earlier. As the extensor advances during flexion, the transverse fibers pulled by the intrinsic muscle act as a stabilizing force on the joint (**Fig. 1.52**).

On the other hand, the sagittal band acts as a passive stabilizer without any muscular force acting on it. This is a sheet of fibrous tissue stabilizing the extensor over the metacarpal. Distally, it is covered by the transverse fibers of the interosseous hood. Superficially and dorsally, it joins the transverse interosseous hood. On the volar side, it is attached to the volar plate.

It basically acts in the following three ways:

- Stabilizes the extensor over the MCP joint passively.
- Extends the MCP joint during hyperextension by the traction of the extensor.
- Limitation of the excursion of the extensor (**Fig. 1.53**).

It can be noticed that the collateral ligament is covered by the sagittal band at the MCP level and by transverse retinacular ligament at PIP. On the volar side, both get attached to volar plate and the respective A1 and C1 pulleys. Similar to the sagittal band, the transverse retinacular ligament stabilizes the extensor at PIP. The comparative areas over the MCP (proximal phalanx base) and PIP region are shown in cross-section (**Fig. 1.54**). The transverse retinacular ligament by its attachment to the conjoint lateral tendon dorsally and to the volar plate and C1 pulley on the volar side prevents excessive dorsal migration of the tendon.

Triangular Ligament and Retinacular Ligaments

On the other hand, the triangular ligament, which is in between the conjoint lateral tendons, prevents its migration

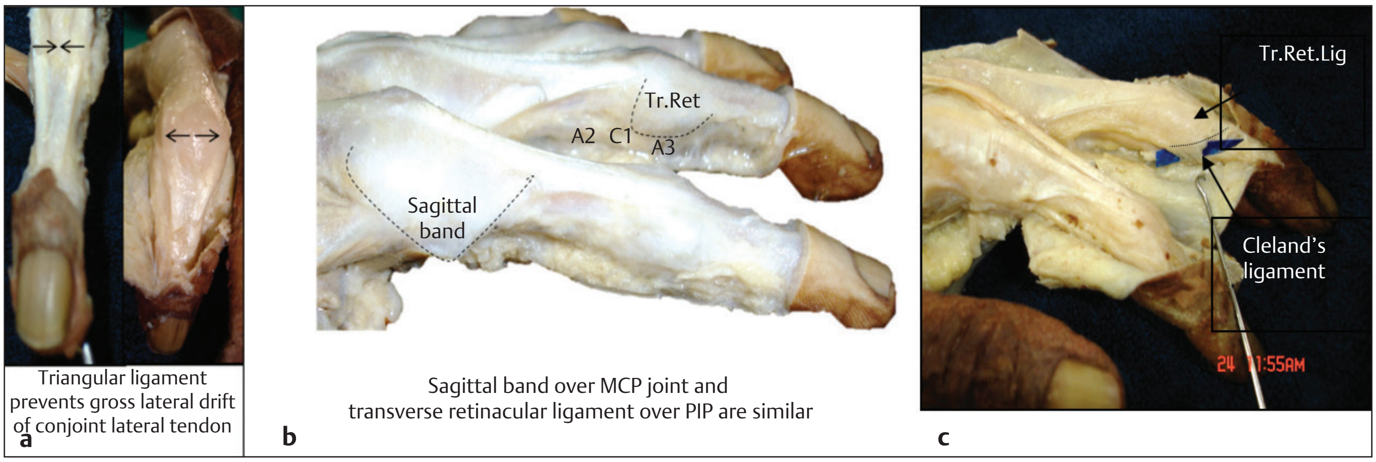

Fig. 1.50 **(a–c)** Retinacular ligaments and sagittal bands. MCP, metacarpophalangeal.

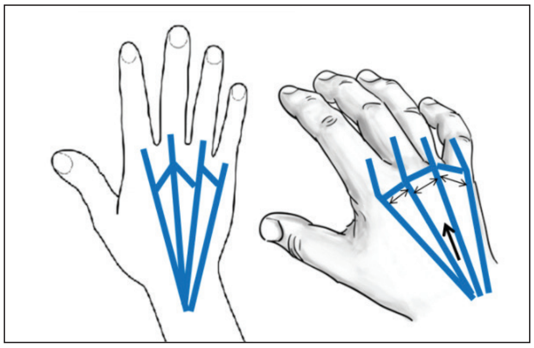

Fig. 1.51 Role of the intertendinous ligaments.

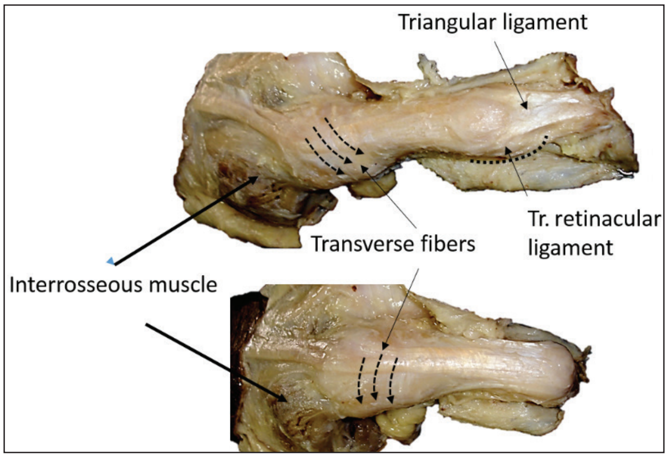

Fig. 1.52 Sagittal band and flexion of the metacarpo-phalangeal joint.

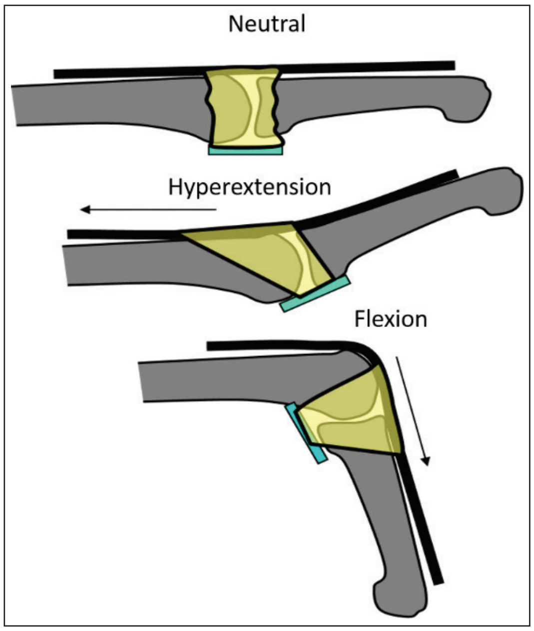

Fig. 1.53 Role of the sagittal band.

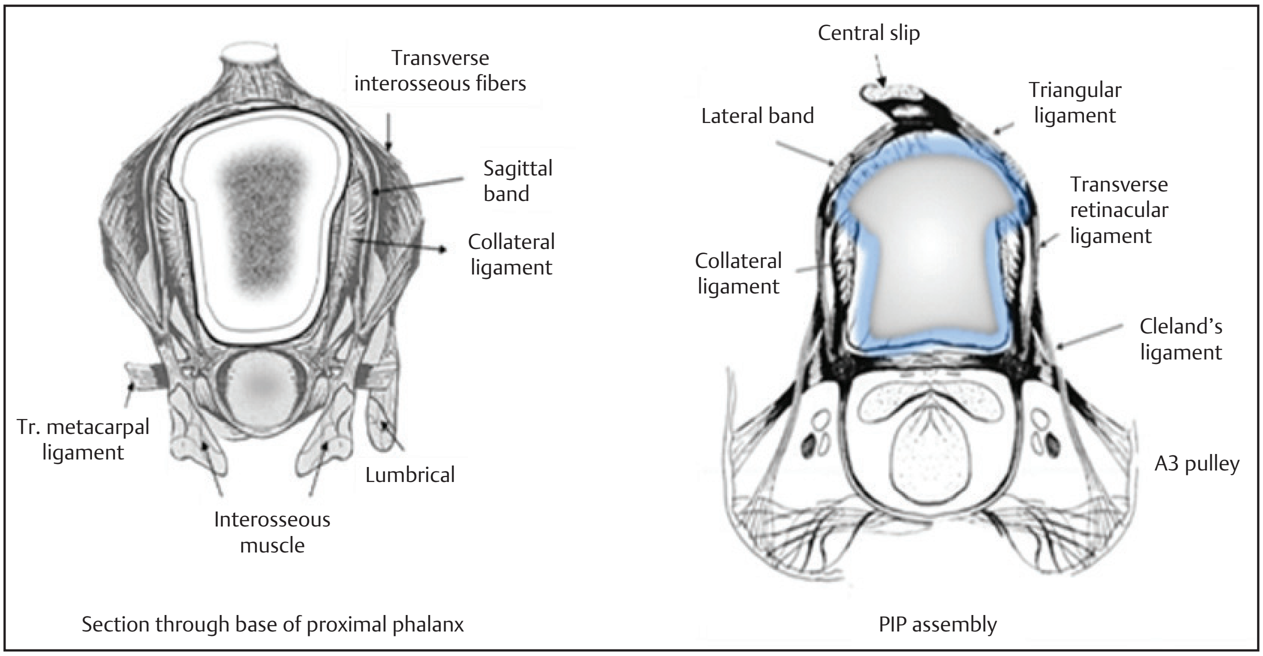

Fig. 1.54 Sectioning through the proximal phalanx and proximal interphalangeal showing the assembly.

volar wide on flexion. On the dorsum of the middle phalanx, it stabilizes the conjoint lateral tendon, and this becomes lax in boutonniere deformity and retracts in intrinsic plus.

There is considerable dispute over the mechanism of the extension of the IP joints. For many years, it was felt that it is only the central slip and the conjoint terminal tendon that extend the IP joints until the oblique retinacular ligament, also called the link ligament, was described by Landsmeer. He established the importance of the oblique retinacular ligaments, as shown in **Fig. 1.55**. When the DIP joint flexes, the extensor migrates distally pulling at the oblique retinacular ligament. By virtue of its proximal attachment to PIP, this flexes PIP. Therefore, DIP flexion leads to PIP flexion. Likewise, when PIP extends, it pulls on the oblique retinacular ligament, which pulls at the extensor leading to the extension of DIP.

This is amply demonstrated by asking a person to flex both PIP and DIP, and then after preventing PIP extension by holding it with a finger, asking the person to extend DIP alone (**Fig. 1.56**).

It will be realized that it is not possible to extend DIP without extending PIP.

In 1971, in the annual meeting of American Society for Surgery of the Hand, Harris and Rutledge[13] presented their work in which dissections were done in fresh cadavers.

By serially cutting various components of the extensor system and studying the result, they stressed that the dorsal and volar migration of lateral bands at PIP is not dependent on the triangular ligament or the transverse retinacular ligament. They also felt that the oblique retinacular ligament does not extend the DIP joint and hence need not be repaired. According to them, gaining length or shortening of extensors occurs simply by virtue of the lateral bands migrating dorsal or volar to the axis of the PIP joint with isometry between the central and dorsal bands. It is the rhombus narrowing in width to gain length during flexion or widening to shorten and extend.

When the finger is flexed and extend, there is a relative skeletal lengthening and shortening as the diameters of the heads of the metacarpal, proximal, and middle phalanges add to the length on flexion and disappear into joint on extension. This on average is approximately 24 mm in the middle finger (**Fig. 1.57**). Therefore, when it is extended, the equivalent 24 mm of length of the extensor must move proximally.

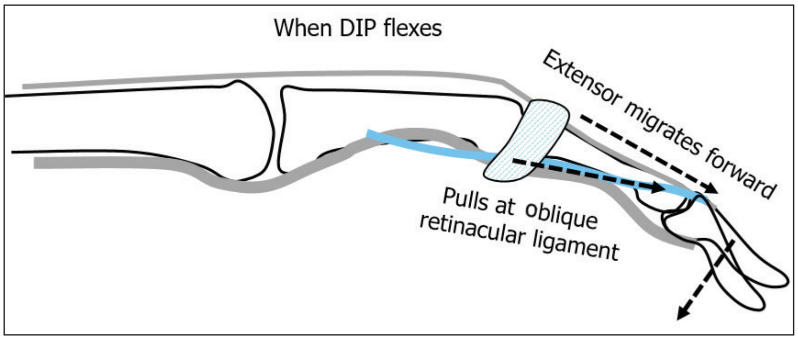

Fig. 1.55 Oblique retinacular ligament.

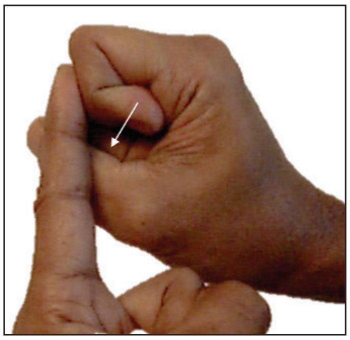

Fig. 1.56 Demonstration of the inability to extend the distal interphalangeal when the proximal interphalangeal extension is blocked.

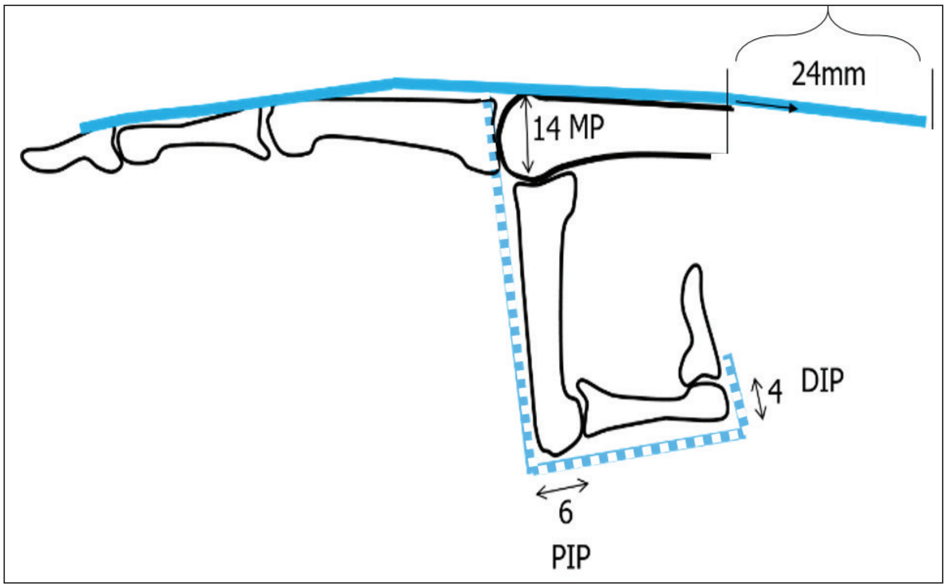

Fig. 1.57 Winslow's rhombus. DIP, distal interphalangeal; MP, metacarpophalangeal; PIP, proximal interphalangeal.

But the stabilizing forces of the sagittal band and intrinsics will allow only 20 mm. This shortage of 4 mm is compensated by the mechanism of Winslow's rhombus (**Fig. 1.58**).

Functional Circuits

When the PIP and DIP flexes by the action of FDS and FDP, the extensor advances putting traction on lateral band. But the lateral band is pulled proximally by the intrinsic muscle, which becomes taut. This bipolar traction flexes the MCP joint. It looks that the initiation of flexion is by the IP flexion, or it may even be just a flicker. This is called proximal functional circuit by the same way DIP flexion initiates PIP flexion by the oblique retinacular ligament and is called distal functional circuit.

Joints of the Hand

Carpometacarpal Joint

The metacarpal bones articulate with the wrist to form five CMC joints.

The CMC joint or the trapeziometacarpal joint of the thumb plays an irreplaceable role in the normal functioning of the thumb. Stability and mobility represent the functional paradox of the thumb CMC joint. The morphological features of these facets, together with a lax but strong joint capsule, give the thumb great mobility and play a major role in the opposition of the thumb. The first CMC joint has a saddle-shaped surface that allows it to move in all directions. The concavoconvex saddle design, described as "articulation by reciprocal reception," imparts arcs of motion in flexion/extension and abduction/adduction. This gives the thumb its freedom of motion: extension/flexion (parallel to the palm) and abduction/adduction (at right angles to the palm), as well as some rotation. Pronation/supination represents composite rotation and translation of this joint based on morphology and muscular activity in planes out of phase with the fingers. In addition, the first metacarpal is set at an angle of 90 degrees from the plane of the other four metacarpals so that the thumb can easily come into contact with each of the fingers. This opposability of the thumb makes it possible to pinch, grasp, and manipulate objects efficiently.

The ligaments and muscles play varying roles in stability, laxity, and proprioception of this complex joint. The joint is held in place by the following seven distinct ligaments (Doyle's hand anatomy[14]):

- Superficial anterior oblique ligament (most important ligament).
- Deep anterior oblique ligament.
- Ulnar collateral ligament.
- Palmar intermetacarpal ligament.
- Dorsal intermetacarpal ligament.
- Posterior oblique ligament.
- Dorsoradial ligament (widest and thickest ligament).

In contrast to the first metacarpal, the other rays of the hand have limited mobility. The second and third metacarpals are sometimes referred to as the "stable rays" because their CMC joints have virtually no movement. The fourth and fifth metacarpals are referred to as the "mobile rays" because their CMC joints have some movement, rotating slightly to allow cupping of the hand.

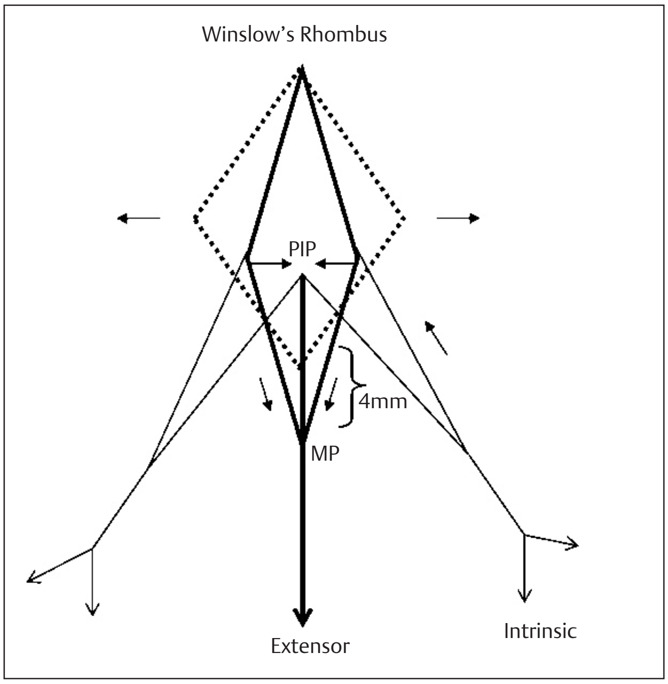

Fig. 1.58 Apparent shortening of finger in extension and distribution of the extensor excursion. MP, metacarpophalangeal; PIP, proximal interphalangeal.

Metacarpophalangeal Joint

The MCP joint is the articulation between the metacarpal and phalanges of the hand. It consists of the metacarpal head, proximal phalanx, volar plate, two collateral ligaments, two accessory collateral ligaments, and sagittal band (**Fig. 1.59**).

It is an ellipsoid joint characterized by an oval convex surface that is opposed to an elliptical but shallow concavity. Metacarpal condyle has a larger AP axis articulating with a smaller and a concave base of the proximal phalanx, which has a longer transfer axis resulting in the so-called cam effect.

It has the outward appearance of a ball-and-socket joint with 3 degrees of freedom (DoFs), but it actually acts more as a multiaxial condyloid joint,[15] with its primary motion in flexion and extension. It is also capable of abduction and adduction (radial and ulnar deviation), as well as rotation about its longitudinal axis.[16] The MCP joint is critical for finger positioning and hand function.[17]

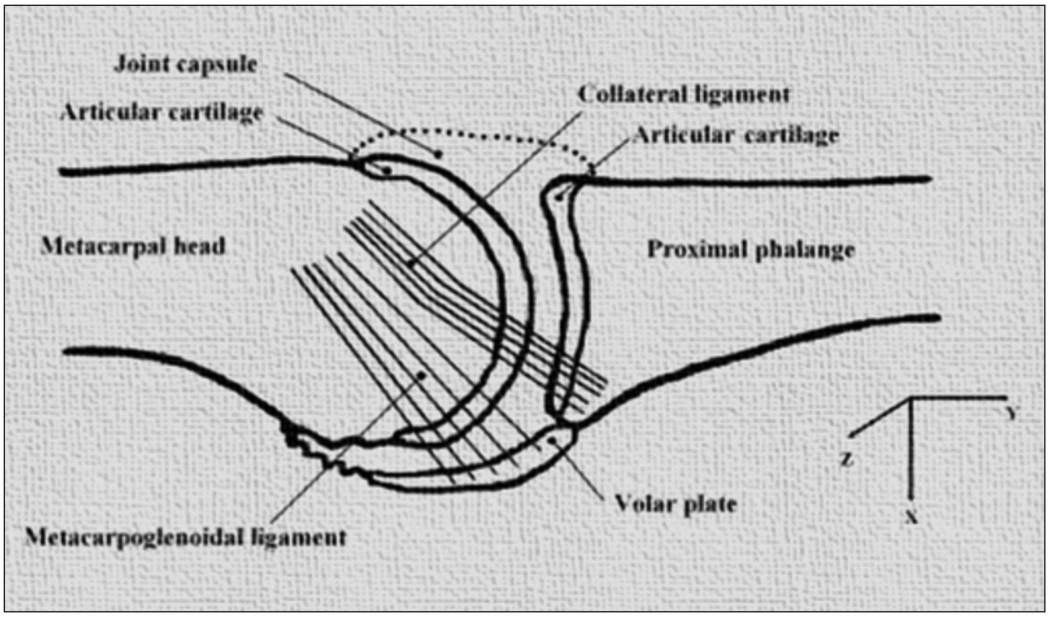

Fig. 1.59 Sagittal sectioning through the metacarpophalangeal joint showing anatomy.

Joint Axes

Primary motion is approximately two orthogonal axes (Flexion/extension and adduction/abduction). When the MCP joints are flexed, abduction/adduction is not possible due to the following reasons:

- Relatively flat articular surface of the metacarpal head on the palmar aspect.
- Eccentric attachment of the collateral ligaments of the metacarpal head making them tight in flexion and the resultant cam effect.
- Wider palmar surface of the metacarpal head accounts for increased tension in the proper collateral ligaments when the joint is flexed (**Fig. 1.60**).

Range of Motion

There are minor differences in the range of motion among the individual MCP joints, with increased flexion proceeding from the index finger to the small finger.[18]

Daily functional activities for an individual need a smaller range of motion to perform most of the necessary tasks requiring finger movement known as a functional range of motion. The functional range of motion of the MCP joint ranges from 33 to 73 degrees of flexion, with an average of 61 degrees. For tasks such as pinch, grasp, and grip, the flexion of the MCP joint was 58, 33, and 72 degrees, respectively.[19]

Forces

The prehensile movements of the human hand can be divided into power grip and precision grip. The grip strength[20] for normal males has a wide range of values from 81 to 672 N, according to the instrument used, hand dominance, subject occupation, and age. The grip force of women is on average 56% that of men.

Tendons, Muscles, and Ligaments

The muscles and associated tendons of the hand are divided into two groups, namely, the extrinsic (EDC, extensor indicis proprius, FDS, FDP) and intrinsic (lumbricals, palmar interosseous, dorsal interosseous). Finger function requires balance of the intrinsic and extrinsic muscles and tendons for stability and strength. The tightening of the MCP joint in flexion has been connected with decreased laxity of the collateral ligaments (Werner et al. 2003).

Clinical Significance of the Metacarpophalangeal Joint

- Collateral ligaments are taut in flexion; hence, the joints are immobilized in flexion.
- Asymmetry of the finger metacarpal head, difference in length, and direction of the proper collateral ligament lead to rotation of the proximal phalanx in flexion/extension. It also accounts for more ulnar deviation than radial deviation.

Metacarpophalangeal Joint of the Thumb

It is an ellipsoid type of joint. Proximally, it has an oval convex surface that is opposed to an elliptical concavity distally. The convex metacarpal head is partially demarcated at the palmar surface resembling a bicondylar joint.

Primary arc of motion is flexion and extension. But it also has limited abduction/adduction and pronation/supination.

Range of motion varies from thumb to thumb; more spherical heads have better range of motion.

The articular surface of metacarpal head is divided into two zones: one that articulates with the proximal phalanx and one that articulates with the sesamoids in the palmar plate.

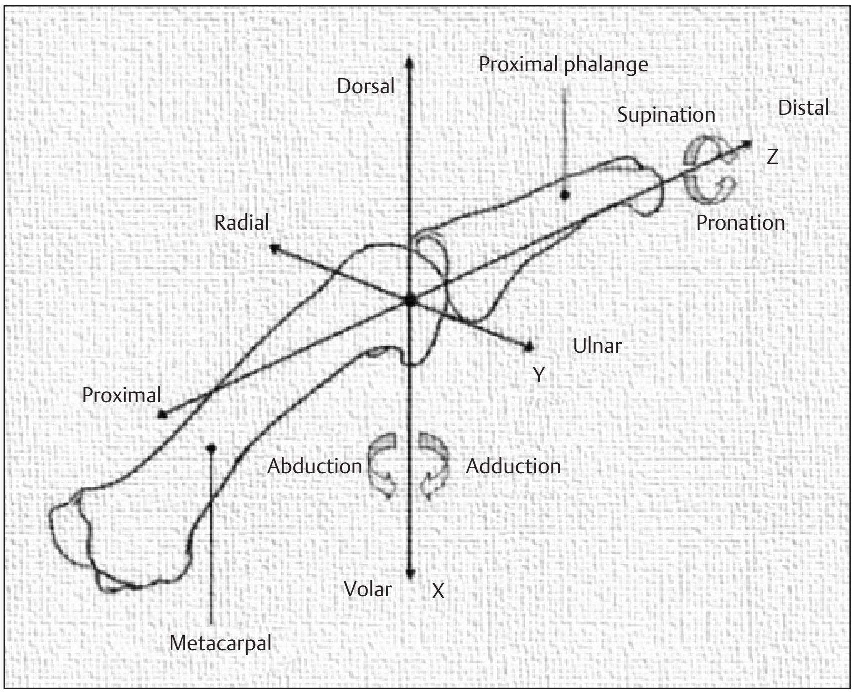

Fig. 1. 60 Axis of rotation.[18]

The flexion/extension axes on the metacarpal passing under the epicondyles.

Abduction/adduction axis passes between the sesamoid just proximal to the beak of the proximal phalanx.

The MCP joint of the thumb differs from finger joints. Metacarpal head in the thumb is slightly wider on the dorsal side than the palmar side. The articular surface of the thumb is in two zones. When viewed from the dorsopalmar aspect, the metacarpal head of the thumb has lesser curvature, which accounts for lesser adduction and abduction.

Proximal Interphalangeal Joints

Type: uniaxial hinge joint.

In contrast to finger MCP joints, they are more stable because of:

- Strong and symmetric proper collateral ligaments.
- The palmar plate.
- Osseous architecture in the form of side-by-side concentric condyles that articulate with matching glenoid cavities, forming a dual shallow tongue and groove arrangement.

Distal Interphalangeal Joints

Type: uniaxial hinge joints.

DIP joints are structurally similar to PIP joints, but demonstrate hyperextension during pulp contact as in pinch.

Average ranges of various joints of the hand are given in **Table 1.2**.

Table 1.2 Average ranges of motion (American Academy of Orthopedic Surgeons)

Thumb	**CMC**	
	Abduction	0–70
	Flexion	0–15
	Extension	0–20
	Opposition	Tip of the thumb to the base or tip of the fifth digit
	MCP	
	Flexion	0–50
	Hyperextension	0–10
	IP	
	Flexion	0–80
Digits 2–5	**MCP**	
	Flexion	0–90
	Hyperextension	0–30
	Abduction/adduction	40° arc
	PIP	
	Flexion: 0–90	0–100
	DIP	
	Flexion	0–90
	Hyperextension	0–10

Abbreviations: CMC, carpometacarpal; DIP, distal interphalangeal; IP, interphalangeal; MCP, metacarpophalangeal; PIP, proximal interphalangeal.

With the knowledge of various biomechanics, kinematic analysis is done to model the human hand for experimentation, building robotics, and prosthesis in amputations.

A brief description of kinematics for completion is given in the following.

Blood Supply

Blood supply to the hand is complex in nature and is contributed mainly by the radial artery ,ulnar artery, to a lesser extent by the interosseous arteries, and, when present, by the arteria mediana. They form arches on the palmar and dorsal sides of the wrist and hand. From these, specific longitudinal pattern of vessels arises and supply the hand and fingers distally. There is rich anastomosis taking place between these arches and also the longitudinal system. On the one hand, the palmar skin is supplied by perforators arising from the longitudinal vessels and is segmental in nature with minimal overlap, which is responsible for ischemia of the palmar skin in extensive avulsion injuries. On the other hand, the presence of significant anastomosis between digital vessels with one another and the dorsal vessels in the fingers helps to elevate flaps based on one digital vessel without causing ischemia to the digit. Vascular pattern may contribute to the avascular necrosis of carpal bones, especially the scaphoid and lunate and also nonunions in scaphoid fractures.

In this section, a broad outline of the blood supply and its common variations are given. Reader can find detailed anatomy of individual vessels in various other relevant chapters.

Radial Artery

The radial artery after branching off from the brachial artery courses in the forearm between the brachioradialis and FCR muscles. At the wrist, it reaches the back of the hand, deep to the APL and extensor pollicis brevis tendons. It crosses the scaphoid and trapezium bones, which are crossed by the tendon of the extensor pollicis longus. In the interval between the two extensors pollicis tendons, it is crossed by the superficial branches of the radial nerve supplying the thumb and index finger. It then enters the palm between the two heads of the first dorsal interosseous muscle. In the palm, it runs transversely across between two heads of the adductor pollicis brevis muscle, and occasionally it pierces the muscle and then runs to the base of the metacarpal bone of the little finger. Here it anastomoses with the deep palmar branch from the ulnar artery, forming the deep palmar arch (**Fig. 1.61**). A superficial branch is given off before it winds down the wrist, and this branch goes through the thenar

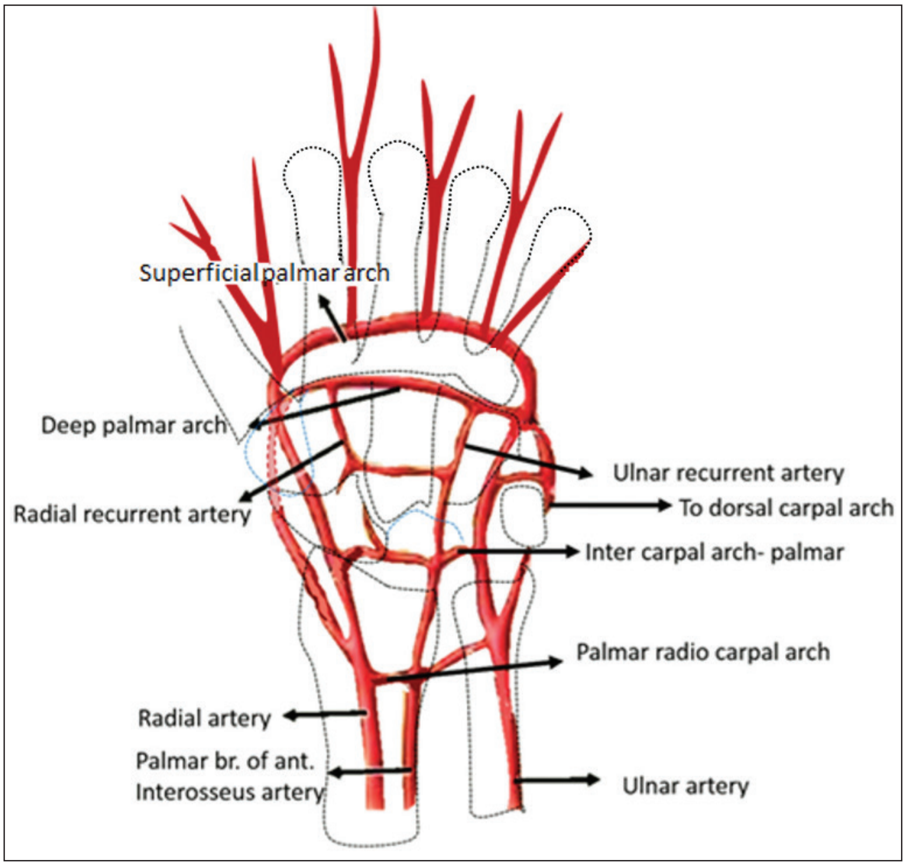

Fig. 1.61 Schematic presentation of the arterial supply (palmar side of hand).

muscle (occasionally goes superficial to muscle) and in the palm is joined by the large superficial branch of ulnar artery forming the superficial palmar arch.

Proximally to this, in the forearm at the lower border of the pronator quadratus muscle, a small branch called radial carpal artery is given off from the radial artery and anastomoses with the palmar carpal branch of the ulnar artery forming a palmar carpal network supplying the carpal bones and wrist. This network is joined by the recurrent branches from the deep arch.

Under the extensor tendons of the thumb, the posterior radial carpal artery is given off from the radial and crosses the dorsum transversely joining the dorsal carpal branch of the ulnar artery and with the palmar and dorsal interosseous arteries forming dorsal carpal arch (**Fig. 1.62**). The radial artery and the posterior division of the anterior interosseous artery are the primary sources of orthograde blood flow to the distal dorsal radius (**Fig. 1.62**). Four vessels that arise from these arteries may supply the dorsal radius with nutrient branches. All of these vessels include an artery and venae comitantes.

Two are outside retinaculum and two are intraretinacular. They are aptly named the 1,2 and 2,3 intercompartmental supraretinacular arteries. The other two are deep vessels located on the floor of the extensor compartments, named the fourth and fifth extensor compartmental arteries (**Fig. 1.62**). These vessels are used for taking vascularized pedicled bone graft from the radius for avascular necrosis of the carpal bones. From this network, the second, third, and fourth *dorsal metacarpal arteries* are given off supplying the adjoining dorsum of the middle, ring, and little fingers, respectively.

Next, the *first dorsal metacarpal artery* (FDMA) is given off before the radial artery passes through the first interosseous space. It immediately divides into two branches that supply the adjacent sides of the thumb and index finger. The FDMA flap is based on this vessel.

The arteria princeps pollicis and radialis indices are the two last important branches arising from radial artery that supply the thumb and index finger, respectively.

The arteria princeps pollicis is given off as the radial artery turns medially deep in the hand. It goes between the first dorsal interosseous and the oblique head of the adductor pollicis, along the ulnar side of the metacarpal bone of the thumb to the base of the proximal phalanx, dividing into two branches.

The arteria radialis indicis arises close to the princeps pollicis, goes between the first dorsal interosseous and the transversus head of the adductor pollicis, and runs along the radial side of the index finger to its extremity, where it anastomoses with the proper digital artery, supplying the ulnar side of the finger. At the lower border of the

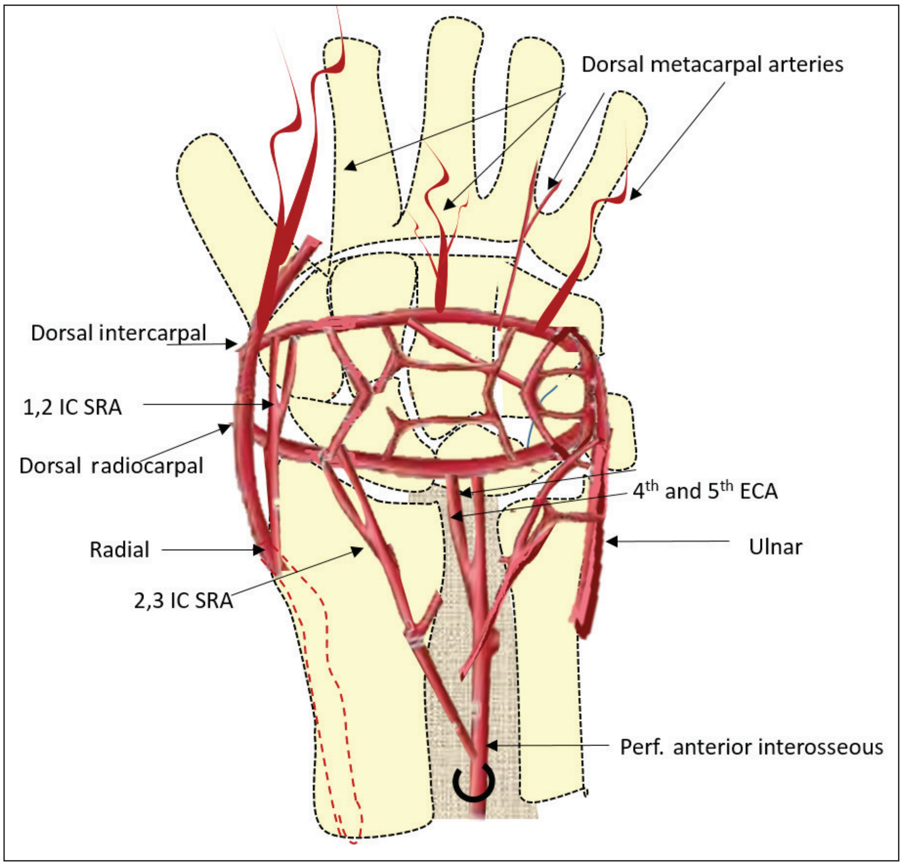

Fig. 1.62 Schematic presentation of the arterial supply (dorsum of hand). SRA, supraretinacular artery; ECA, extensor compartment artery.

adductor pollicis, this artery anastomoses with the princeps pollicis and gives a communicating branch to the superficial palmar arch.

The variation in branching off these two vessels includes a common trunk arising from the radial artery, which may bifurcate into the two aforementioned branches.

Ulnar Artery

From the wrist, the ulnar artery enters the hand with the nerve on its dorsoulnar aspect through Guyon's canal. The ulnar artery divides into superficial and deep branches, which ultimately anastomose with corresponding radial branches completing the superficial and deep palmar arches. The dorsal branches form along with the dorsal branches of the radial and interosseous arteries the dorsal network (**Fig. 1.61, Fig. 1.62**).

Among the branches, the palmar carpal artery is given off from the ulnar artery just like on the radial side, crosses the front of the carpus deep to the FDP tendons, and anastomoses with the corresponding branch of the radial artery.

Similarly, the dorsal carpal branch arises immediately above the pisiform bone and winds back beneath the FCU tendon; it passes across the dorsum of carpals deep to the extensor tendons to anastomose with a corresponding branch of the radial artery. It also gives off a branch that runs on the ulnar side of the fifth metacarpal bone and supplies the ulnar side of the dorsum of the little finger.

The deep palmar branch passes between the ADM and flexor digiti minimi and through the origin of the opponens digiti; it anastomoses with the radial artery and completes the deep palmar arch.

The superficial palmar arch is formed by the ulnar artery and is usually completed by a branch from the radial artery but sometimes by the superficial volar or by a branch from the arteria princeps pollicis of the radial artery. The arch passes across the palm, describing a curve, with its convexity distally.

The superficial palmar arch is covered by the palmaris brevis and the palmar aponeurosis. It lies upon the transverse carpal ligament, the flexor digiti minimi brevis and opponens digiti minimi, the tendons of the FDS, the lumbricals, and the divisions of the median and ulnar nerves.

Three common digital arteries arise from the convexity of the arch forming the volar metacarpal artery and then divide into a pair of proper volar digital arteries that run along the contiguous sides of the index, middle, ring, and little fingers, behind the corresponding digital nerves; they anastomose freely in the subcutaneous tissue of the finger tips and by smaller branches near the neck of the phalanges. Each gives off a couple of dorsal branches that anastomose with the dorsal digital arteries and supply the soft parts on the back of the second and third phalanges, including the matrix of the fingernail. The proper volar digital artery for the medial side of the little finger springs from the ulnar artery under cover of the palmaris brevis.

Dominance of Vascularity in a Hand

Various studies with plethysmography and Doppler have been done to assess the dominance of the artery in a normal hand.

Kleinert et al[21] studied pulse volume plethysmography on 1,249 digits in 125 volunteers to determine relative blood flow to each digit. Only 5% were found to have ulnar artery dominance (pulse volume plethysmography amplitude larger during radial artery compression) in all digits and 28% were found to have complete radial artery dominance. Ulnar dominance in three or more digits was seen in 21.5% compared with 57% with radial artery dominance, and 21.5% had equal dominance. Overall, 87% of thumbs and 70.5% of index, 60% of long, 52% of ring, and 52% of small fingers, were radial dominant.

Patsalis et al[22] in their study on arterial dominance in 164 hands using digital pulse electronic oscillography and the Allen test agreed that the radial was more dominant, but also noted that there is a significant number of situation where no collateral circulation is present (absolute dominance). This was observed in 3 and 1.2% of the cases for the radial artery and the ulnar artery, respectively.

Variations

Occasionally, the ulnar artery arises directly from the axillary artery and runs superficially in the forearm. Natsis et al[23] reported frequency ranges from 0.17 to 2%.

Gellman et al[24] studied the arterial patterns of the deep and superficial palmar arches. The superficial palmar was classified into complete or incomplete. An arch is considered to be complete if an anastomosis is found between the vessels constituting it. Complete superficial palmar arches were seen in 84.4% of specimens. In the most common type, the superficial arch was formed by anastomosis between the superficial volar branch of the radial artery and that of the ulnar artery. This was seen in 35.5% of specimens. In 31.1%, the arch was formed entirely of the ulnar artery. Incomplete superficial arches were seen in 15.5% of specimens. In 11.1%, the ulnar artery formed the superficial arch but did not contribute to the blood supply to the thumb and index finger.

The deep palmar arch was found to be less variable, with 44.4% formed by an anastomosis between the deep volar branch of the radial artery and the inferior deep branch of the ulnar artery.

Vascular Pattern in Carpal and Metacarpal Bones

Blood supply can significantly contribute to the healing of fracture in bones and also play a significant if not entire role in avascular necrosis. Panagis et al[25] described three major patterns of blood supply in the carpal bones:

- Group 1 bones in which vessels enter on only one surface or supply a large area without additional anastomotic supply. The capitate, scaphoid, and 20% of all lunates are in this group, which may have a relatively large risk for avascular necrosis.
- Group 2 bones have at least two distinct areas of vessel entry but lack intraosseous anastomoses in all, or a significant portion, of the bone. The trapezoid and hamate are placed into this group.
- Group 3 bones with at least two surfaces receiving nutrient arteries, no large areas of bone dependent on a single vessel, and consistent intraosseous anastomoses. The trapezium, triquetrum, pisiform, and 80% of lunates are in this group.

The trapezium probably has the richest internal blood supply of any carpal bone.

Approximately 35% of all metacarpal heads have a single arteriole in the distal epiphysis, making them dependent on small circumferential pericapsular arterioles; hence, gross stripping of soft tissues from bone may lead to delayed union or nonunion in fractures.

Venous Drainage

The superficial and deep palmar venous arches return blood to the heart and are located near the arterial arches. They drain into the deep veins of the forearm. Dorsal digital veins drain into dorsal metacarpal veins, which form the dorsal venous network. This blood drains into the cephalic and basilic veins.

Kinematics

Kinematics, a branch of mechanics, is concerned with the motion of objects without reference to the forces that cause the motion. It studies the features or properties of motion in an object.

Robotics has assumed significance in medical and surgical field. Telesurgeries and some precise surgical procedures use robotics. Many of these devices require human machine interphase, especially the human hand. The motion of the hand is replicated in robot. This requires proper study of the hand motion. This study also helps in designing prosthetic hand in rehabilitation. The motions of the hand are analyzed mathematically and models are created and validated to replicate the hand motion.

The robotic hand must be capable of manipulating the object, must ultimately grasp it, and firmly hold and transport it to achieve the goal such as grasping and moving an object from one place to other. The stages are shown in **Fig. 1.63.**

Many softwares are available, and parameters for the human hands have been standardized.

The complicated nature of the human hand raises the desire for a truly kinematic model of the hand based on the physiology of its joints.

Denavit–Hartenberg set parameters describing the kinematic chain of each finger, depending on natural movement occurring in the fingers and thumb.

Author has given in the following some basic points considered in building these models.

The kinematic structure of the hand model is defined by base transformations relating the finger bases to the hand base.

If the skeleton of hand is looked at, it can be seen that the thumb has a base formed by the CMC joint. Since the index and middle finger CMC joints have no movement, the kinematic model takes into account only the MCP joint as base. On the other hand, since there is some lateral (sideways) flexion and extension in the CMC joint level in the ring and little fingers, the CMC joint is taken as basal. The chain is built over the following bases:

- Thumb:
  - CMC.
  - MCP.
  - IP and tip.

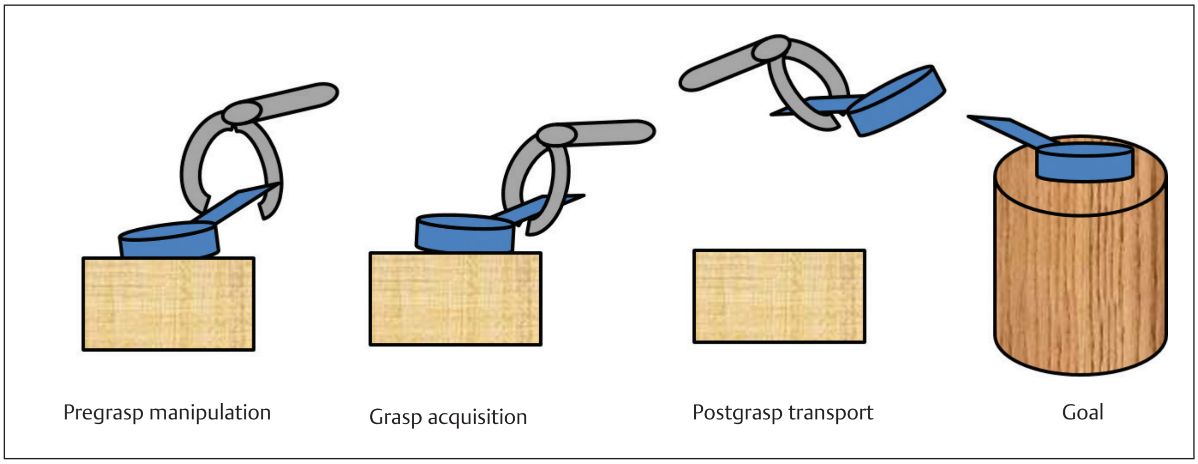

Fig. 1.63 Stages of grasp in a robotic hand.

- Index and middle fingers:
  - MCP.
  - PIP.
  - DIP and tip.
- Ring and little fingers:
  - CM.
  - MCP.
  - PIP.
  - DIP and tip.

The joint motions are next defined as DoF of movement, meaning the type of movement that takes place at each of these joints with relation to different axes. They are defined in x–y–z axes. By this model, human hand joints can be expressed as follows:

Index and middle fingers (total 4 DoF):

MCP flexion/extension = 1, abduction/adduction = 1.

PIP flexion/extension = 1, DIP flexion/extension = 1.

Ring and little fingers: both consist of 5 DoF. One DoF CMC: lateral (sideways) flexion/extension in addition to what was seen for the index and middle fingers.

Thumb: the thumb model consists of 6 DoF, enabling realistic thumb–finger opposition.

CMC: 2 DoF. Flexion/extension –1; adduction/abduction –1 (ante position–retroposition). These axes cross but do not coincide, forming a saddle joint.

MCP: 3 DoF. Flexion/extension parallel to the previous flexion axis –1, abduction/adduction parallel to the previous abduction axis 1, and axial rotation collinear with the proximal finger segment –1.

IP: flexion/extension –1.

After defining the base, chain, and DoF of movement, linear measurements are expressed as length of each component as a percentage of hand length (**Table 1.3**). The joint axis and center of joint are defined, and these data are collated and the model is built (**Fig. 1.64**). It is validated and

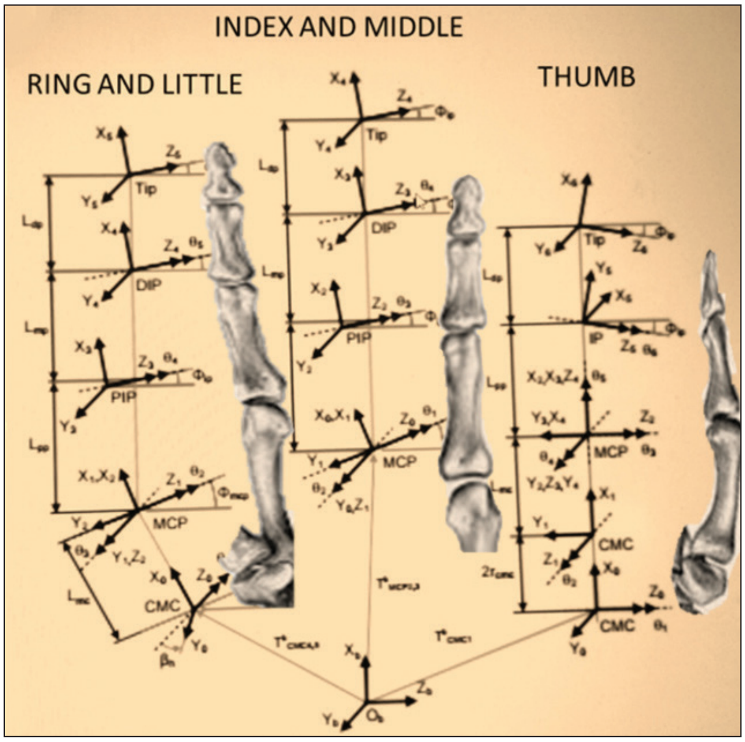

Fig. 1.64 Kinematic scheme of the finger and thumb.

Table 1.3 Hand length to phalange length in percentage

Digit	Proximal (LPP)	Middle (LMP)	Distal (LDP)
Thumb	17.1		12.1
Index finger	21.8	14.1	8.6
Middle finger	24.5	15.8	9.8
Ring finger	22.2	15.3	9.7
Little finger	17.7	10.8	8.6

further experiments are done to design robotic hand and prosthetic hand. Lot of research is going on in fabricating the most ideal prosthesis and robot.

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