Retinacular structures, called pulleys, maintain the flexor tendons of the hand in constant relationship to the joint axes and promote economy and efficiency in finger flexion. This system is composed of the transverse carpal ligament, the palmar aponeurosis pulley, and the digital flexor pulley system. Of these three components, the digital pulleys are the most critical to finger flexion. In their normal state, these pulley components are ideal in all aspects including configuration and location, which accommodates a 260° arc of motion without impingement and with minimum friction while at the same time using muscle tendon excursion that is well within the natural range of the muscle. An absent pulley results in an increased moment arm and requires increased tendon excursion to produce the same arc of motion. Because muscle excursion is not a limitless factor and is directly proportional to muscle fiber length, the effectiveness of tendon excursion is dependent on maintenance of the critical relationship between pulleys and their respective joint axes. Preservation and reconstruction of this system is based on knowledge of the anatomy and an understanding of the relative functional significance of each component of the system.

Most tendons about the flexor side of the wrist and hand that span two or more joints are restrained by retinacular structures called, by common use, pulleys. Pulleys maintain the flexor tendons close to the joint axis and prevent bowstringing, thus promoting efficiency and economy in finger flexion. This unique system functions under multiple constraints and requirements including a 260° arc of motion in the fingers, incremental forces of many kilograms and complex nutritional, circulatory, diffusion, and lubrication factors.14,20,28,29

The system is composed of the transverse carpal ligament, the palmar aponeurosis pulley, and the digital flexor pulley system. These three components represent a unique and complex biomechanical system that provides for complete digital flexion without limiting extension. Of these three systems, the digital component is the most critical to finger flexion and must be preserved or reconstructed if satisfactory finger function is to be maintained.

These three systems maintain a constant relationship (moment arm) between the flexor tendons and the joint axis and thereby provide for maximum joint movement within the constraints of muscle tendon excursion. Because excursion is not a limitless factor and is directly proportional to muscle fiber length, the effectiveness of tendon excursion is dependent on maintenance of the critical relationship between the pulleys and their respective joint axes. An absent pulley results in an increased moment arm and requires increased tendon excursion to produce the same arc of motion. Because excursion is not a limitless resource, joint motion is decreased when the moment arm is increased. Even a slight increase in the moment arm can be associated with tendon bowstringing, loss of digital flexion or even a
fixed flexion contracture. This fixed flexion contracture is attributable to the contractile nature of the scar tissue that builds up along the palmar aspect of the joint. When bowstringing occurs, the angle of attack of the flexor tendon is increased, which causes greater forces on the pulleys and can lead to pulley elongation and additional bowstringing.

**Anatomic Features of the Pulley Systems**

**Transverse Carpal Ligament**

In 1992, Kline and Moore\(^\text{15}\) proposed that the transverse carpal ligament was an important component of the digital finger flexor pulley system. This broad and substantial ligament that spans the volar side of the carpus was sectioned in fresh-frozen cadavers and the authors observed a 25% increase in the required excursion for the profundus and a 20% increase in excursion for the superficialis. They reported that the increased excursion that was consumed after release of the transverse carpal ligament resulted in less remaining excursion for flexion of the other joints and might contribute to weakness of grip observed after carpal tunnel release. The authors concluded that the main purpose of the transverse carpal ligament was to act as a flexor pulley at the wrist.

**Clinical Relevance**

However, the significant increase in flexor tendon excursion was shown only when the wrist was in the flexed position. This could result in decreased grip strength when the wrist was flexed although much of power gripping is done with the wrist in neutral or in extension. However, some functional requirements require a forceful grasp with the wrist in flexion. The importance of the transverse carpal ligament as a pulley is supported by the current author’s personal observation of flexor tendon bowstringing and subluxation during wrist flexion that followed a carpal tunnel release that was performed by excision of a portion of the transverse carpal ligament rather than the usual technique of incision of the ligament.

**Palmar Aponeurosis Pulley**

In 1983, Manske and Lesker\(^\text{22}\) described the palmar aponeurosis pulley. The palmar aponeurosis pulley is formed by the transverse fibers of the palmar aponeurosis, which are anchored on each side of the synovial sheath by vertical fibers or intertendinous septa that attach to the deep transverse metacarpal ligament and thus form an archway over the flexor tendons (Fig 1). Its average width is 9.3 mm and its proximal edge begins 1 to 3 mm distal to the beginning of the membranous sheath.\(^9\) Although not as closely applied to the flexor tendons as the digital pulleys, closer approximation may occur with increased tension on the palmar aponeurosis as in grasping. This proximal tension may be provided by the palmaris longus, the flexor carpi ulnaris, or both.\(^9\)

Manske and Lesker\(^\text{22}\) established the functional significance of this structure as a pulley by noting a significant preservation of total range of finger motion if the palmar aponeurosis pulley was intact in conjunction with section of the critical first and second annular pulleys. Baseline total range of motion (ROM) was determined for each finger in 12 hands from cadavers and the palmar aponeurosis, first annular, and second annular pulleys were cut sequentially in various orders. The results of these studies indicated that functional loss associated with absence of any one of the three proximal pulleys is minimal. The loss of flexion associated with the absence of the first or second pulley is insignificant as long as the palmar aponeurosis pulley is present. The loss of flexion increases if the absence of the first or second annular pulley is combined with absence of the palmar aponeurosis pulley. The authors concluded that as one functioning pulley, the second annular pulley was the most important, followed closely by the first annular pulley. They reported that although the position of the palmar aponeurosis pulley was the least critical of the three, its importance as a pulley was evident in the increased loss of flexion from 5.7% when it alone was present, to 12.6% when all three (palmar aponeurosis, annular one, and annular two) pulleys were cut.
Clinical Relevance

Although the palmar aponeurosis pulley may be considered an accessory pulley, its preservation is warranted because it may provide some form of substitution if annular one or annular two pulleys are not present. The palmar aponeurosis pulley is at risk during fasciectomy for Dupuytren’s disease. All surgeons should recall that the transverse elements of the palmar fascia are not involved in Dupuytren’s disease and that these transverse fibers that form the roof of the palmar aponeurosis pulley may be preserved while the longitudinal and superficial diseased elements of the palmar fascia are removed.

Digital Flexor Sheath

The digital flexor tendon sheath is composed of synovial and retinacular tissue components, which have separate and distinct functions. The membranous portion is a synovial tube that is sealed at both ends. The retinacular (pulley) portion is a series of transverse, annular, and cruciform fibrous tissue condensations, which begin in the distal palm and end at the distal interphalangeal joint (Fig 2). The floor or dorsal aspect of this tunnel is composed of the deep transverse metacarpal ligament, the palmar plates of the metacarpophalangeal, the proximal interphalangeal, and distal interphalangeal joints and the palmar surfaces of the proximal and middle phalanges. In the index, long, and ring fingers, the membranous portion of the sheath begins at the neck of the metacarpals and continues distally to end at the distal interphalangeal joint. In most instances, the small finger synovial sheath continues proximally to end at the

Fig 1A–B. (A) Composite view of the palmar aponeurosis (PA) pulley showing its relationship to the annular pulleys and its component parts including the transverse fibers of the palmar aponeurosis, the transverse metacarpal ligament, and the vertical septa that span these two structures. (Reprinted with permission from Doyle JR: Anatomy of the finger flexor tendon sheath and pulley system. J Hand Surg 13A: 473–484, 1988.) (B) Cadaver dissection of the palmar aponeurosis pulley as viewed from distal to proximal showing the transverse (tr) fibers of the palmar aponeurosis, the vertical septa (vs), transverse metacarpal ligament (tml), palmar plate (pp), and the first annular pulley (a-1). The cut ends of the flexor tendons at the distal edge of the palmar aponeurosis pulley and the lumbrical muscles retracted on each side can be seen. (Reprinted with permission from Doyle JR: Anatomy and function of the palmar aponeurosis pulley. J Hand Surg 15A:78–82, 1990.)
wrist.10,24,25 Visceral and parietal synovial layers were identified, which also were reported previously.6,7,10,26,29 A prominent synovial pouch is observed proximally and represents the confluence of the visceral and parietal layers. A visceral layer reflection or pouch also is seen between the two flexors at the neck of the metacarpal but is 4 to 5 mm distal to the more visible proximal and external portions of the synovial sheath (Fig 3). The membranous or synovial portions of the sheath are most noticeable in the spaces between the pulleys where they form plicae and pouches to accommodate flexion and extension (Fig 4).

The retinacular (pulley) portion of the sheath is characterized by fibrous tissue bands of annular and cruciform configuration, which are interposed along the synovial sheath in a segmental fashion and maintain the flexor tendons in a constant relationship to the joint axis of motion. The cruciform fibers sometimes are single oblique limbs or Y-shaped.

Five annular and three cruciform pulleys have been identified (Fig 2). The first of the five annular pulleys begins in the region of the palmar plate of the metacarpophalangeal joint. The majority of fibers (approximately 2/3) arise from the palmar plate, with the remainder arising from the proximal portion of the proximal phalanx (Fig 2). Although the most usual configuration of the first annular pulley is that of one annular pulley, which averages 7.9 mm in width, it sometimes is represented by two or

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**Fig 2.** Artist’s depiction of the membranous and retinacular portions of the sheath including the palmar aponeurosis (PA) pulley, and the five annular (A) and three cruciform (C) pulleys. (Reprinted with permission from Doyle JR: Anatomy of the finger flexor tendon sheath and pulley system. J Hand Surg 13A:473–484, 1988.)

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**Fig 3.** Sagittal section of the middle finger just proximal to the metacarpophalangeal joint. The vertical arrows point to the proximal and distal edges of the transverse fibers of the palmar aponeurosis and the curved arrow points to a portion of the longitudinal fibers. The visceral and parietal synovial layers (S) are seen as a proximal pouch beneath the flexor tendons; A1 = first annular pulley; pp = palmar or volar plate; tml = transverse metacarpal ligament. (Stain, hematoxylin and eosin; magnification, × 2.5). (Reprinted with permission from Doyle JR: Anatomy of the finger flexor tendon sheath and pulley system. J Hand Surg 13A:473–484, 1988.)
three annular bands. A distinct separation between the first and second annular pulleys is the usual configuration. This separation ranges from 0.4 mm to 4.1 mm and is most wide on the palmar aspect. In those cases that do not have a distinct separation between the first and second annular pulleys, there may be a pronounced thinness to the retinacular tissue for a distance of several millimeters at the usual site of separation or large triangular-shaped openings laterally. This allows for flexion at the metacarpophalangeal joint without any buckling of the pulley complex and thus the potential for impingement of the tendon is avoided (Fig 4).

In contrast to the variability in configurations of the first annular pulley, the proximal edge of the second annular pulley is constant in shape, with oblique fibers of origin beginning at the proximal and lateral base of the proximal phalanx, which joined annular fibers to make a prominent and thick leading edge (Fig 2). Some authors think that these oblique fibers are part of the cruciform system of pulleys and have designated these fibers as cruciate pulley zero. The current author thinks that these oblique fibers are an integral part of the second annular pulley and do not warrant a separate designation. These fibers overlay the annular fibers of the second annular pulley and are not distinct functioning units as are the three cruciform pulleys. Synovial outpouching is common in the spaces between the pulleys (Fig 4). The second annular pulley is 16.8 mm in average width and is thickest in the distal end. The deeper annular fibers of the second annular pulley are overlaid with oblique fibers, which at the distal end interdigitate to form the first cruciform pulley (Fig 2).

The third annular pulley is located at the proximal interphalangeal joint and attaches to the palmar plate. The third annular pulley is present in the majority of cases and its average width is 2.8 mm (Fig 2).

The fourth annular pulley, located in the midportion of the middle phalanx is overlaid with oblique fibers at its distal aspect that form the third cruciform pulley. The fourth annular pulley is 6.7 mm in average width and thickest in its midaspect (Fig 2).

The fifth annular pulley is thin, 4.1 mm in average width and it is attached to the underlying palmar plate at the distal interphalangeal joint. The membranous synovial sheath ends at the level of the distal interphalangeal joint, and no pulleys are present beyond the distal joint.

There are three cruciform pulleys in the finger, and they are located at the distal ends of the second and fourth annular pulleys and between the third and fourth annular pulleys. Variation in their shape is common: some are represented by one oblique limb and some are Y-shaped (ypsiloform). The third cruciform
pulley at the distal end of the fourth annular pulley is formed by prominent extensions of oblique fibers overlying the fourth annular pulley and is not always a separate structure.

**Clinical Relevance**

Significant flexion in the finger is achieved without buckling of the retinacular system or impingement of the underlying tendon(s) because (1) the broader pulleys, annulars two and four, are located between joints, whereas the more narrow pulleys, annulars one and three, are over the joints; (2) the pulleys are arranged in a segmental fashion with synovial pouches and windows between; and (3) the thinner and more narrow cruciform pulleys are located near joints where they can more easily accommodate to the confined space in acute flexion (Figs 2, 4). The functional adaptation of the retinacular system to the requirements of flexion also is apparent in the region of the metacarpophalangeal joint where some anatomic accommodation always is present between the first and second annular pulleys, either in the form of definite separation between these two pulleys, thinning of the contiguous margins of the first and second annular pulleys, or triangular shaped openings in the lateral margins of the retinaculum so that flexion can occur without buckling (Fig 4).

**Special Features of the Digital Flexor Sheath**

Bunnell reported that a tendon sheath was an adaptation that allowed a tendon to turn a corner. Bunnell stated, “It glides around a curve on a thin film of synovial fluid between two smooth synovial lined surfaces, just as metal surfaces in machinery glide on a thin film of oil.” Bunnell also reported that a tendon sheath had two layers of synovia, a visceral layer investing the tendon, and a parietal layer lining the fascial (retinacular) tunnel through which the tendon glided. Lundborg and Myrhage observed a well vascularized membrane with plicae and pouches at the margin of the pulleys that were important for flexion and stretching of the sheath. The authors were not able to show any continuity of the synovial cell layer on the friction surface of the second annular pulley but observed chondrocytelike cells in the superficial layers of this pulley. Knott and Schmidt also observed cartilagelike tissue at the distal end of the second annular pulley. In certain avascular areas of the palmar portion of the tendons, visceral synovial tissues were absent on histologic sections. Furthermore, in some scattered areas of the palmar surface of the tendon there were areas with cartilaginous differentiation similar to the findings in the second annular pulley. Lundborg and Myrhage concluded that the friction surface of the pulleys is devoid of vessels and that the friction and gliding in the digital sheath system takes place between two avascular structures, namely the palmar aspect of the flexor tendons and the inner aspect of the pulleys. These avascular gliding surfaces are nourished by diffusion from the synovial fluid. Histologic studies by Lundborg and Myrhage showed that the vascular plexus of the synovial sheath is in continuity on the outside of the rigid pulleys and by this arrangement, the pulleys can meet the mechanical forces associated with finger flexion while the synovial membrane avoids vascular compression and thus the microcirculation is not compromised. The well vascularized synovial elements of the sheath represent a dialyzing membrane that produce a plasma filtrate, the synovial fluid, which acts as a lubricating agent and also acts as a nutritional agent for the relatively avascular retinacular system and tendon.

The findings of Lundborg and Myrhage are appropriately compared with the findings of Cohen and Kaplan, who in a study of the gross, microscopic, and ultrastructure (electron microscopy) of the flexor tendon sheath, observed that the sheath consists of a noninterrupted layer of parietal synovium reinforced externally at intervals by dense bands of collagen (the retinacular system). Cohen and Kaplan also observed that the contents of the sheath were covered independently by a second similar layer of visceral synovium and
that the two layers were continuous at the proximal cul-de-sac, the vincula origins, and the tendon insertions. The synovial cells lining the pulley and covering the tendons were quantitatively, but not morphologically, different from the synovial cells of the membranous (synovial) portion of the sheath. The thickness of the synovial layers was greatest at the spaces between the pulleys and thin or attenuated beneath the annular pulleys and on tendon surfaces distant from vincula and cul-de-sacs.

Additional nutritional pathways were observed by Weber who identified nonvascular channels in the flexor tendons of dogs and chickens. These channels were mainly on the palmar surface, which is the least vascular. The channels appeared to be associated with non-parallel collagen fibers. Body fluid, marked by fluorescein dye was observed to penetrate the tendon in its least vascular area. Motion of the flexor tendon augmented dye penetration into the central portion of the tendon. Weber concluded that his findings supported the concept that synovial fluid nourished the flexor tendons within the digital theca.

Amis and Jones focused on the interior of the flexor tendon sheath and observed that the inner aspect of the sheath was not a continuous smooth surface. They reported that the thin (membranous) parts of the sheath did not attach directly to the proximal and distal borders of the pulleys in continuity, but often overlapped the superficial edges of the pulleys. Thus, on the inner aspect of the sheath the pulleys often stood proud of their surroundings with free edges pointing proximally and distally. The significance of these observations is that these free pulley edges may be sites for impingement or triggering of a partially cut tendon, a bulky or irregular tendon suture site, or a prominent suture knot. Although the fibrous portions of the sheath become contiguous near the end of the flexion arc, it is obvious that impingement possibly may occur about any free pulley edge during the act of flexion. This anatomic finding is most noticeable about the distal end of the second annular pulley and the proximal end of the first annular pulley (Fig 5).

Clinical Relevance
The digital flexor sheath is a complex structure with retinacular mechanical components (pulleys) combined with a membranous synovial component. These two distinct components provide mechanical support and guidance to the flexor tendons and nutrition and lubrication, respectively.

Biomechanical Principles
To understand this system more fully certain biomechanical principles must be discussed including: muscle excursion, the joint motion concept called moment arm, the geometric concept of the radian, the concept of work of flexion, and lubrication factors.

Excursion
Excursion of muscle is the sum of the length the muscle can be stretched from its resting length plus the length it can contract from its resting state (Fig 6). Muscle fibers are known to shorten by approximately 40% during active contraction (active excursion), and they can be lengthened passively by approximately 40%. Excursion is directly proportional to muscle fiber length. Therefore, excursion is not a limitless factor. The importance of this fact will be shown later when the relationship between excursion and moment arm is discussed. Brand defined excursion as potential, required, and available excursion. Potential excursion is the resting fiber length of muscle without reference to the state of the connective tissue restraints. Required excursion is the maximum excursion that might be required of a muscle in situ. A muscle never is required to lengthen or shorten through a larger excursion than it takes to move the joints that it crosses through their full passive range. Available excursion (a term also used by Freehafer et al) is a measure of the maximum excursion a muscle can produce when it has been freed from its insertion. Practically speaking, the amount of available excursion often is approximately the same as...
Fig 5A–B. (A) The prominent proximal edge of the first annular (A1) pulley and the fact that the pulley edge stands proud of the synovial sheath that attaches well beyond its leading edge (opposing arrows) is shown. FC = flexor canal (Stain, hematoxylin and eosin stain; magnification, × 20). (B) A similar arrangement at the distal end of the second annular pulley (A2) is shown. These findings show that the synovial membrane attaches to the outside of the pulley at some distance from its free edge which could result in catching or impingement of a partial tendon laceration or bulky tendon repair. The blood vessels are in the sheath external to the synovial membrane. FC = flexor canal; C1 = first cruciform pulley (Stain, hematoxylin and eosin; magnification, × 20). (Reprinted with permission from Doyle JR: Anatomy of the finger flexor tendon sheath and pulley system. J Hand Surg 13A:473–484, 1988.)

Fig 6. The muscle excursion is the sum of the length that a muscle can be stretched from its resting length plus the length it can contract from its resting state. In this diagram passive extension (A) plus active contraction (B) equals excursion. Muscle fibers are known to shorten by approximately 40% with contraction and can be passively lengthened by approximately the same amount. FDP = flexor digitorum profundus. (Reprinted with permission from Doyle JR: Tendon and Nerve Surgery in the Hand—A Third Decade. In Hunter JM, Schneider LH, Mackin EJ (eds). St Louis, Mosby-Yearbook 254–262, 1997.)
required excursion but available excursion is responsive to the pattern of use. Available excursion, according to Brand, probably is a measure of the limitation imposed by surrounding connective tissue, paratenon, paramysium, and intramuscular collagen. This excursion may be increased by exercise or stretching but it also may be diminished severely by adhesions after injury.

Some current indications of fiber length have been given by Brand et al (Table 1). It is the active muscle contraction component of excursion that accounts for tendon movement and subsequent joint movement. This active component of excursion must be understood to represent approximately ½ of total excursion. In a study of differential tendon gliding in the hand, Wehbe and Hunter reported a mean flexor profundus tendon active excursion of 32 mm (range, 15–43 mm) when the finger moved from full extension to full flexion with the wrist in neutral (Table 2). This observed excursion range correlated with the anticipated active excursion based on muscle fiber length and the commonly accepted figures for profundus tendon excursion. It also fits closely with the projected active excursion as determined by the geometry of the system (Table 3).

**TABLE 1. Mean Fiber Length of the Various Finger Flexors**

<table>
<thead>
<tr>
<th>Flexor</th>
<th>Length (centimeters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexor digitorum profundus</td>
<td></td>
</tr>
<tr>
<td>Index</td>
<td>6.6</td>
</tr>
<tr>
<td>Middle</td>
<td>6.6</td>
</tr>
<tr>
<td>Ring</td>
<td>6.8</td>
</tr>
<tr>
<td>Little</td>
<td>6.2</td>
</tr>
<tr>
<td>Flexor digitorum superficialis</td>
<td></td>
</tr>
<tr>
<td>Index</td>
<td>7.2</td>
</tr>
<tr>
<td>Middle</td>
<td>7.0</td>
</tr>
<tr>
<td>Ring</td>
<td>7.3</td>
</tr>
<tr>
<td>Little</td>
<td>7.0</td>
</tr>
</tbody>
</table>

(Table adapted from data from Brand PW, Beach, RB, Thompson DE: Relative excursion and potential excursion of muscles in the forearm and hand. J Hand Surg 6:209–219, 1981.)

**Clinical Relevance**

The implications for significant loss of motion and function in the finger is obvious when decreased muscle excursion attributable to intrinsic or extrinsic factors is combined with adhesions or scarring of the sheath or joint capsule.

**Moment Arm**

Moment arm is defined as the perpendicular distance between the line of application of a force and the center of rotation (axis) of a body (joint). Stated another way, the moment arm is the distance between the joint axis of motion and the central longitudinal axis of the adjacent flexor tendon. Some average and comparative figures for joint moment arm are metacarpophalangeal, 10 mm; proximal interphalangeal, 7.5 mm; and distal interphalangeal, 5 mm.

In reference to moment arm, a question must be asked: does the moment arm change with motion? Evidence supporting the concept of a constant moment arm has been given by Brand et al in a biomechanical study of the metacarpophalangeal joint from fresh cadavers. This study showed a virtual straight line plot of joint angle change to tendon excursion, indicating that significant changes in the moment arm do not occur with motion. Some joints including the wrist and metacarpophalangeal joint have two axes of rotation (similar to a universal joint) but in the current study, the axis of the metacarpophalangeal joint is considered to be in the coronal plane only.

**Clinical Relevance**

Although digital moment arms probably do not change in the natural state when the nor-

**TABLE 2. Flexor Tendon Excursions**

<table>
<thead>
<tr>
<th>Tendon</th>
<th>Mean (millimeters)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superficialis</td>
<td>24</td>
<td>14–37</td>
</tr>
<tr>
<td>Profundus</td>
<td>32</td>
<td>15–43</td>
</tr>
</tbody>
</table>

mal pulley system is intact, the potential for change in the moment arm is great if significant disruption of the pulley mechanism occurs or if a disrupted pulley system is not reconstructed adequately. Because most, if not all, of the available excursion is used to achieve full finger flexion, it is obvious that an increased moment arm will result in significant loss of function.

### Radian

A rule of geometry states that when a radius of a circle moves through an angle of $57.29^\circ$ (one radian), any point on that radius moves through an arc equal in length to the distance between that point and the center of the circle (Fig 7). If the radius of a circle is moved $57.29^\circ$ (one radian), it will have moved a distance of one radian along the circumference of that circle. A radian is that distance on a circumference of a circle that is equal to the radius of that circle. A practical application immediately comes to mind in terms of the prior discussion about excursion and moment arm: when a joint moves $57^\circ$, tendon excursion and moment arm are equal. When the metacarpophalangeal joint moves through its normal range of $85^\circ$, it moves through an arc equal to $1.48$ radian equivalents ($85$ divided by $57.29 = 1.48$.) The moment arm of the metacarpophalangeal joint is $10$ mm. Ten multiplied by $1.48$ equals $14.8$ mm, which is the required excursion of the flexor tendon to move the metacarpophalangeal joint through an arc of $85^\circ$. Similar calculations may be made for the proximal interphalangeal and distal interphalangeal joints (Table 3). An increase in the moment arm will result in significant loss of function.

### Table 3. Radian, Moment Arm, and Excursion

<table>
<thead>
<tr>
<th>Joint</th>
<th>ROM</th>
<th>Radian*</th>
<th>Moment arm (millimeters)</th>
<th>Excursion (millimeters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MP</td>
<td>85</td>
<td>1.48</td>
<td>×</td>
<td>10.0 = 14.8</td>
</tr>
<tr>
<td>PIP</td>
<td>110</td>
<td>1.92</td>
<td>×</td>
<td>7.5 = 14.4</td>
</tr>
<tr>
<td>DIP</td>
<td>65</td>
<td>1.14</td>
<td>×</td>
<td>5.0 = 5.7</td>
</tr>
</tbody>
</table>

*1 Radian = $57.29^\circ$  

MP = metacarpophalangeal; PIP = proximal interphalangeal; DIP = distal interphalangeal.

![Fig 7. When a radius of a circle moves through an angle of 57.29° (1 radian), any point on that radius moves through an arc equal in length to the distance between that point and the center of the circle. The segments ab, bc, and ac are equidistant. The distance the flexor tendon moves while producing 1 radian of movement is equal to the perpendicular distance or moment arm between the flexor tendon and the joint axis. Any increase in the moment arm that might occur secondary to loss of a pulley results in an increase in the excursion required to achieve the same arc of motion. This graphic display shows the active excursion required for complete range of motion at the distal interphalangeal (65°), metacarpophalangeal (85°), and proximal interphalangeal (110°) joints with their normal moment arms. For example, the normal 7.5 mm moment arm at the proximal interphalangeal joint requires a tendon excursion of 14.4 mm to achieve 110° of motion (Table 3). (Reprinted with permission from Doyle JR: Tendon and Nerve Surgery in the Hand—A Third Decade. In Hunter JM, Schneider LH, Mackin EJ (eds). St Louis, Mosby-Yearbook 254–262, 1997.)
moment arm attributable to absence or loss of integrity of a pulley can result in significant loss of function. Table 4 shows the loss of function that occurs with even a slight increase in the moment arm. Table 5 shows the relationship between normal joint ROM, normal or increased moment arms, and the required excursion.

**Clinical Relevance**

The concept of the radian provides a useful conceptual tool because when the required joint ROM is divided by one radian, and multiplied by the moment arm the result is the required excursion.

**Work of Flexion**

To understand the dynamics of function of the flexor tendon pulley system additionally, it is necessary to discuss work of flexion first introduced by Lane et al\textsuperscript{17,18} and more recently applied to flexor pulley function.\textsuperscript{23} Although one can use tendon excursion as a valid parameter to evaluate pulley function or efficiency, work of flexion that represents the resistance to gliding encountered by the tendon during flexion is a more comprehensive parameter. Work of flexion probably is a more useful parameter to evaluate the multiple factors that are responsible for success or failure in the treatment of patients with flexor tendon injuries. This is because it measures intrinsic and extrinsic factors other than the mechanical status of the pulleys such as viscoelastic forces of the skin and subcutaneous tissues, tendon adhesions, joint stiffness, and incongruity between tendon and sheath to name a few. Peterson et al\textsuperscript{23} reported that work of flexion was found to increase to a greater extent by pulley loss than was tendon excursion; for example, a comparatively slight increase in the moment arm results in a significant loss of finger flexion.

**TABLE 4. Moment Arm and Motion at the Metacarpophalangeal, Proximal Interphalangeal, and Distal Interphalangeal Joints**

<table>
<thead>
<tr>
<th>Joints</th>
<th>Moment Arm (millimeters)</th>
<th>Lost Joint Motion (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metacarpophalangeal</td>
<td>2 mm increase (10 to 12)</td>
<td>85 to 68</td>
</tr>
<tr>
<td>Proximal interphalangeal</td>
<td>1.5 mm increase (7.5 to 9)</td>
<td>110 to 88</td>
</tr>
<tr>
<td>Distal interphalangeal</td>
<td>1 mm increase (5 to 6)</td>
<td>65 to 52</td>
</tr>
<tr>
<td></td>
<td></td>
<td>260 to 208* (total)</td>
</tr>
</tbody>
</table>

*Finger tip fails palm: 2.5 +/- cm (1 inch).
A comparatively slight increase in the moment arm results in a significant loss of finger flexion.

**TABLE 5. Joint Range of Motion, Moment Arm, and Tendon Excursion**

<table>
<thead>
<tr>
<th>Joint (ROM)</th>
<th>Moment Arm (millimeters)</th>
<th>Excursion (millimeters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metacarpophalangeal (85)</td>
<td>10*</td>
<td>14.8*</td>
</tr>
<tr>
<td>Proximal Interphalangeal (110)</td>
<td>7.5*</td>
<td>14.4*</td>
</tr>
<tr>
<td>Distal Interphalangeal (65)</td>
<td>5*</td>
<td>5.7*</td>
</tr>
</tbody>
</table>

*Normal Values

34.9* versus 41.9

The relationship between required range of motion, normal and increased moment arm, and the resultant excursion. Joint range of motion divided by one radian multiplied by the moment arm yields excursion (see text.) MA = moment arm.
loss of the second annular pulley resulted in only an 8.5% increase in tendon excursion, but a 44% increase in work of flexion.

**Clinical Relevance**

Work of flexion is a more sensitive measurement of overall tendon function because it represents the integration of all the factors that resist tendon gliding. A comparative percent difference between increased tendon excursion and increased work of flexion with excision of various pulleys is given in Table 6.

**Lubrication Factors**

When a tendon or muscle moves around a bend it is constrained by some form of fibrous tissue or adjacent bone to make it efficient. The interface formed may develop an element of friction. In the normal state however, significant friction does not occur because of synovial membranes that produce fluid for lubrication. These synovial tissues may be organized into special configurations such as bursae or sheaths. A prime example of a bursa is the subacromial bursa interposed between the deltoid muscle and the underlying tendons of the rotator cuff. In the finger, the flexor tendons are covered with a visceral synovial layer that interfaces with a parietal synovial layer that is most prominent in the spaces between the pulleys. The form of lubrication in the sheath is called boundary lubrication in contrast to hydrodynamic lubrication as seen in joints. Synovial fluid is a viscous fluid that exhibits resistance to flow which is called thixotropy. This property is vital to lubrication in joints and tendon sheaths. The smaller the radius of curvature about a joint the greater the pressure and the greater the potential for loss of function attributable to friction and shear stresses.

**Clinical Relevance**

A practical application of these principles, especially the radius of curvature, would relate to width, height, and location of reconstructed pulleys. The natural system seems to provide a suitable model.

**Clinical Relevance Summary**

The preceding comments about anatomy and biomechanical principles have provided an appropriate foundation for a practical application of these facts as they might apply to the clinical situation. Preservation of all components of the pulley system is a worthy goal, but is not always possible. Multiple studies using sequential excision of various pulleys have shown the importance of preserving or reconstructing the second and fourth annular pulleys.

In addition, it must be observed that the pulley system in its normal state is ideal in all aspects including its configuration and loca-

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**TABLE 6. Flexor Tendon Biomechanics After Pulley excision with the Skin Intact**

<table>
<thead>
<tr>
<th>Pulley(s) Excised</th>
<th>Intact</th>
<th>Tendon Excursion</th>
<th>Work of Flexion</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>A2, A4</td>
<td>−0.64 ± 2.04</td>
<td>10.00 ± 8.16</td>
</tr>
<tr>
<td>A2</td>
<td>A1, A4</td>
<td>8.50 ± 1.62</td>
<td>44.10 ± 7.15</td>
</tr>
<tr>
<td>A4</td>
<td>A1, A2</td>
<td>9.93 ± 3.40</td>
<td>19.95 ± 10.21</td>
</tr>
<tr>
<td>A1, A2</td>
<td>A4</td>
<td>20.56 ± 3.67</td>
<td>62.36 ± 13.91</td>
</tr>
<tr>
<td>A2, A4</td>
<td>A1</td>
<td>33.66 ± 4.60</td>
<td>107.04 ± 22.77</td>
</tr>
<tr>
<td>A1, A4</td>
<td>A2</td>
<td>9.69 ± 1.91</td>
<td>39.83 ± 8.70</td>
</tr>
<tr>
<td>A1, A2, A4</td>
<td>none</td>
<td>65.09 ± 6.21</td>
<td>172.35 ± 15.30</td>
</tr>
</tbody>
</table>

A = annular pulleys.

tion, which accommodates a 260° arc of motion without impingement and with minimum friction while at the same time using muscle tendon excursion that is well within the natural range of the muscle tendon unit. Also, the digital pulleys possess great strength and breaking strengths have been determined that exceed most normal functional requirements. Because digital pulleys have high breaking strengths is an indication that reconstructed pulleys should be as strong as possible. Preservation of the pulley system is the goal throughout all phases of flexor tendon surgery. However, an intact pulley system is not always present after injury and repair. The basic principles that function in the normal system have been discussed and may serve as a guide to pulley preservation and reconstruction.

References