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The quadriga phenomenon: A review and clinical relevance

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The Journal of Hand Surgery
(European Volume)
0E(0) 1–10
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DOI: 10.1177/1753193411430810
jhs.sagepub.com


Abstract

The flexor digitorum profundus tendons are markedly interconnected, making them less able to move independently than the tendons of the flexor digitorum superficialis. This difference is often attributed to the common muscle belly of the profundus, but also, more importantly, to cross-connections between the tendons of the profundus. The effect of this quadriga phenomenon is important in several clinical situations, including testing for strength, assessing movement of the tendons, and when deciding which exercises to teach the patient after a tendon injury. The anatomy and biomechanics of this phenomenon are reviewed in this article to help explain why certain conditions occur, and to improve the diagnosis and treatment of some conditions in rehabilitation medicine.

Keywords

Quadriga phenomena, profundus tendon blockage, flexor digitorum profundus, tendon interconnections, interdependent movements of fingers

Date received: 27th June 2011; Revised: 29th October 2011; accepted: 2nd November 2011

Introduction

The quadriga syndrome is a condition in which the flexor tendon excursion is reduced in an unaffected finger when the excursion of the flexor digitorum profundus (FDP) tendon of the adjacent finger is altered by stiffness, injury, or adhesion (Verdan, 1960). It is due to the interconnectedness between the FDP tendons of the fingers, so that restricted motion in one finger will affect the others. When this occurs after injury it could be called a syndrome, but because the effect also occurs in the normal hand it is better to call it the quadriga phenomenon. The phenomenon was named by Verdan (1960), who saw a resemblance between the reins of the four horses of a Roman chariot and the interconnectedness of the four FDP tendons (Giambini et al., 2010) (Figure 1). The quadriga phenomenon is frequently attributed to the common muscle belly of the FDP. However other factors, such as the interconnections between the FDP tendons, may be even more important.

Anatomy books frequently disregard the connections between the FDP flexor tendons and their surroundings, and show them as four fully separated tendons, neatly arranged and equal in diameter and size. In his book *Clinical Mechanics of the Hand*, Brand (1999) stated that the middle, ring, and little fingers have little independence from each other. The middle finger profundus has its own distinct muscle fibres, but connective tissue binds it to the ring finger profundus. The ring and little

finger profundus muscle are intricately linked, with some fibres common to both. The tendons may even be difficult to assign to a single finger, because they form a sheet of multistranded tendon material in the distal forearm. The interconnectedness of the profundus muscles is supplemented by tendinous cross-connections at the level of the carpal tunnel and by the fact that in the palm the lumbricals to the ring and little fingers usually arise from the adjacent sides of the profundus tendons.

Leijnse made an elaborate study of the phenomenon and — using his own hands — found the effect of releasing the connections surgically. He found four levels of interconnections from proximal to distal (Leijnse, 1997a; 1997b; Leijnse et al., 1997):

- existing within the muscle bellies themselves;
- cross-linking of tendon fibres in the distal forearm and carpal tunnel;
- synovial sheaths interconnecting between tendons in the carpal tunnel;
- resulting from the tight origins of lumbricals originating from two adjacent tendons.

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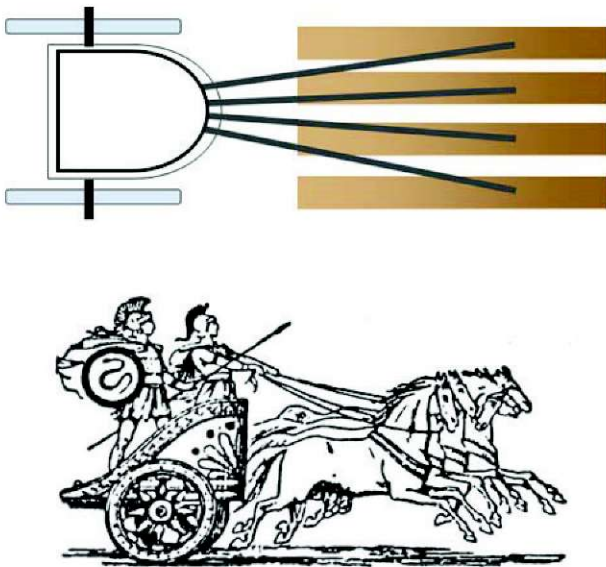


Figure 1. Diagram and illustration of a Roman chariot representing the quadriga phenomena of four connected reins/tendons. Illustration reproduced by the kind permission of Jill O. Miles from www.historyforchildren.blogspot.com [accessed 9 November 2011].

Proximally, the FDP tendons are disassembled and crisscross before they enter the carpal tunnel (Figure 2). Most remarkable are the fibrous connections between the FDP tendons at the wrist level, which consist of strong tendinous or fascia-like structures (Leijnse et al., 1992). These intertendinous fibres tether the FDP tendons together, which then form a single functional unit (Schmidt and Lanz, 2004). Within the carpal tunnel, all flexor tendons are enveloped by thick masses of synovial sheaths. These consist of multiple layers of thin synovial membranes which, in their totality, present as a thick opaque mass (Figure 3). It has been noted that the independence of the profundus tendon to the index finger is lost as a result of the tenacious attachment of the synovium at the level of the carpal tunnel, called the fibromembranous retinaculum by Fahrer (1979), which envelops all the tendons of the FDP and attaches them to the sides and floor of the carpal tunnel.

The ulnar sheath consists of up to 12 tendon units, clearly linked together before forming the three definitive tendons (Fahrer, 1979; Neu et al., 1985). These synovial membranes are frequently attached to the tendons themselves; they form strong and tight connective membranes, which can interconnect the deep flexor tendons to the different fingers over distances of centimetres, sometimes from the proximal end of the carpal tunnel up to and including the lumbrical origins. Even if these membranes are thin, the combined strength of their continuous insertion in the tendons is well able to resist large forces, especially because the opposite

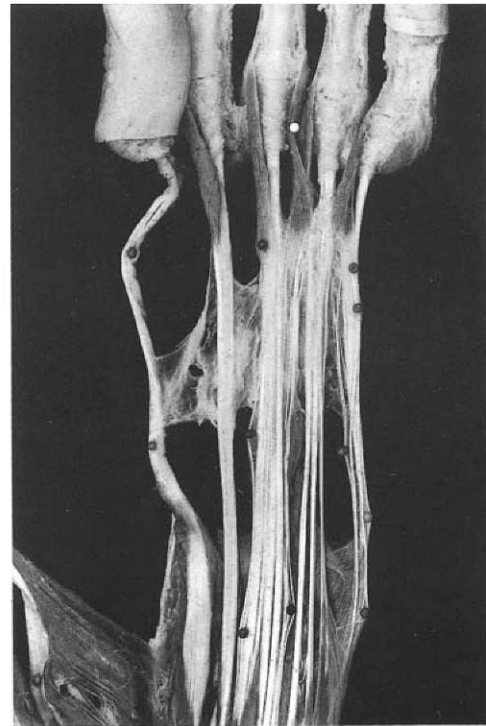


Figure 2. FDP and FPL tendons at the level of the carpal tunnel. Far left: FPL tendon. A trapezium-shaped tendinous-synovial connection runs from the FPL to FDP of the index finger. The three ulnar tendons are highly interconnected by synovial membranes, tendinous crossovers, and minute tendon fibres dissolved in the synovial membranes. Reproduced with kind permission from: S. Karger AG (Leijnse et al., 1997).



Figure 3. Dense connective tissue between the FDP tendons (the ring finger FDP is lifted) at the carpal tunnel level consisting of multiple layers of thin synovial membranes.

displacement of the connected tendons will generally tauten all connecting membrane fibres at the same time (Leijnse, 1997a). Only distal to the carpal tunnel do the FDP tendons transform into round, compact, and smooth finger tendons.

The quadriga effect is noticeable when full proximal excursion of one of the FDP tendons is prevented by holding one or more fingers in extension. For example, when the ring finger is fully extended, the FDP tendon is pulled distally, the FDP tendons to the middle and

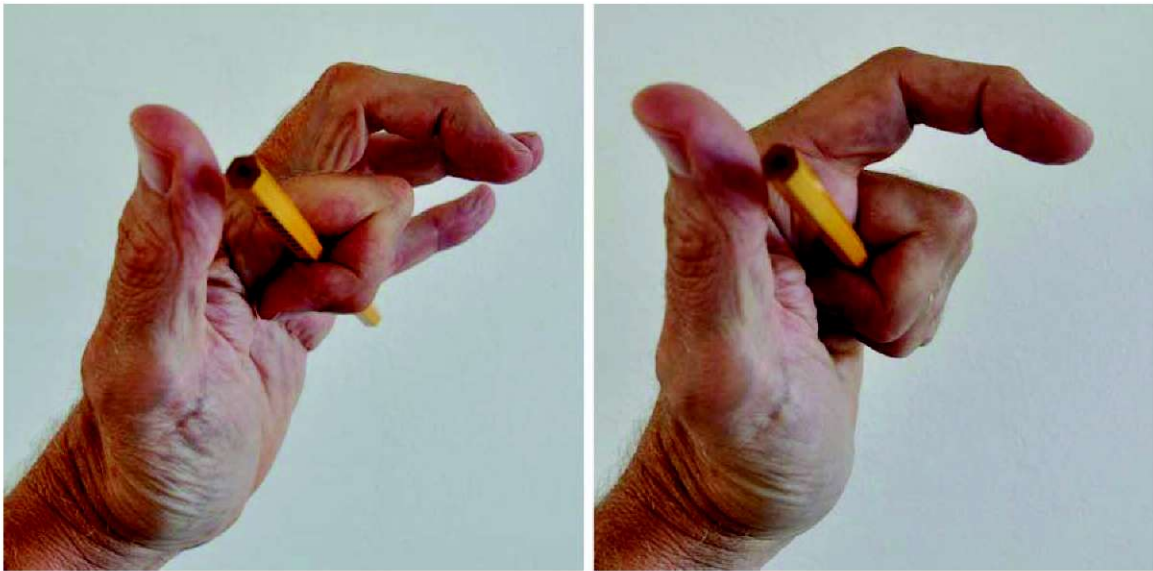


Figure 4. Effect of flexion with FDP on neighbouring fingers when holding a pencil with index finger in full active flexion (left) where the long finger cannot be fully extended. When the three ulnar fingers are fully flexed (right) the index finger cannot be fully extended.

small fingers become lax and will be unable to actively flex their distal joints (Smith, 1974).

When the index finger is actively holding a pencil (Figure 4, left) and an attempt is made to extend the ulnar three fingers, a limited extension of the interphalangeal joints of the middle finger and/or other fingers can be seen. Similarly, when actively holding a pencil with the three ulnar fingers, full extension of the index finger is not always possible (Figure 4, right). This is not due to the intertendinous connections of the extensors, because passive extension is possible. Only when the middle finger distal interphalangeal (DIP) is allowed some extension can the index finger be fully extended.

Although the word *quadrige* seems to nicely describe the interdependence of the four FDP tendons, not all of the 'reins' behave in the same way, and some hands will have some or even complete independence of the FDP of the index finger. In addition, connections have also been found between the FDP tendon of the index finger and the flexor pollicis longus (FPL) tendon to the thumb (Linburg and Comstock, 1979), thus making the word *quadrige* less appropriate.

It is not known if all persons are equally likely to show the *quadrige* phenomenon, or whether anatomical or physiological variations place some at high risk of clinically significant effects, whereas others are relatively immune to the problem. Substantial differences between the left and right sides have also been found (Horton et al., 2007).

In contrast with the FDP tendons, the flexor digitorum superficialis (FDS) tendons can act more independently of each other. However, the FDS tendons also have some

interdependence, especially between the FDS of the ring and little fingers, which has been reported to occur in 21–38% of all persons tested (Austin et al., 1989; Baker et al., 1981; Puhaindran et al., 2008).

This review aims to describe the situations in which the interconnections play a role, for example in relation to hand tests, to the appearances after nerve injuries, and when advising a patient with a tendon injury about specific exercises.

Clinical signs of the *quadrige* phenomenon

Testing FDS

Clinicians know that FDS excursion and strength can be tested in isolation by maintaining the adjacent fingers in extension (Figure 5). When the fingers are extended — that is, with metacarpophalangeal joint (MCPJ) and proximal interphalangeal joints (PIPJ) in full extension — flexion of one finger and activation of the FDP in that finger will not result in distal interphalangeal joint (DIPJ) flexion. The only joint that can be flexed is the PIPJ, which is flexed by the FDS and can thus be tested in isolation. The floppy distal phalanx shows the inactivity of the FDP on the DIP joint. As mentioned earlier, an exception to this is when the middle finger is kept in extension; in this case some persons will be able to flex the DIPJ of their index finger, especially when the MCPJ is allowed some extension.

Ohe and Miura (2011) found that flexion of fingers was restricted by 32% for the index, 41% for the middle, 32% for the ring, and 54% for the little finger when the



Figure 5. Test of the FDS strength and excursion by maintaining the adjacent fingers in extension. The examiner can also assist this by holding the fingers in extension.

middle or ring fingers were held in extension. Holding the index finger extended had the least effect on the other fingers.

Measuring grip and pinch strength

Both Bunnell [1948] and Verdan [1960] noticed that a patient with a stiff finger may also experience a loss of grip strength that exceeds the lost contribution of the stiff finger alone; this is caused by weakness of the adjacent fingers as a result of their restricted finger flexion. Horton et al. [2007] quantified this effect by mimicking stiffness of one finger and observing the effect on the strengths of the other three fingers of the same hand. Thermoplastic wedges were used to simulate mild, moderate, and severe stiffness of each finger, and the individual strengths of each finger during power grip were measured with a dynamometer. The strength of the middle, ring, and small finger significantly diminished when each of the other fingers, including the index, was stiffened. For example, if the ring finger was blocked with a wedge, increasing the fingertip to distal palmar crease distance to 2 cm, all the other fingers had unrestricted grip, but there was a median 28% decrease of strength in the middle finger and 69% in the little finger. The independent movement of the index finger was demonstrated, because its strength was largely unaffected by simulated stiffness of the other



Figure 6. Test of the FDP strength should be done with all fingers in flexion; by attempting to extend the DIP joint the strength is assessed. The middle finger is tested by attempting to extend the DIP joint.

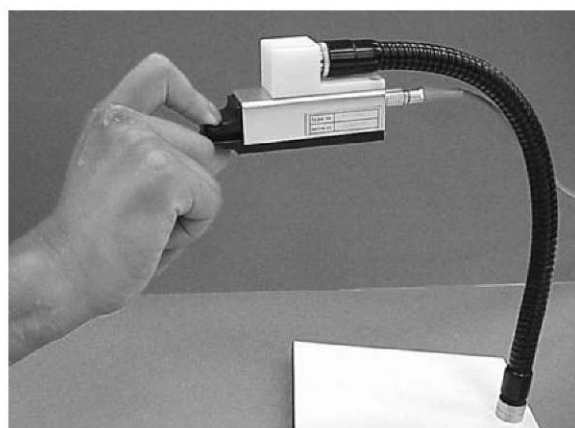


Figure 7. Testing the pinch grip strength with a dynamometer should be done with all fingers in flexion.

fingers. They found considerable intersubject variability, suggesting the significance of the quadriga effect varies between individuals.

In assessing grip strength or when testing the strength of FDP in active flexion of the DIPJs of the fingers, it is advisable that all the fingers should be allowed to flex and be tested as a group, that is, by asking the patient to make a fist with all fingers and subsequently testing for DIP flexion for all fingers separately (Figure 6). Similar to testing grip strength, FDP of the index finger and FPL tendon might exert more force when allowed to work together. For the same reason, it is better to allow the ulnar three fingers to flex when testing pinch strength (Figure 7). This has been confirmed by McCoy and Dekerlegand [2011], who compared thumb tip to index tip pinch strength with the ulnar three digits of the hand in extension with pinch strength when the ulnar three digits were flexed into the palm of the hand. They also found significant differences between the left and right hands.



Figure 8. One-finger-pocket hold grip position, with all other fingers flexed to support the strength of the ring finger through the connections between the FDP tendons.

It has been suggested by Schweizer (2003) that rock climbers make use of the quadriga effect in the one-finger-pocket hold (Figure 8). To increase the maximum force of the holding finger, the interphalangeal (IP) joints of the adjacent fingers are maximally flexed. Similarly, avulsion fractures of the FDP, known as the Rugby jersey finger, occur more often in the ring finger than in other digits. This is thought to be due to the central pull of the conjoined FDP of the ulna three digits on the ring finger, as a result of the quadriga effect and the fact that the ring finger has the least independent motion of all fingers (Tuttle et al., 2006).

Flexor tendon repair

When the FDP tendon is injured it usually retracts in the palm of the hand, although this retraction can be slight. The assumption is made that if the vincula are found to be intact after an injury, they must have prevented the retraction. However, the vincula are very fragile structures and are insignificant, especially when

compared with the connective tissue between the FDP tendons. The fact that a vinculum remains intact is caused by the connections between the FDP tendons. Harvesting an FDP tendon in a similar way to what is common practice for an FDS tendon (e.g. in tendon transfer) by cutting the distal insertion and retracting the FDP tendon at wrist level takes a surprising amount of force.

In the management of flexor tendon injury rehabilitation, knowledge of the connections can be helpful when considering which finger the elastic band should be attached to, or which finger can or must be exercised. For example, when a patient has injured the FDP tendons of the index and middle fingers and is afraid of moving, or the therapist doubts whether the patient is moving, the therapist can add an exercise, such as holding the two injured fingers in flexion and allowing active flexion of the ring and small fingers. The therapist can explain to the patient that this is a safe movement when the radial fingers are kept in flexion. In practice, some tension will be delivered to the tendons of the injured fingers, but in a controlled way. Conversely, when a patient is too energetic during exercises, one can attach the elastic band to the other fingers or explain that the patient should not use the ulnar two fingers.

In flexor tendon repair adhesions often cause decreased gliding of the tendons. Even when only one tendon is injured, the effect on the other fingers is apparent and, in some cases, can be due to the quadriga effect. Allowing the neighbouring fingers to flex with the repaired tendon will increase the force on that tendon and help move the tendon of the finger proximally. When the tensile strength of the repaired FDP tendon is sufficient, the tendons should be exercised together for maximum proximal glide. Grip exercises for all fingers and thumb will make use of the quadriga effect when all are working together.

Silfverskiold et al. (1993) used the four-finger method, which includes all four fingers in the traction (even if not injured). They found that with a programme that combined dynamic traction and passive flexion to all four digits, the excursion of the FDP tendon was more than twice the mean size of the excursions previously achieved with a modified, traditional Kleinert traction programme. A plausible explanation for this is that the normal connections between the FDP tendons help to move the repaired tendon(s). This has been confirmed by *in vivo* ultrasound study of the excursion of the long finger FDP tendon in healthy subjects, which showed large and significant differences between the different rehabilitation protocols in terms of absolute and relative tendon displacements (Korstanje et al., in press). When all fingers were included during flexion, as proposed by Silfverskiold et al. (1993), the median excursion was

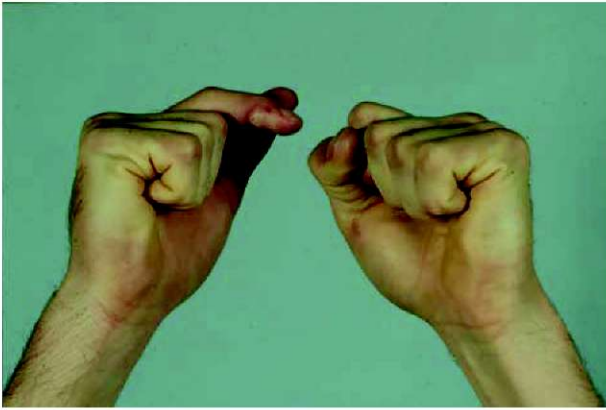


Figure 9. High median nerve lesion of the left hand; the 'pointing finger' is caused by inability to flex the IP joints of the index finger while the middle finger is fully flexed. The MP joint is flexed by the intrinsic muscles of the index finger. Notice that this posture is not the same as the so-called hand of benediction, as often referred to in a high median nerve lesion.

17.8 mm, which approximated to the active range of motion in terms of relative excursion, which had a median of 23.4 mm. The median excursion in the standard Kleinert splint with only the long finger attached to the elastic band was 10.0 mm. Interestingly, an additional experiment with all the adjacent fingers fixed in flexion showed a large median excursion of 13.9 mm. The differences in excursions between all protocols were statistically significant. The clinical relevance is that the position of adjacent fingers in tendon mobilization protocols has a large influence on both absolute and relative tendon excursions.

Appearance of median and ulnar nerve lesions

Bunnell (1948) reported that high median nerve lesion (i.e., above the elbow with paralysis of the FPL, and the radial half of the FDP to the index and middle fingers) causes the two fingers not to bend at the PIPJ, often referred to as the hand of benediction. It is not seen in clinical practice, first, because the fingers flex at the MCPJ due to the interosseous muscles, which are innervated by the ulnar nerve, and second, because the middle finger is often pulled into flexion due to the connections between the FDP tendons of the ring and middle fingers. When the patient is asked to make a fist, the hand is held as if pointing with the index finger (Kennedy et al., 1997) — pointing finger or orator's hand are much better descriptions (Grisold et al., 2001) (Figure 9). One has to keep in mind that, occasionally, as Kaplan (1965) stated, the distal phalanx of the middle finger can be flexed due to an additional nerve supply to the flexor profundus of the middle finger from the ulnar nerve.



Figure 10. High ulnar nerve lesion; flexion of the ring finger is possible because of connections with the FDP of the middle finger. The patient apparently has an FDS to the little finger.

Brand (1999) also noted that in a palsy of the ulnar or median nerve, the ulnar part of the FDP muscle to the middle, ring, and small fingers moves together. In high ulnar nerve lesions, the FDP to the ring and small finger are paralyzed, although this often results in little loss of flexion of the fingers. Here, similar to the case with a high median nerve lesion, the ring finger is pulled into flexion by the FDP of the middle finger. Full active flexion of the ring finger is often possible, but when tested there is often some weakness compared with the middle finger FDP (Figure 10).

Restrictions of tendons can cause dystonia

For over 100 years, ambitious pianists have submitted themselves to surgery for division of the tissues connecting the ring finger extensor tendon to that of adjacent fingers, but with no real improvement. The limitation of extension in the ring finger is influenced by the intertendinous connections between the extensor tendons, but according to some, should be regarded as more of a flexor problem (Lanzetta and Conolly, 1996). The anatomical constraints caused by connections between the flexor tendons of the fingers and thumb create less favourable conditions for smooth movements. As a result, it is possible that conditions like writer's cramp or focal dystonia may be triggered by these biomechanical constraints. Medical opinion remains undecided on the pathophysiology of dystonia and, because it also involves changes in the central nervous system, it can remain after the apparent precipitating cause has been removed.

Some authors have argued that persons with stronger and more restrictive connections might suffer from dystonia in the hand (Leijnse et al., 1992; 1997;

Rosset-Llobet et al., 2009). One of the fundamental axioms in the teaching of a musical instrument is that exercise increases the independence of the fingers. However, the interconnections are generally strong tendinous or fascia-like structures, which are not likely to be significantly stretched or lengthened by exercise in the mature hand (Leijnse, 1997a; Leijnse and Hallett, 2007). Leijnse (1997b) pointed out that anatomical interconnections between tendons can be considered as possible causes of focal dystonia in the hand of the musician. His hypothesis was that focal dystonias arise when the constraints on movement resulting from these anatomical limitations impede playing movements with a low expenditure of energy. For example, active DIP control and, therefore, deep flexor use is required when playing the violin (left hand), classical guitar (left and right hand), and harp. Limitations of tendon displacements or joint mobility constitute constraints that require the use of more force and, thus, energy to play the instrument, which may lead to overuse of muscles and/or tendons. An overuse situation occurs when constraints prevent movements that allow the instrument to be played with a sufficiently low expenditure of energy.

Leijnse, who suffered from dystonia in the hands, found that removal of the intertendinous connections between the extrinsic tendons resulted in improved independent extension of the fingers. However, only release of the passive connections in the FDS and FDP tendons, division of the bi-tendinous origins of the lumbricals, and removal of the connective fascia between the lumbrical muscles in the left hand, gave the maximal range of finger independence (Leijnse, 1995) (Figure 11). These findings provide evidence that the quadriga effect is not due to the common muscle belly of FDP, but is a result of the connections between the tendons, especially at the carpal tunnel level.

Thumb and index finger flex together: connection between FPL and FDP of index finger

The anomalous connections between the FPL tendon and the index finger FDP tendon was first described by Linburg and Comstock (1979). This interconnection prevents the IP joint of the thumb from flexing without the distal IP joint of the index finger also flexing, and vice versa. Clinical examination of 136 volunteers suggested that the Linburg–Comstock anomaly was present in 13%, unilateral in 9%, and bilateral in 4% (Karalezli et al., 2006). Leijnse (1997a) considered the FPL and FDP to be one morphological unit and found that the prevailing direction of the connections between the two tendons was from the FPL towards the FDP tendon of the index finger.

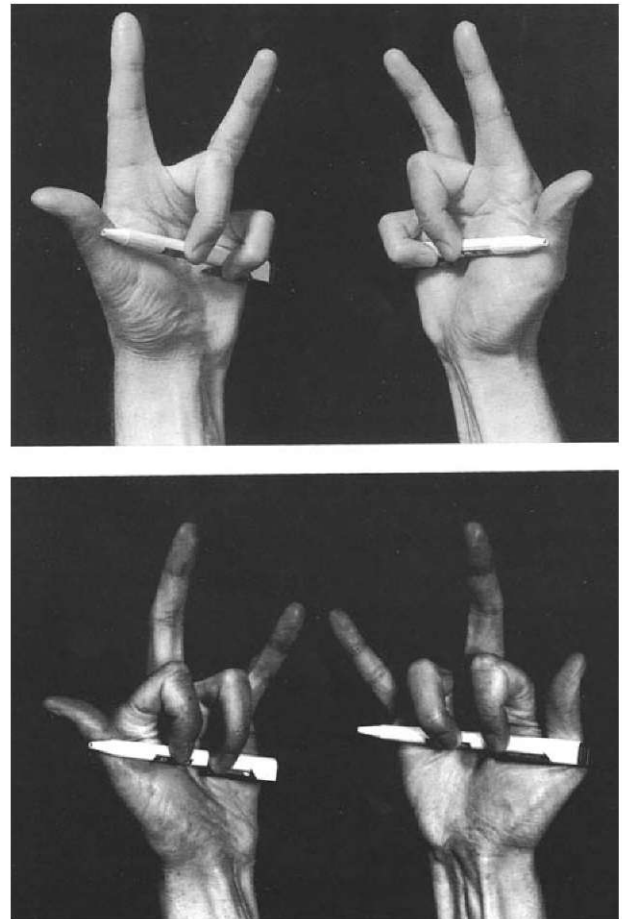


Figure 11. Postoperative active independent flexion ranges after release of the connections between the FDPs. With the neighbouring fingers extended, this operated hand is able to flex the DIP joints proving an unrestricted FDP action that is normally not possible because of the connections. (Reproduced with kind permission of Dr J. N. A. L. Leijnse.)

To test the presence of this connection, the patient is asked to extend all fingers and maintain this position while flexing the thumb as far as possible towards the hypothenar eminence. If the Linburg–Comstock anomaly is present, the index finger (and sometimes even more fingers) will be pulled into flexion (Figure 12). When the examiner pulls the fingers into extension, the patient might report pain at the flexor aspect of the forearm near the carpal tunnel; this where the connection is usually found (Blair and Omer, 1981; Nakamura and Kubo, 1993).

Allowing unrestricted motion of the index finger or thumb, if one or both tendons have undergone surgical repair, can result in excessive tension in active flexion and rupture of the repaired tendon (Stahl and Calif, 2005). Therapists need to take into account the possible presence of this connection when, for example, increasing the active excursion of the FDP of the index finger

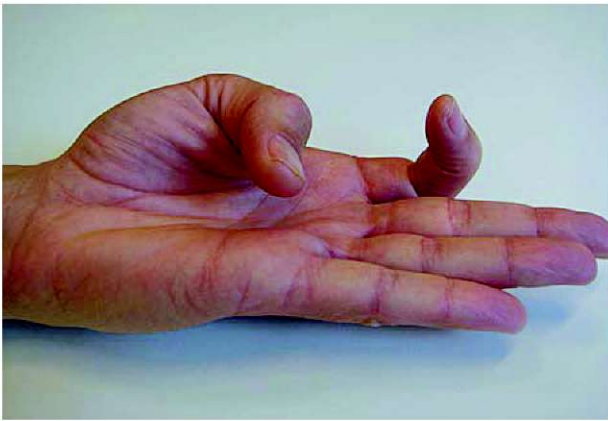


Figure 12. Resultant movement of the index finger after flexing of the thumb due to a Linburg–Comstock connection between the FDP tendon of the index finger and FPL tendon of the thumb.

or the FPL of the thumb. It is advisable to instruct the patient to simultaneously flex the other digit to maximize the concurrent proximal excursion of both tendons.

Similar to the examples of dystonia discussed above, the presence of the connection between the FPL and FDP of the index finger has also been reported as a reason for dystonia [Leijnse, 1997b]. However, it has been pointed out by Rosset-Llobet et al. (2009) that dystonia may remain after the apparent precipitating cause has been removed.

Decreased grip strength after finger joint arthrodesis

Arthrodesis of a finger joint limits grip strength, not only due to dysfunction of the fused digit, but also because the neighbouring fingers, although intact, will often have limited flexion because of the quadriga mechanism [Burton et al., 1986; Lin et al., 2008; Linscheid, 2000].

Morgan et al. (2000) assessed the impact of DIP joint fusion on grip strength and how this may be related to a profundus quadriga. Nineteen adults (12 men and 7 women) with an average age of 32.6 (range 24–61) years underwent a series of grip strength measurements with simulation of DIP arthrodesis of the index, long, and both the index and long (index–long) finger. The nondominant hand served as a control for the testing. All participants were tested in the same manner. Baseline recordings for dominant and nondominant hands without DIP block were followed by blocking DIP flexion in the dominant hand for the index, index–long, and long finger. The nondominant hand was also tested each time, but without blocking, to serve as a control for normal changes in grip strength with repeated testing. Significant decreases in grip strength were seen for all DIP blocking compared with baseline values, but



Figure 13. Inability to flex the little finger after arthrodesis of the PIP joint of the ring finger.



Figure 14. Decreased flexion in the DIP joint of the long finger after amputation of the middle and distal phalanges of the index finger.

no significant differences were noted in the equivalent trials in the nondominant, nonblocked hands.

These findings have clinical relevance to DIPJ arthrodesis, and probably have an even greater impact when a PIPJ arthrodesis is done. In several patients we have observed decreased flexion in adjacent fingers and a considerable decrease in grip strength (Figure 13).

Decreased flexion of intact fingers after fingertip amputation

After finger amputation, if the stump of the FDP tendon is attached to the tip or spontaneous adhesions of the tendon that occur in the finger or palm, flexion of the adjacent uninjured finger(s) will be hindered as a result of the decreased excursion of the profundus tendons to the intact fingers. This causes a decrease in the power and range of movement of the terminal joints of the uninjured fingers when they are fully flexed (Figure 14). Neu et al. (1985) described three degrees of severity of

this weakness. In 20 patients they demonstrated that the condition was surgically correctable by release of the adherent profundus tendon to the amputated digit. Full, active flexion and extension of the intact fingers in the early postoperative period after primary amputation should prevent these patients from developing profundus tendon blockage.

Acknowledgment

I would like to thank Dr. J. N. A. L. Leijnse from the Hand and Upper Extremity Research Laboratory, Université Libre de Bruxelles, Belgium for reading the paper and his valuable comments.

Conflict of interests

None declared.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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