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Tendon transfers for the upper extremity in cerebral palsy

Spastik üst ekstremitede cerrahi tedavi: Tendon transferi uygulamaları

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Upper extremity deformities in cerebral palsy are caused by the imbalance between spastic and weak muscles acting on unstable joints. The basic goals of surgical treatment of spastic hands and upper extremities of patients with cerebral palsy can be summarized as reducing the strength of spastic muscles, strengthening the antagonist muscles, and permanent stabilization of unstable joints. Surgical techniques to achieve these goals include lengthening of spastic muscles, tendon transfers, release or plication of the joint capsule, joint arthrodesis, neurectomies, and skin procedures. Amongst these surgical treatment options, this article will present, in more detail, tendon transfers which are performed especially to achieve balance and restore motor functions.

Key words: Cerebral palsy/surgery; child; contracture/surgery; forearm/surgery; hand deformities, acquired; muscle spasticity/surgery; tendon transfer/methods; upper extremity.

Beyin felcine bağlı üst ekstremite deformiteleri, spastik ve güçsüz kaslar arasındaki dengesizliğin stabil olmayan eklemlere etki etmesi sonucunda meydana gelir. Bu olgularda spastik el ve üst ekstremitelerin cerrahi tedavisindeki temel amaçlar, spastik kasların kuvvetinin azaltılması, antagonist kasların güçlendirilmesi ve stabil olmayan eklemlerin kalıcı stabilizasyonları olarak özetlenebilir. Bu amaçları yerine getirebilecek cerrahi teknik yelpaze ise, spastik kasların uzatılması, tendon transferleri, eklem kapsülünün serbestleştirilmesi veya plikasyonu, eklem artrodezleri, nörektomiler ve cilt prosedürlerinden oluşmaktadır. Bu yazıda, cerrahi tedavi seçenekleri ve uygulamaları arasında, özellikle dengenin sağlanması ve motor fonksiyonların cerrahi restorasyonunu sağlayan tendon transferleri ön planda sunulmaktadır.

Anahtar sözcükler: Beyin felci/cerrahi; çocuk; kontraktür/cerrahi; önkol/cerrahi; el deformitesi, edinsel; kas spastisitesi/cerrahi; tendon transferi/yöntem; üst ekstremite.

Tendon transfer is the transfer of a functional tendon to another point by changing its direction -without compromising blood flow and innervation- by separating it at the adhesion point. The prerequisites of tendon transfer can be listed as follows: analysis of patient's needs, informing the patient about the surgical expectations and limitations, stabilization of the skeletal structure, absence of edema and inflammation, presence of sufficient soft tissue source, mobility of the joints, availability of a donor muscle of sufficient strength, excursion and elasticity, and presence of appropriate tension direction and pulley.[1,2]

Candidates for tendon transfers

Among the cases with cerebral paralysis (CP), the most appropriate group for surgical intervention is the spastic group. Due to the challenges of performance and unpredictability of the results, surgery and especially dynamic tendon transfers are not recommended for the dyskinetic cases.

The targets of the surgical treatment must be realistic and achievable. Prior to the operation, both the patient and his/her family members must be thoroughly informed about matters like functional heal-

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ing, procedures involving combinations of hygiene and aesthetics, and expectations. The success of surgery hinges not only on the degree of neuromuscular defect and the surgical technique performed, but also on the patient's age, apprehension, and his/her desire and ability to use the affected hand.[3]

Zancolli et al.[4] defined the qualities required in patients suitable for surgery as follows: spastic neuromuscular defect, sufficient IQ and emotional stability, limited effect of spasticity on emotional status, infantile hemiplegia, presence of basic senses, a certain amount of voluntary control on the spastic muscles, sufficient concentration and cooperation capacity for the postoperative term, motivation and support by the family members, and good neurological state in general.

In addition to increased muscle strength and movement ability, the results of surgery should be assessed in terms of the degree of achievement of other targets previously defined and improvements in grabbing of the hand and activities of daily living (ADL).

Assessment of a patient with CP with respect to existing deformities, and classifying and defining the problem is a multi-staged process. A close cooperation is needed with the physical treatment and rehabilitation team following the patient.

Timing of surgical treatment

In recent years, the ideal age limit for reconstructive surgery in CP has been reduced. Although there are diverse views on the subject, it is pointed that ideally the reconstructive surgery should be performed at ages 4 to 6. At this age range, the central nervous system has become maturated, the deformities are easily detected, and the child can cooperate with the rehabilitation team.[4-9] It is not appropriate to delay surgical treatment due to concerns about the child's ability of cooperating with a specific exercise program. Even though surgery is recommended at early ages, a relatively older age is not a contraindication as long as the patient tries to control the hand voluntarily and restoration improves the functionality of the hand.[10]

Through the years, tissues continually regenerate and keep on adapting to the new post-spasticity state. Contractures develop in the motionless joints, while the skin and soft tissues loose elasticity. Therefore, tendon transfers must be made as early as possible. In the meantime, joint movement span and the elasticity of soft tissues must be maintained via passive exercises until surgery. It should be noted that no tendon transfer can activate a joint lacking passive movement and that postoperative active movement of a joint cannot surpass its pre-transfer passive movement. If intense and continuous rehabilitation treatments fail to overcome spasticity, joint movement limitations and soft tissue contractures, these problems must be solved via surgical loosening and lengthening techniques prior to tendon transfer, weak muscles must be backed up through tendon transfers and, if necessary, permanent stabilization of the joints should be performed.

Surgical applications for the upper extremity segments

Elbow

The elbow enables the upper extremity to be spatially directed towards the target. Severe elbow flexion contractures may hold the arm adjoined to the body. In addition to hygienic and cosmetic problems, the functionality is impeded.[11] Usually, the elbow deformity observed in CP is the flexion deformity. The reason of the deformity is the spastic contracture of the muscles on the front part of the elbow. In long-term cases, soft tissue contractures may be present, as well.

Although elbow flexion deformity is rather common, it is rarely severe as to merit surgical indication. In general, flexion contracture in the elbow of less than 30° does not cause functionality limitations.[12] Fixed contractures of 45° or above[6,7] or flexion deformities exceeding 80° during activity[6,10] are considered to meet surgical indications.

Among the most frequently employed surgical techniques are loosening/lengthening of elbow flexor muscles/tendons, releasing contracted soft tissues, and separating the flexor-pronator muscle group from the adhesion point and shifting them distally.

Forearm pronation deformity

Being an upper extremity deformity very commonly seen in patients with spastic CP,[6] forearm pronation deformity significantly limits the hand's functionality.[13] Interosseous membrane contracture, secondary curvatures at the radius and ulna,[14] and dislocations at the radius head –especially in posterior direction–

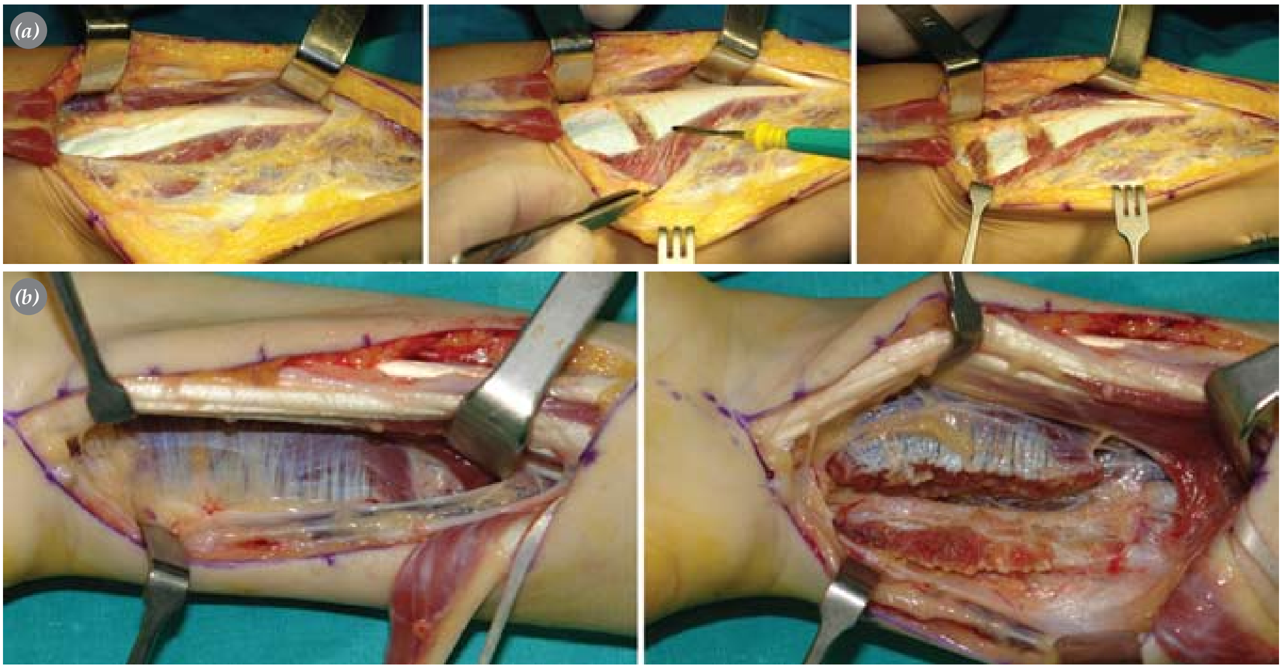

Fig. 1. (a) Pronator teres myotomy-lengthening. **(b)** Pronator quadratus myotomy.

are likely to develop as a result of long-lasting pronation contractures.[6,15]

Both pronation and supination movements are needed for a sufficient functionality of the hand.[6] Therefore, the ideal surgical method of the pronation deformity treatment in patients with CP must aim to restore the active supination movement without compromising the existing pronation movement.

The surgical methods used to restore the pronation deformity can be classified in two groups: In the first group, we benefit from certain procedures which originally aim to restore another deformity; hence, pronation contracture release, flexor/pronator loosening, or transferring the flexor carpi ulnaris (FCU) to the elbow extensors. In the second group, there are surgical methods that directly pertain to the release of pronation contracture, which include pronator teres myotomy or lengthening (Fig. 1a), pronator quadratus myotomy (Fig. 1b), transfer of the pronator teres to the elbow extensor, and transferring the FCU tendon to brachioradialis (BR) tendon insertion.

Concerning the treatment of pronation deformity, controversy exists whether to perform pronator loosening alone or loosening combined with active tendon transfer. Elimination of the resistance leading to pronation deformity may help supination. However, it is obvious that generating an active motor working voluntarily –enabling supination– would provide higher supination.

As shown in Table 1, Gschwind and Tonkin[16] defined four types of pronation deformity and recommended treatment methods for each one. In our practice, we use a modified version of this classification and treatment algorithm with inclusion of brachioradialis re-routing technique for type 3 and type 4 cases.

Taking these principles into account, the techniques used in surgical treatment of pronation deformity can be summarized as follows:

Table 1. Pronation deformity classification and treatment options by Gschwind and Tonkin[16]

Type		Treatment
Type 1	Active supination beyond neutral	Surgery is unnecessary
Type 2	Active supination to less than, or to, neutral position	Pronator quadratus loosening, flexor aponeurotic loosening
Type 3	No active supination, free passive supination	Pronator teres transfer (Brachioradialis re-routing)
Type 4	No active supination, tight passive supination	Pronator quadratus and flexor aponeurotic loosening (Pronator teres lengthening/loosening + Brachioradialis re-routing)

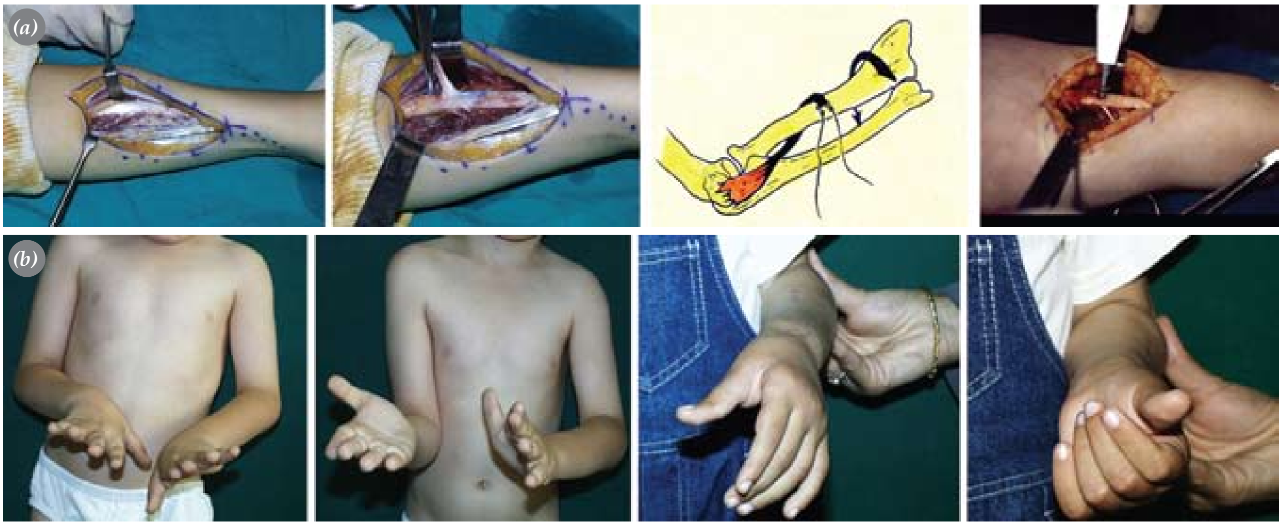

Fig. 2. Pronator teres re-routing. **(a)** Surgical technique: While the forearm is brought to maximum supination, the pronator insertion at the mid-1/3 radius is palpated. Entering through an approximately 3 cm incision made in this area, the pronator teres insertion is found through the brachioradialis and ECRL tendons. The pronator teres tendon is abraded from the radius with a 2-cm periost. At the proximal of the original insertion point, the interosseous membrane is dissected extra-periosteally and the pronator teres tendon is brought through this span at the volar-dorsal direction. At a point close to the original insertion, the tendon is re-inserted to the lateral side of the radius via classical methods or with a suture anchor. Alternatively, with a Z-lengthening on the pronator tendon, the distal tendon piece is taken from the dorsal to volar and sewed to the proximal tendon piece. In the post-operative term, the elbow is kept at 45°-90° flexion with an above-elbow splint, while the forearm is at a supination of 45°-60°. **(b)** Case: A 5-year-old child with cerebral paralysis, who has supination weakness in the left forearm. Preoperative (first 2 pictures on the left) and postoperative (last 2 pictures on the right) views of active supination and protected active pronation.

FCU→ECRB (Extensor carpi radialis brevis) transfer. Defined by Green and generally used as a classical method to increase wrist extension, the FCU tendon is transferred to the ECR tendon. The primary target of this technique is to restore wrist extension. As a secondary benefit, the forearm gains substantial active supination. This additional advantage was documented in biomechanical studies.[17]

Pronator teres re-routing. This procedure was first defined by Sakellarides et al.[18] and its results were then published by Strecker et al.[13] and Gschwind and Tonkin.[16] Van Heest et al.[19] demonstrated mechanically on cadavers how supination improved after swathing the pronator teres around the radius (Fig. 2).

Brachioradialis re-routing. Defined by Özkan et al.,[20] this technique is used to correct the forearm pronation deformity and restore active supination. Here, the forearm gains sufficient active supination by altering the direction of the BR (re-routing) tendon. Since the pronator teres muscle, which is the major pronator muscle of the forearm, is not used as motor, the forearm pronation is not interrupted. In a biomechanical study, Cheema et al.[17] demonstrated brachioradialis re-routing as the second best technique compared to the other methods (Fig. 3).

Transferring the brachialis muscle to the re-routed biceps tendon. This is an alternative technique that can be used to restore forearm supination. It can be performed especially in the absence of a suitable motor tendon. In addition, it is an option when there is a need to decrease excessive flexion at the elbow (Fig. 4).

Other surgical techniques used for the correction of pronation deformity. An active increase in the forearm supination can be expected by combining pronator teres loosening with swathing the FCU around the ulnar side of the forearm and transferring it to the ECBR or BR tendons.[10] By transferring the pronator teres to the ECBR tendon, the pronator dominance in the forearm is eliminated and this force can be conveyed to the weak wrist or finger extensors.[21]

Wrist

Wrist and finger flexion deformities are among the most common problems in patients with spastic paralysis.[22] The flexion deformity of the wrist is caused by the forces exerted by the wrist flexors, in particu-

Fig. 3. Brachioradialis re-routing. **(a)** With an incision on the distal volar-radial side of the forearm, the brachioradialis muscle-tendon unit is exposed. The radial artery and the radial nerve branch are retracted. The brachioradialis muscle and tendon are dissected and prepared for transfer. A very important step at this point is to separate the muscle from all surrounding fascial connections; otherwise, the excursion of the muscle would not suffice. The free end of the tendon released and separated from the distal adhesion point is conveyed beneath the flexor pollicis longus muscle and taken to the volar from dorsal through the interosseous span. After its re-routing extraperiosteally around the radius –while preserving the radial artery– and with the forearm held at neutral, the tension is adjusted to preserve the original length of the tendon and the tendon is re-inserted to the radius via classical methods or with a suture anchor. **(b)** Case: A 12-year-old child with cerebral paralysis, who has supination weakness in the left forearm. Preoperative (first 2 pictures on the left) and postoperative (last 2 pictures on the right) views of active supination and protected active pronation.

lar the flexor carpi ulnaris, with spastic finger flexors worsening the situation.

When the wrist is in flexion, the finger flexors present substantial dysfunction especially during grabbing. Lengthening spastic wrist flexors decreases the flexor dominance in the wrist, thus providing a mechanical advantage for the extensor muscle group. If the wrist extensors are not strong enough to offset this flexor dominance, they may be actively supported by tendon transfers.

Prior to the transfer to strengthen the wrist extensors, the spasticity of the extrinsic finger flexors should be assessed. When the wrist is in neutral position, the mechanical advantage of the spastic finger flexors will increase. The patient cannot loosen the clenched fist, which impedes grabbing. When this is the case, lengthening of the finger flexors must be included in the surgical plan.

If the patient has active extension loss, this should be repaired through a tendon transfer.

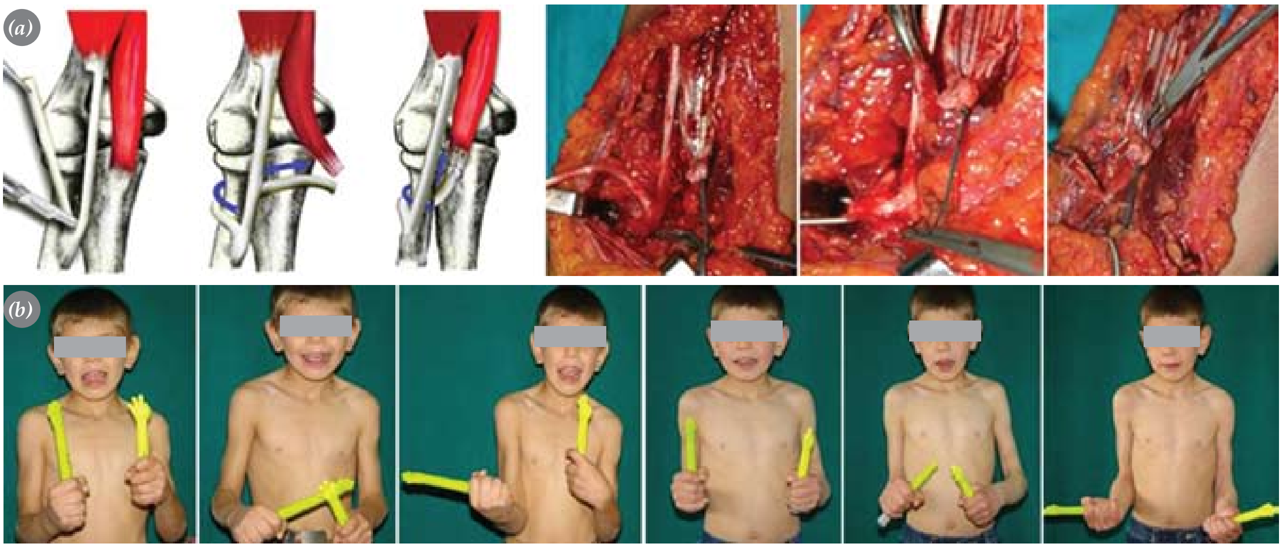

Fig. 4. Transferring the brachialis muscle to the re-routed biceps tendon. **(a)** The brachialis muscle is completely separated from its insertion and released proximally. The biceps tendon is splitted longitudinally while the adhesion point is preserved. The biceps slip on the radial side is re-routed around the radius neck and fixed to the musculo-tendinous segment of the brachialis muscle, prepared beforehand, and supinatorplasty is completed. **(b)** Case: A 10-year-old child with cerebral paralysis, who has supination weakness in the left forearm. Preoperative (first 3 pictures on the left) and postoperative (last 3 pictures on the right) views of active supination and protected active pronation.

Wrist flexion deformity

There are several drawbacks of continuous wrist flexion: *(i)* Flexed wrist creates a mechanical disadvantage for the flexor muscles and reduces the grabbing power. *(ii)* Especially in patients with deficient stereognosis, the coordination of hand movements may be maintained visually. With the flexion posture of the wrist, the fingers remain inward segment of the hand, which impedes visualization. *(iii)* The aesthetic appearance of the wrist in flexion may be bothering for the patient and the family members. *(iv)* In case of severe flexion, there may be skin lesions on the volar side of the wrist.

The wrist plays a key role in hand movements. Even when there is no active movement in the fingers, flexion and extension may be present with the tenodesis effect. A moving wrist provides at least 25% of passive hand function. Therefore, wrist arthrodesis should be performed only in severe deformities, where treatment with dynamic methods falls short. In CP surgery, a mobile wrist is always among the prior targets.

Wrist deformity may develop due to tenseness of flexor tendons, insufficiency of wrist extensors, contracture of the volar capsule of the wrist, or a combination of the mentioned factors.

I. Tenseness and treatment of wrist and finger flexors. Wrist flexion deformity is generally caused by spasticity of the FCU tendon. In some patients, the flexor carpi radialis (FCR) and palmaris longus tendons are also spastic. Tenseness of the finger flexors, if any, prevents full extension of the wrist, contributing to deformity. Before performing a transfer to bring the wrist to extension, factors impeding the passive joint movement span must be eliminated.

The treatment algorithm below may facilitate treatment preferences for restoring passive movement of the wrist:

Lengthening of the wrist flexor tendons. The muscle mostly hindering the passive extension of the wrist is the spastic FCU. The spasticity of this muscle may also cause ulnar deviation of the wrist. In addition, the extensor carpi ulnaris (ECU) muscle in pronation may cause a strong ulnar deviation in the wrist and, in the presence of volar subluxation, it can cause flexion deformity of the wrist. In the latter case, the ECU tendon can be transferred to the ECRB tendon. In moderate cases, only functional or Z plasty lengthening of the FCU tendon may be sufficient. If an active wrist extension is desired, the FCU tendon can be transferred to the wrist extensor tendons. The palmaris longus tendon can be separated from the distal adhesion point and be used for transferring (e.g. to the thumb extensor tendon). Although the flexor carpi radialis tendon can also be used in tendon transfers, only lengthening of the tendon is recommended, because releasing both wrist flexors may lead to hyperextension deformity, which may give rise to complications especially when the finger extension is not sufficient.

Loosening of the finger flexor tendons. All flexor tendon lengthening techniques to some extent result in loss of strength in the flexor tendons. However, this can be compensated by the wrist, strengthening the grabbing in extension. While fractional lengthening creates minimal strength loss, superficialis-to-profundis (STP) tendon transfer procedure may cause severe strength loss, with the effect of Z-lengthening standing between these two.

Bone procedures like proximal row carpectomy and wrist arthrodesis are not preferred in functional hands. These methods may be reserved for rather severe cases on hygiene and cosmetic grounds.

i) Fractional tendon lengthening. This technique has the least negative effect on grabbing power of the fingers and imposes the lowest risk for overlengthening; therefore, it is preferred in well-functioning hands. If only fractional lengthening is to be performed, a longitudinal incision would suffice at the volar 1/3 aspect of the forearm.

Most probably, lengthening would not suffice if the fingers do not reach passive extension when the wrist is in complete flexion. In this case, either one of the other two elongation techniques should be considered (Fig. 5).

ii) Tendon Z-lengthening. This method can be used in cases where fractional lengthening would not be sufficient. It is especially used in flexor pollicis longus (FPL) lengthening. Here, the most important criterion is to elongate the tendon by 0.5 cm for each degree of joint range of motion desired. The tendon is cut at the radial and ulnar sides. After lengthening, the tendon ends are fixed with a Pulvertaft weave or end-side technique. If the lengthening is for the thumb, fixation is performed when the wrist is in the neutral position

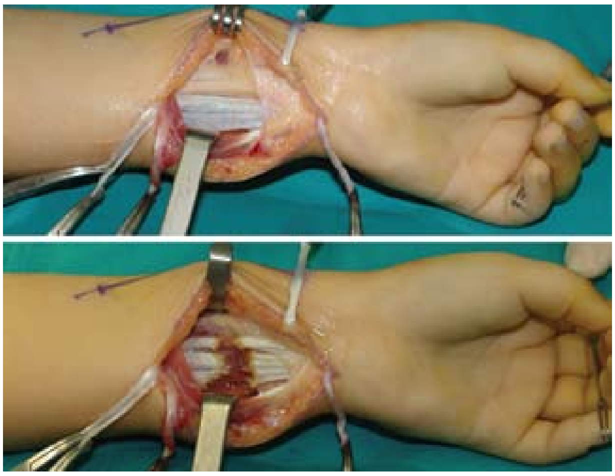

Fig. 5. Fractional tendon lengthening.

and the metacarpophalangeal (MP) and interphalangeal (IP) joints are in slight flexion. When the wrist is in extension, the thumb must be touching the second finger, and the thumb must be apart from the palm with the flexion of the wrist.

iii) Superficialis-to-profundus procedure (STP). As it causes considerable loss in grabbing power, this procedure must be performed in dysfunctional hands with severe flexion contracture (Fig. 6).

Flexor/Pronator slide. The pronator teres can be detached from its origin, the medial epicondyle, and moved distally. This procedure, called the flexor-pronator slide (Fig. 7), is usually performed in patients with CP sequela and central hemiparesis, having severe flexor dominance in the elbow, wrist, and fingers. The procedure may also be include all the flexors rooting from the pronator/flexor common origin at the medial epicondyle level.[23]

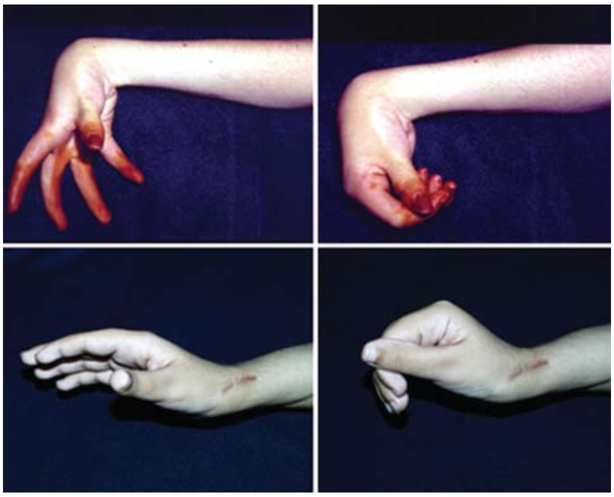

Fig. 6. Superficialis-to-profundus transfer. Preoperative (top) and postoperative (bottom) views.

In addition, proximal row carpectomy can shorten the forearm by approximately 1 cm, providing a passive dorsiflexion increase of 25º in the wrist.

II. Extension insufficiency of the wrist and its treatment. After having eliminated the factors hindering the passive extension of the wrist, active extension of the wrist should be obtained. The surgical classification offered by Zancolli[4] can serve as a reference for the active tendon transfer.

The cases in *group 1* can have full finger extension with a wrist flexion of less than 20º. In this group, usually the FCU muscle is spastic. Lengthening of this muscle solves the problem in most cases.

In *Group 2*, active finger extension can be achieved with a wrist flexion higher than 20º. In subgroup 2A, there is a weak wrist extension when the fingers are

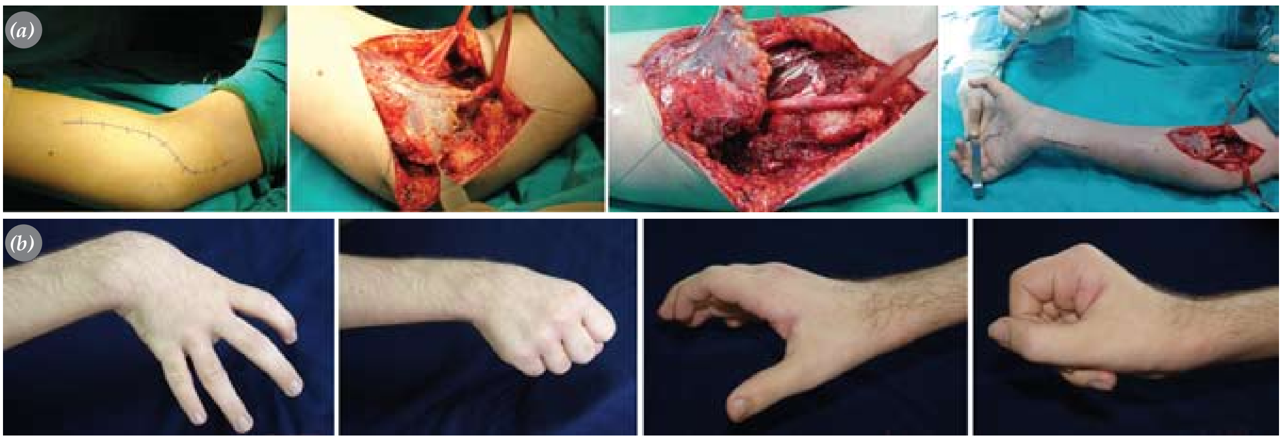

Fig. 7. Flexor/Pronator slide. **(a)** Surgical technique. **(b)** Case: Preoperative (first 2 pictures on the left) and postoperative (last 2 pictures on the right) views of the patient with spasticity in the wrist and fingers.

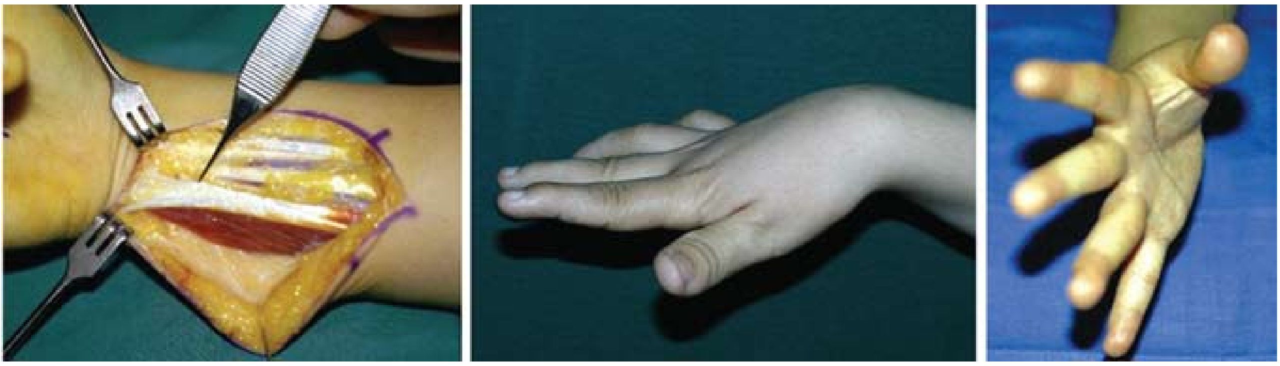

Fig. 8. Green transfer. (Left) Access to the FCU tendon is through an incision on the volar ulnar side of the distal forearm. The FCU tendon is released from the pisiform bone it is attached to. The ECRB and ECRL tendons are exposed with a second incision in the dorsal of the wrist. A subcutaneous tunnel is formed on the ulnar side of the forearm, between the two incisions. The FCU tendon is brought through this tunnel and attached to the transfer tendon with Pulvertaft weaving. The tension is adjusted when the transferred tendon is at maximal tension and the wrist is in neutral-mild dorsiflexion. The wrist should be making a passive flexion of 20°; otherwise, the anastomosis will remain tense.[11] The preoperative (middle) and postoperative (right) views of a case undergoing Green transfer.

in flexion, whereas in subgroup 2B there is no wrist extension at all. The latter group needs supportive transfer procedures to provide wrist extension after flexor loosening.

The transfers mostly used for wrist extension are: FCU→ECRB, ECU→ECRB, PT→ECRB, BR→ECRB, and flexor digitorum superficialis (FDS)→ECRB. If a higher radial deviation of the wrist is desired, these transfers should be made to the extensor carpi radialis longus (ECRL) tendon. The FCU→ECRB transfer performed to maintain wrist extension actively supports the forearm supination, as well.

The cases in *group 3* do not have active finger extension and, in general, have severe involvement. Transfer to the finger extensors (e.g., FCU→Extensor digitorum communis-EDC) should be performed after the release of contractures of the flexor muscles.

Surgical techniques commonly used in the treatment of wrist extension insufficiency

1. Green transfer (Flexor carpi ulnaris tendon to extensor carpi radialis brevis tendon). Technical details of this method are summarized in Figure 8.

2. Transferring extensor carpi ulnaris tendon to extensor carpi radialis brevis tendon. This transfer is performed in cases who have sufficient wrist extension, but their wrists become flexed during fisting due to finger flexors. This transfer must always be performed together with fractional lengthening of the FCU muscle. It cannot be performed simultaneously with transfer of the wrist flexors to wrist extensors; otherwise, extension deformity may develop.[12,24]

3. Transferring pronator teres tendon to extensor carpi radialis brevis tendon. This technique is suitable for patients whose FCU tendon is dysfunctional or used as a motor for another transfer. However, due to the limited excursion of the pronator teres, the wrist movements are reduced. Since the pronator teres is often spastic, this transfer may be beneficial especially in terms of tenodesis. The pronator teres tendon, released from its insertion at mid-1/3 forearm is attached to the ECRB tendon.

4. Transferring brachioradialis tendon to extensor carpi radialis brevis tendon. The brachioradialis tendon can be used for wrist extension when the other motors are not suitable for transfer. However, as stated above, the fascial connections around the muscle must be completely released to provide sufficient excursion of the brachioradialis muscle.

5. Transferring flexor carpi ulnaris to extensor digitorum communis tendons. As explained before, the reason for finger extension and for the difficulty in releasing the hand may either be the contracture of the volar structures or the weakness of the finger extensors. Flexor carpi ulnaris transfer may support the finger extensors. Superficial flexor tendons of the third and fourth fingers can also be used to strengthen the finger extensors.

Technique: Similar to Green transfer, the FCU is exposed with an incision on the volar-ulnar side of the forearm. The FCU tendon is swathed around the ulnar side of the forearm subcutaneously. On the wrist extensor side, the EDC tendons are exposed with an incision of 4-5 cm in the fourth extensor compartment. The FCU tendon is brought through the subcutaneous tunnel and woven side-by-side with Pulvertaft weaving. The tension of the tendons is adjusted accordingly to keep the MP joints in neutral position and the IP joints in mild flexion. The hand is immobilized for four weeks while the wrist is held at 30° extension.[10,24,25]

The treatment algorithm that we follow in the surgical restoration of the problems related to finger and wrist spasticity is summarized in Fig. 9.

Surgical treatment of finger and thumb deformities

"Swan neck" deformity

The presence of hyperextension of the proximal interphalangeal (PIP) joint and flexion deformity of the distal interphalangeal (DIP) joint is known as the "swan neck" deformity. It is caused by the hyperactivity of the intrinsic hand muscles and the tenodesis effect of the EDC tendons when the wrist is in spastic flexion posture. Swan neck deformity is a common problem in CP. Surgical intervention is needed only when the fingers are locked in hyperextension position and there are progressive extension deformities of the PIP joint that cannot be prevented with splinting.[26]

In CP, swan neck deformity is associated with the relatively shorter central slip. This shortness is relative and does not impede the flexion of the PIP joint. Both the spasticity of the intrinsic muscles and the hyperactivity of the extrinsic finger extensors play a role in the pathophysiology of the tenseness on the central slip.[12] The high tension generated by the spasticity of the intrinsic muscles is conveyed to the central slip via medial interosseous bands, leading to hyperextension on the PIP joint. If loosening of the retinacular ligament accompanies the condition, dor-

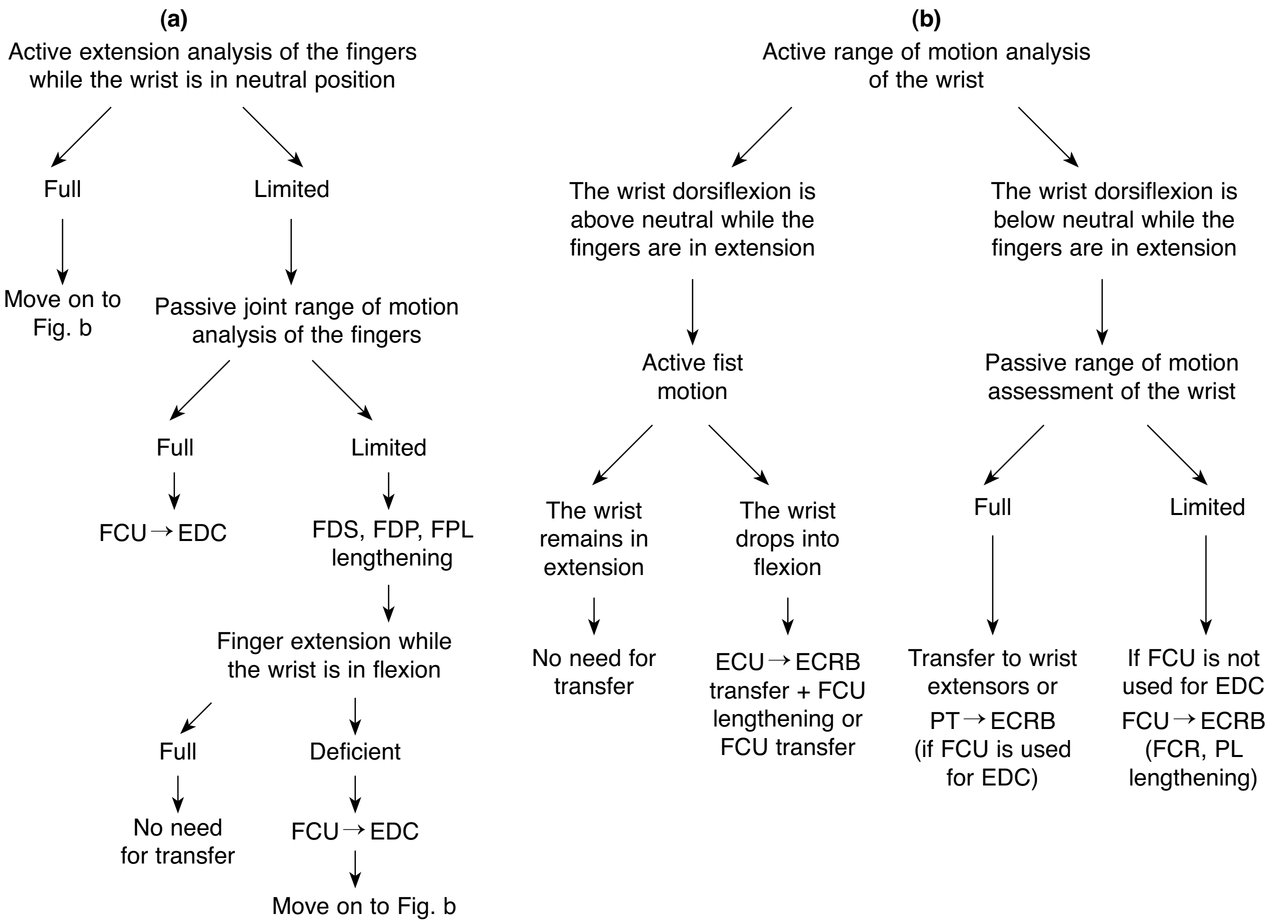

Fig. 9. Assessment and treatment algorithm of wrist and finger extension.

sal subluxation of the extensor mechanism occurs. With simultaneous loosening of the volar plate, the hyperextension of the PIP joint increases and recurvatum deformity ensues. Meanwhile, the dorsal subluxation of the extensor mechanism leads to relative insufficiency of the lateral bands, causing flexion of the DIP joint.

Furthermore, patients with insufficient wrist extensors try to compensate the wrist extension function with the extrinsic finger extensors. Within the frame of the system explained above, the increased load on the central slip augments the severity of the swan neck deformity. In addition, after lengthening operations of the superficialis flexor tendons, the swan neck deformity may become more prominent.

The MP joint flexion observed in swan neck deformity is explained as follows: The wrist and finger joints make up a kinetic chain. The weakest ring of this chain is the PIP joint, followed by the MP joint. The extension of the PIP joint leads to flexion of the proximal and distal joints. Moreover, these forces cause a subluxation of the MP joint in the volar direction. Maintaining flexion of the PIP joint will prevent the deforming effects of these forces, thereby preserving the normal axis of the finger. Based on this rationale, the following treatment methods are recommended for the treatment of swan neck deformity:[10]

1) Decreasing the load on the central slip by cutting the ligaments connecting the intrinsic muscles to the central slip;
2) Keeping the lateral bands on a more volar position by shortening the retinacular ligament;
3) Preventing load exertion on the central slip by attaching the extensor tendon to the proximal phalanx, not to the central slip;
4) Limiting joint hyperextension by placing a tendon graft on the volar side of the PIP joint;
5) Arthrodesis of the PIP joint in flexion;
6) Preventing extension of the joint by using the flexor digitorum sublimis tendon or by performing volar capsulorrhaphy: sublimis tenodesis (Fig. 10);
7) Advancing the interosseous muscles;[11]
8) Ulnar motor neurectomy;
9) Sling procedure;[4]
10) Flexion osteotomy of the metacarpal neck.

Surgical treatment of thumb-in-palm deformity

Thumb-in palm deformity is one of the most common and complicated deformities of CP. It is caused by spasticity of the thumb adductor and flexor muscles. Locked inside the palm, the thumb cannot function and hinders the grabbing function of the other fingers.

Parallel to the evolution of CP surgery, thumb operations have turned to dynamic soft tissue procedures rather than static bone operations. Goldner, Inglis, and Keats, and alike succeeded in forming mobile thumbs by maintaining the muscular balance via tendon transfers and selective joint arthrodeses.[27]

The objectives of the surgical treatment of thumb-in-palm deformity are to generate a strong lateral pinch in the mid-phalanx of the second middle finger during fist formation, and to maintain sufficient radial abduction during grabbing.[28] The major challenge of the treatment is the multifactorial nature of the deformity. For this reason, so as to make a systemic definition of the deformity and propose a treatment plan, House[27] and Sakellarides[29] formulated two different classification systems (Table 2).

The etiology of the thumb deformity is multifactorial. There are four main reasons for this deformity: *(i)* Spasticity of the adductor and flexor muscles, *(ii)* loose paralysis in the extensors and abductors, *(iii)*

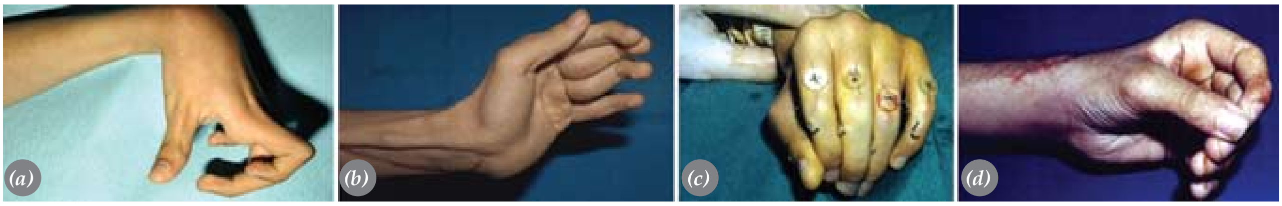

Fig. 10. Correction of swan neck deformity with the sublimis tenodesis technique. **(a)** The preoperative view of the 13-year-old child with severe spasticity in the left hand. **(b)** Swan neck deformity occurring as a result of the overcorrection after loosening and tendon transfer. **(c)** Short-term and **(d)** long-term results after sublimis tenodesis surgery.

Table 3. Surgical classifications of thumb-in-palm deformity: (a) House[27] and (b) Sakellarides[29] classifications

(a)	Deformity	Reason
Type I	Simple metacarpal adduction	Spastic adductor and first dorsal interosseous muscles
Type II	Simple metacarpal adduction+MP flexion deformity	Spastic adductor, first dorsal interosseous, and spastic flexor pollicis brevis muscles
Type III	Simple metacarpal adduction+MP hyperextension deformity/instability	Spastic adductor, first dorsal interosseous, and EPB muscles+ hyperextensible MP joint
Type IV	MP and IP joint flexion deformity+ simple metacarpal adduction contracture	Spastic adductor and first dorsal interosseous+ flexor pollicis longus muscles
(b)	Cause of deformity	Treatment
Type I	Weak EPL	Transferring PL or FCR to EPL
Type II	Spastic or contracted intrinsic muscles of the thumb	Releasing tenar muscles - the 1st dorsal interosseous muscle and the carpal tunnel+releasing the 1st web skin, if contracted
Type III	Weak abductor pollicis longus	Swathing the abductor around the FCR
Type IV	Spastic or contracted FPL	Z-lengthening of FPL

hypermobile MP joint, and *(iv)* contracture of the first web skin.

Assessing each of these conditions in the preoperative term would facilitate the formulation of a surgical plan. The assessment involves physical examination, electromyography, and diagnostic nerve blocks. In general, increased tonus of the muscles and the thumb's position at rest point to the muscles mainly responsible for the deformity. **(a)** In the deformity related to the spasticity of the tenar muscles, there is flexion of the MP joint and extension of the IP joint. **(b)** In the deformity related to the spasticity of the FPL muscle, there is predominating flexion of the IP joint with varying degrees of flexion of the MP joint. **(c)** Involvement of the adductor pollicis muscle leads to flexion of the MP joint and adduction of the first metacarp towards the center of the palm. **(d)** Involvement of the opponens pollicis muscle or the first dorsal interosseous muscles results in adduction of the metacarp in line with the palm, trapping the thumb at the web span.

I. Treatment of adductor and flexor muscle spasticities. Release of the adductor pollicis, first dorsal interosseous, and flexor pollicis brevis muscles can be performed as muscle myotomy at the origin, insertion or between the two.[10] Release at the insertion is not very often preferred since it removes the entire functionality of the muscle. Release at origin, on the other hand, preserves the functionality to a certain extent because of the adhesion of the muscle to the adjacent tissues. During muscle myotomy, the muscle is kept at a tense position and the tendinous part is cut while the muscle fibers are protected.

a) Adductor/flexor release. An incision parallel to the tenar line is made. The dissection is advanced up to the tenar muscles. The flexor pollicis brevis and abductor pollicis brevis are isolated at their beginning point on the transverse carpal ligament and are released from the ligament. Meanwhile, the finger proximal phalanx is brought to extension to facilitate the radial movement of the muscles. With proper splinting in the postoperative term, these muscles are adhered to their new place. If spastic, the adductor muscle is also released during the same session. If the muscle is released from its origin, the flexor tendons of the second and third fingers and neurovascular structures are retracted and stripped off over the third metacarp. If the muscle is released from the insertion point, it is followed along the radial side and cut at the tendinous insertion point. In cases where the adductor muscle is to be released without any intervention to the flexor muscles, access to the adductor muscle is via an incision in the first web.

b) Releasing the dorsal interosseous muscle. An incision is made through the palpable ulnar border of the first metacarp. The radial nerve branches and the extensor pollicis longus (EPL) tendon are retracted. The first dorsal interosseous muscle is a bipinnate muscle, with its origin adhering to the first and second metacarps. Its origin in the first metacarp is released, while the segment in the second metacarp is left untouched. This preserved segment helps the flexion and abduction of the second finger. If the incision is advanced distally to the MP joint, the abductor can also be released through this incision.

c) FPL tendon lengthening. The FPL spasticity which is manifest in type IV deformity is treated with fractional lengthening or Z-lengthening of the FPL tendon in the proximal wrist, just like in the wrist flexors.

II. Supporting the abductor and extensor tendons. Tendon reinforcement procedures include abductor pollicis longus (APL) for the abduction of the first metacarp, extensor pollicis brevis (EPB) for the extension of the proximal phalanx, and EPL for the extension of the distal phalanx. This reinforcement can be performed as tendon plication, tendon transfer, or fixing the tendon on a periosteal bone or another tendon with a proper tension (tenodesis).

1) Tendon transfers. Transfer of the BR, PL, ECLR, ECRB, FCR, FCU, and FDS tendons have been recommended to restore the thumb extension and remove the thumb from inside the palm. The APL tendon is the most important tendon acting on the carpometacarpal joint. By taking the APL tendon out of the first compartment and giving it a volar placement, a mechanical advantage is provided for the abduction of the first metacarp. In addition, sewing the PL tendon (end-side) on the volarly placed APL tendon may increase the abduction.[27] If the extension vector is to be preserved, the same transfer can be performed by protecting the pulley of the first compartment. As an alternative, the APL is cut and its distal end is reinforced with an appropriate motor, while the proximal end is transferred to the EPB tendon (end-side) tensely. This technique provides both metacarp abduction and proximal phalanx extension.

In cases where an appropriate motor muscle cannot be found for transfer, the APL is cut and its distal end is re-routed volarly. Then it is fixed on the FCR tendon (end-side). This may create a tenodesis effect and restore the metacarpal abduction.

Figure 11 shows an a case in which the above-mentioned techniques were combined to reinforce the thumb abductor and extensor tendons.

2) Shortening of the abductor pollicis longus and extensor pollicis brevis tendons via plication

3) Extensor pollicis longus re-routing. The EPL tendon which surrounds the Lister's tubercle has an adductor effect due to its trajectory. Therefore, procedures radializing this route are expected to have a positive effect on abduction. Goldner[24] removed the EPL tendon from its fibro-osseous channel, created a new pulley over the radial styloid, and radialized the route of the tendon. Later, Manske[30] took the EPL tendon through the first dorsal retinacular compartment, eliminating the need for a new pulley. With further modification of the technique, Rayan and Saccone[31] cut the EPL tendon at the proximal of the retinaculum and anastomosed the proximal end of the tendon to the distal end brought through the first dorsal compartment. The authors reported satisfactory abduction.

4) Flexor pollicis longus abductorplasty (Fig. 12). The spastic FPL tendon to be loosened is cut on the proximal phalanx. The distal segment is used for the stabilization of the IP joint in children. The proximal segment is taken through a second incision on the wrist and then radialized through a second subcutaneous tunnel opened radially.

III. Hypermobile MP joint. The stability of the MP joint is crucial for reinforcements made on the EPL or EPB tendons. If the MP joint already has a hyperextension exceeding 20º, these reinforcements would result in excessive hyperextension of the MP joint. In order to avoid this, capsulodesis or arthrodesis of the MP joint should be performed in deformities where the MP joint is hyperextensible. Capulodesis is an attempt to refrain from arthrodesis, especially in children younger than 13 years.[7] Filler et al.[32] obtained satisfactory long-term results by performing capulodesis in 13 patients with CP. According to their technique, the volar plate is cut and fixed proximally on the metacarp while the MP joint is at 30º flexion. In cases in which capulodesis is insufficient, arthrodesis

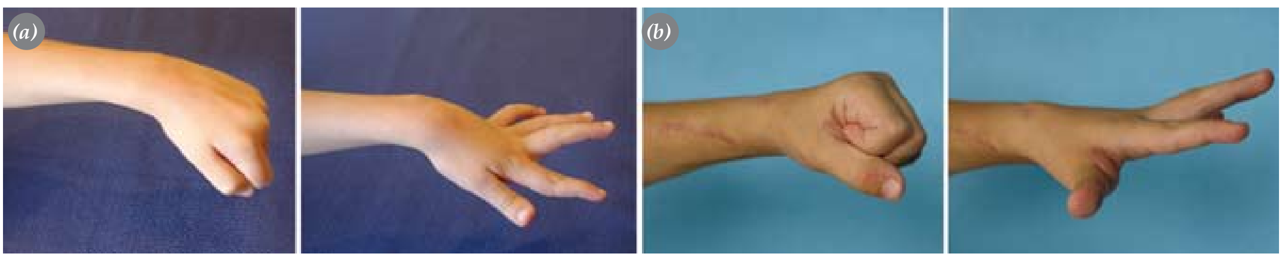

Fig. 11. Reinforcement of the thumb abductor and extensor tendons: **(a)** Preoperative and **(b)** late postoperative appearance of the patient.

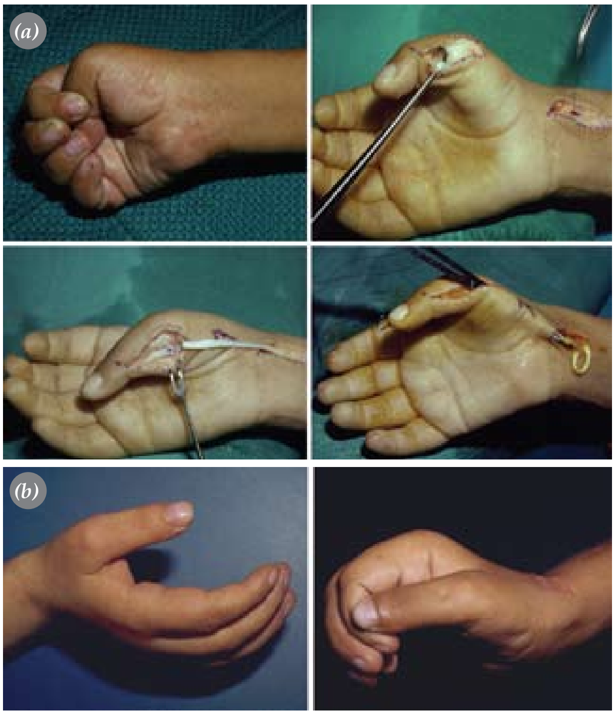

Fig. 12. Correction of the thumb-in-palm deformity with the FPL abductorplasty technique: **(a)** Preoperative appearance and surgical technique. **(b)** Postoperative appearance.

of the MP joint may be considered. During arthrodesis, the growing plate on the epiphysis can be preserved by performing only joint cartilage resection, enabling this operation to be performed in young children (4-5 years old) without growth arrest.[8]

IV. Release of the first web skin. Any contracture of the skin can be released via two- or four-flap Z-plasties.

Conclusion

This paper summarizes surgical restorative procedures, in particular active tendon transfers, involving the hand and upper extremity in CP and briefly explains the functional and cosmetic benefits of these procedures. Obviously, these surgical procedures make up only a minimal part of the treatment, compared to lifelong conservative methods and rehabilitation practices.

The prerequisite of the surgical success is to assess and follow the patients with a well-equipped team that can offer the best treatment options for CP.

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