Review article

Tendon lengthening and transfer

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Abstract
Tendon lengthening and transfer are usually indicated for certain neuromuscular disorders, peripheral or central nerve injury, congenital disorder or direct traumatic or degenerative musculotendinous lesion. In musculotendinous lengthening, technique depends on muscle anatomy, degree of correction required, and the need to avoid excessive loss of force. Lengthening within the muscle or aponeurosis is stable. In the tendon, however, it may provide greater gain but is not stable and requires postoperative immobilization to avoid excessive lengthening. Tendon transfer consists in displacing a muscle’s tendon insertion in order to restore function. The muscle to be transferred is chosen according to strength, architecture and course, contraction timing, intended direction, synergy and the joint moment arm to be restored. Functions to be restored have to be prioritized, and alternatives to transfer should be identified. The principles of tendon transfer require preoperative assessment of the quality of the tissue through which the transfer is to pass and of the suppleness of the joints concerned. During the procedure, transfer tension should be optimized and the neurovascular bundle should be protected. The method of fixation, whether tendon-to-bone or tendon-to-tendon suture, should be planned according to local conditions and the surgeon’s experience.

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1. Introduction
Tendon lengthening and transfer made a considerable contribution to the treatment of neuromuscular conditions, and poliomyelitis in particular. The techniques have become less widely known, but are still employed in a variety of indications. The present article will deal successively with lengthening and with transfer, setting out the guiding principles and presenting a few of the many techniques.

2. Tendon lengthening
2.1. General considerations

Tenotomy is defined as surgical sectioning of a tendon. It can be used to treat contracture or harmful muscle action, but impairs force and joint moment arm [1]. Musculotendinous lengthening serves to restore a more physiological course while conserving function.

Both are usually indicated for musculotendinous retraction complicating a neuromuscular condition, whether congenital (such as club-foot) or degenerative traumatic. Several techniques have been described and differ both technically and in the anatomic level of the musculotendinous unit involved. The technique is chosen according to various criteria: location, muscle anatomy (tendon and muscle body length, aponeurosis), degree of correction required and avoidance of excessive loss of force. Lengthening within the aponeurosis or muscle is stable, with or without postoperative immobilization, whereas pure tendon lengthening requires immobilization to avoid excessive lengthening or recurrence of contracture. Certain studies have, however, shown that over-correction may be due not only to the lengthening technique but also to certain biomechanical consequences of lengthening as such [2].

2.2. Percutaneous techniques

Percutaneous techniques have several advantages: less scarring, possible out-patient treatment, and low rates of complication. They can, however, only be used on superficial tendons, as sectioning is performed blindly.

2.2.1. Total tenotomy

Total tenotomy in the lower limbs should be indicated only with caution in patients able to walk. The tendon is palpated and gripped between thumb and forefinger. A minimal incision is made on one
edge; the tendon may then be held with forceps and pulled out through the incision. Complete sectioning is performed using a cold blade. The main indication is Achilles tenotomy for varus equinus club-foot on the Ponseti method. Healing is in 6 steps, with a normal tendon structure aspect on ultrasound achieved by 6 months [3]. The adductor longus and gracilis can also be lengthened in this way. Tenotomy of the long part of the brachial biceps in rotator cuff tendinopathy may be performed arthroscopically, allowing resection of the intra-articular part.

2.2.2. Alternating and sliding hemi-tenotomy

Lengthening is achieved by sliding within the sheath in the full tendon body. This technique is especially indicated for the Achilles tendon (Figs. 1 and 2). The length of the tendon is palpated and 2 or 3 small incisions are made, using a cold blade, at various levels, medially and laterally, along the edges of the tendon. The knife needs careful handling, as hemisectioning is performed blindly. A No. 11 blade is recommended, with a blunted proximal part to avoid accidental skin lesions or excessive tendon sectioning. At each level, the blade is introduced into the middle of the tendon parallel to the long axis, then turned 90° to enable hemisectioning forward and backward. In the Achilles tendon, low internal transverse hemisectioning is performed just above the calcaneal insertion, followed by high external transverse hemisectioning. A third hemisection can be performed in the same direction as the first, at a higher level. A forced joint movement along the stretching plane of the muscle enables lengthening by sliding of the tendon fibers. If sliding is not achieved, the procedure has to be carefully repeated until sectioning is complete. Closure is by simple skin suture, followed by 6 weeks’ cast immobilization.

2.3. Open surgery techniques

Open surgery techniques may be presented according to anatomic level. The more distal the lengthening, the greater the gain, but at the cost of instability, as demonstrated on biomechanical tests [4].

2.3.1. Proximal release

The proximal insertion of the muscle or muscle group is exposed between two Farabeuf retractors and sectioned by cold blade at the aponeurotic fascia. The technique is used for hamstring and gastrocnemius tendons (Silverskiöld procedure), sometimes associated to partial neurotomy [5]. In the upper limbs, the Pagé-Scaglietti-Gosset procedure consists in releasing all of the flexor/pronator muscles of the medial epicondyle (Fig. 3). In sequelae of obstetric paralysis of the brachial plexus, the subcapsularis muscle may also be released from the scapula in case of retraction in internal rotation of the glenoid joint.

2.3.2. Intramuscular lengthening

In intramuscular lengthening, the musculotendinous junction should be sectioned several centimeters above the end of the last muscle fibers, to avoid any muscle tear on stretching [6]. Several options are available, depending on muscle anatomy and the required gain.

2.3.2.1. Transverse sectioning of the musculotendinous junction. The aponeurotic sheath at the origin of the tendon is exposed then sectioned transversally. This procedure can be applied in certain thigh muscles (gracilis and semitendinosus) and in the flexor muscles of the wrist or digits in case of spastic retraction (Fig. 4). The technique may be high or low and at 1 or 2 levels; a cadaver study of the tibialis posterior muscle showed that correction is greater in low tenotomy, but with a greater risk of tear [7].
2.3.2.2. Gastrocnemius tendons. The Vulpius technique consists in chevron sectioning of the terminal gastrocnemius aponeurotic sheath at 2 levels, then sectioning the medial raphe of the soleus from the back forward (Fig. 5). This chevron technique can also be used for the semimembranosus muscle, which anatomically associates a large muscle body and a short tendon. Another gastrocnemius lengthening technique consists in simple transverse sectioning of the terminal aponeurotic sheath (Strayer’s technique).

2.3.3. Distal tendinous lengthening
2.3.3.1. Z-plasty lengthening. This technique has been described for the Achilles tendon. The tendon is exposed over a sufficient length (6 to 7 cm for the calcaneal tendon). A vertical incision is performed using a cold blade in the middle of the tendon, taking care to protect elements lying forward. The incision is continued over a sufficient length, then the blade is turned 90° laterally to section the half tendon. The contralateral half is then sectioned at the opposite end of the lengthening (Fig. 6). An extension movement is imposed to lengthen the tendon, and the two free edges are sutured edge-to-edge. It is essential to adjust tension in this technique. Potential lengthening is considerable, with a risk of over-correction leading to muscle insufficiency [8]: for example, the maximal isometric moment of the soleus muscle in mid-stance is reduced by 30% with 1 cm lengthening of the tendon and by 85% with 2 cm lengthening [1].

2.3.3.2. Lengthening by doubling. The more rarely used calcaneal tendon is the main target for lengthening by doubling. Transfixion by the blade, held flat, divides the tendon in two in the frontal plane. The blade is turned 90° above so as to exit the back, and likewise below so as to exit forward. A movement of forced flexion in the stretching plane of the tendon is imposed, breaking the part of the sheath that continues to resist. If the doubling is sufficiently extensive, the two slices of tendon can be superimposed for 1 to 2 cm, holding the corrected segment in the correction position. The two slices are then joined together with several sutures.

2.3.3.3. Baker’s aponeurotomy. The whole width of the tendon is exposed over a sufficient length, and then schematically divided in three widths, with a U-shaped incision using a cold blade (Fig. 7). Lengthening is achieved by stretching the joint of the muscle. Tension is adjusted and the tendon edges are fixed with several sutures. This technique can be applied for the Achilles tendon.

3. Tendon transfer

Tendon transfer is a major advance in orthopedic repair surgery: fields of application and technique continue to develop. The present section will not seek to list all possible tendon transfers, but rather to sum up the main rules of the technique, from preoperative planning to expected results, illustrating certain technical aspects in a given tendon transfer.

3.1. General considerations

Tendon transfer is defined as the release of the terminal (or sometimes proximal) tendon insertion from one muscle-tendon unit, with reinsertion onto the bone or suture to a different tendon, to
restore lost or deficient muscle action. It is usually indicated in peripheral or central neural lesion or in direct traumatic or degenerative lesion of the muscle-tendon unit.

The term “tendon transplant” refers to resection of a tendon for use as a free graft. “Muscle transplant” refers to detaching the origin and termination of a muscle to transfer the entire muscle–tendon unit to a receiver site, with the pedicle intact (e.g., latissimus dorsi transfer to restore elbow flexion) or sutured microsurgically to the receiver site (e.g., free gracilis muscle transfer). Tendon and muscle transplants will not be dealt with here.

Carl Nicoladoni, an Austrian surgeon practicing orthopedic and reparative surgery in Vienna, in 1881 described the first tendon transfer of the fibular muscle to the Achilles tendon for posterior pes cavus following poliomyelitis, an illness that was endemic in Europe in the late 19th century. In 1899, Codivilla, a surgeon in the Rizzoli Institute in Bologna, Italy, reported one of the first series, with 30 tendon transfers. He described the principle of agonist/antagonist balance and stressed the need for prior assessment of force in the muscle to be transferred. The main principles of tendon transfer surgery were established in the first half of the 20th century by pioneers such as Mayer, Almqvist, Starr, Steindler and Bunnel [9,10], contributing to our understanding of muscle physiology and biomechanics.

Indications continue to develop, now including degenerative tendon tear and rheumatoid polyarthritis, brachial plexus palsy and congenital deformity.

3.2. Principles of tendon transfer: prerequisites

The principles of tendon transfer can be summed up in 10 points [11]:

- choice of transfer:
  - the transferred muscle must have sufficient force for its new function. Selection needs to be rigorous, with precise analytic assessment on the international 0–5 muscle scoring system: 0 = no voluntary contraction; 1 = weak contraction (visible or palpable) without perceptible movement; 2 = movement possible if gravitational effects are eliminated; 3 = movement against the weight of the segment possible; 4 = possible to overcome resistance greater than weight, but with impaired force; 5 = normal muscle force. Muscles usually lose 1 point of force with transfer [12], so that only muscles scoring 4 or 5 are suitable. In children, force is hard to assess before the age of 6 years, which may require delaying tendon transfer,
  - one muscle–tendon unit per function: a transferred muscle with two tendons cannot fulfill two different functions. It is usually the tendon with the greatest tension that is active; e.g., when a tibialis anterior hemi-tendon is transferred outward to restore eversion, the hemi-tendon with the greatest tension ensures the movement,
  - synergy: it is preferable to transfer a muscle with a contraction sequence in phase with the muscle to be repaired [13]. This may involve dynamic preoperative electromyography. For example, the wrist flexors and digit extensors have synergic action, which some authors claim facilitates rehabilitation after transfer. However, experience shows that it is possible to integrate function with a non-synergic muscle [14], as in extensor indicis proprius transfer to the opponens pollicis. Integration is easier in children, due to their greater cerebral plasticity;
  - the excursion of the transferred muscle must be close to that of the muscle to be replaced. As muscle fiber length affects tendon course, transfer choice should take account of the literature data regarding the ratio between muscle fiber length and muscle length [15]. The course of the transferred tendon can be altered by extensive release of the muscle body from the surrounding fascia attachments. Transfer efficacy can also be improved, even when the course is less than that of the muscle to be repaired, by a tenodesis effect: for example, the wrist flexors have shorter muscle fibers than the digit extensors; flexor carpi ulnaris transfer to the extensor digitorum will show greater efficacy in wrist flexion [16];
  - the functional loss incurred by transfer is to be weighed against the expected gain. If, for example, one of the wrist flexors is transferred to the extensors, it is important that the other wrist flexor should be functional;
  - functional motion needs to be restored in the joints around which the transferred muscle is to act. For example, tibialis posterior muscle transfer to restore ankle dorsiflexion should not be performed in case of fixed equinus; intensive rehabilitation is needed with postural casts to achieve sufficient passive dorsiflexion. In case of persistent retraction, surgical release may be required. The best treatment is, of course, prevention by intensive rehabilitation to maintain joint suppleness as soon as palsy begins to set in;
  - a tunnel should be created with enough space to pass the transferred tendon. The paratendon and synovial sheath should be spared as well as possible during dissection. Certain authors prefer to pass the tendon under the deep fascia rather than subcutaneously, to avoid adherence [17]. The intermuscular septa should be widely resected to create sufficient space to pass from one compartment to another, if necessary. A blunt instrument of adequate size (e.g., Kelly forceps) should be used to create the subcutaneous passage, so as to avoid large incisions that might lead to adherence. During release, skin vascularization by the perforating arteries should be respected, to limit the risk of hematoma. In case of scar tissue adjacent to the transfer passage, a preliminary step of resurfacing by free flap may be required; a tendon spacer may be positioned under the flap to conserve the space and create a neo-sheath for the passage of the tendon;
  - the muscle’s neurovascular pedicle should be protected throughout surgery. Before fixing the tendon, it is necessary to check that there is not too great a traction on the pedicle or torsion or pressure from an anatomic obstacle liable to induce compression;
  - the new muscle direction between the origin and the new insertion should be as direct as possible. This often requires optimal
muscle release to alter the direction. For example, flexor carpi ulnaris transfer to the extensor digitorum for radial palsy requires muscle body release to change the direction (Fig. 8). When direction is changed, the tendon should pass around an anatomic pulley, as for example when transferring the 4th flexor digitorum superficialis around the pisiform bone to improve thumb opposition [10]:

- receiver site fixation can be onto bone or tendon, with adequate tension. Tension adjustment is the main difficulty, and is more a matter of operator experience than of established rules. In indications for peripheral palsy, the tendon, once fixed, needs to maintain the limb segment in an optimal position during surgery. In cerebral palsy, lack of motor control in the transferred muscle may induce an inverse deformation if tension is excessive. In lower limbs, the powerful transferred muscle preferably requires bone fixation to resist forces engendered by the stance phase of gait. In upper limbs, fixation is usually onto another tendon. Whatever the fixation, the distal part of the transferred tendon should be freshened by resecting the peritendon, to promote healing:

- the position of postoperative immobilization (usually by cast) should place the transferred muscle in rest position. For example, tibialis posterior muscle transfer to the back of the foot should be immobilized in 10–20° ankle dorsiflexion [18]. Immobilization time is usually 6 weeks;

- the principles of postoperative rehabilitation must be strictly adhered to. For young children, it should focus on the playful aspects of motricity.

3.3. Biomechanical considerations

The factors bearing on active joint motion are the following: the course of the muscle–tendon unit, the force generated by the muscle, and the joint moment arm. As seen above, the choice of transfer and harvesting technique may affect the first two. The choice of fixation area with respect to the center of joint rotation can enhance force (Fig. 9A and B). A force F acting at a distance d from a given point exerts a moment M on the point, calculated as $M = F \times d$. The greater the distance from the point of application of the force, the greater the moment arm. For example, latissimus dorsi transfer to restore elbow flexion will be more effective if fixed to the ulnar crest (further from the center of elbow joint rotation) than to the biceps tendon.

3.4. Tendon–bone fixation techniques

Several authors recommend bone fixation for powerful muscles needing to resist stance phase force [19]. At the donor site, harvesting the tendon insertion should include the adjacent periosteum and, if possible, cortical chips. At the receiver site, the periosteum should be incised and carefully detached around the fixation point. This is easier in younger patients. After tendon fixation, the periosteum is sutured as well as possible, preferably onto the edges of the tendon.

The suture, which is generally non-resorbable, must be solid. Stitches with at least 3 loops are made on either side of the tendon (Fig. 10A–G). This is particularly resistant to detachment, as shown in several biomechanical studies [20] and suits basically flat structures: joint capsule, patellar ligament, etc. Judet suture is also possible, on the same principle, with the stitch changing plane by 90° at each passage.

3.4.1. Traditional fixation

Several types of bone fixation have been described [19]:

- tendon apposition in contact with the bone fixation point. This requires freshening the bone surface. Distally, a transverse bone tunnel is created, through which the sutures are passed and fixed to the bone surface (Fig. 11);

- intra-osseous tendon fixation:
  - powerful muscles require large and solid intra-osseous fixation. A cortical window is performed down into the cancellous bone. Two tunnels, exiting distally, are drilled through the cortical bone (Fig. 12); the sutures are passed through them, and traction pulls the tendon into the medullary canal. The sutures may either be tied directly onto the cortex or fixed by staple or screw;
  - a transplant can also be passed through the bone (Fig. 13). This is possible at certain locations such as the tarsus, calcaneus or phalanges [21]. The suture is passed in the tendon to be transferred and a bone tunnel is drilled. Two suture strands are placed in a long straight needle or suture passer, passed through the tunnel and picked up on the other side through the skin. Traction pulls the tendon into the tunnel, allowing solid fixation and precise tension adjustment. If the tendon is

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long enough, it can be sutured onto itself; if it is flat, it can be tubularized by continuous suture,

- for large-volume muscles such as the psoas or hip abductors, the tendon is harvested with its bone insertion, which is then fixed to the receiver site after freshening by screw, staple, K-wire or cerclage fixation.

3.4.2. Anchor fixation

Whether by apposition onto the cortex or by intra-osseous fixation, anchors greatly facilitate bone fixation of tendons and ligaments. They are especially useful in deep approaches, as in the shoulder, where arthroscopic surgery has led to the development of various anchorages. There are several models and sizes: umbrella anchors, screw or impaction anchors, resorbable anchors, anchors not requiring knotting, etc. Optimal indications, nevertheless,
concern post-traumatic tendon or capsule-ligament repair (rotator cuff instability or tear) rather than tendon transfer, where anchorage can reinforce traditional fixation.

3.5. Tendon-tendon fixation techniques

There are many tendon-tendon suture techniques, but the reference remains the “weave” described by Pulvertaft [22] in 1956. It consists in joining tendons of differing diameters, the more slender passing through two or three slots cut into the thicker one (Fig. 14). Initially used for proximal fixation of tendon grafts in flexor tendon lesion, the technique was then widely extended to tendon transfer, showing better mechanical resistance than other tendon suture techniques [23,24]. It moreover allows precise adjustment of transfer tension. However, several authors have highlighted drawbacks: risk of wide separation of the fibers of the thicker tendon, and difficult tension adjustment in end-to-edge suture; if the two tendons are of similar diameter, volume may create difficulties, especially in superficial locations, hindering suture sliding.

More recently, in vitro biomechanical studies have offered alternatives to the Pulvertaft weave: chevron remodeling of the end of the tendon to be sutured, to limit suture volume [25], lasso technique [26], a modification of Pulvertaft, tendon enveloping (Fig. 15), or spiral suture (Fig. 16) [27]. These have several advantages, being simple to perform, with the same biomechanical traction resistance as Pulvertaft weave with lower volume.

3.6. Example of transfer: tibialis posterior muscle transfer for foot elevator palsy

Common peroneal nerve palsy is most frequent in the lower limbs [28], inducing eversion paralysis and step gait. When paralysis is definitive, the reference attitude is tendon transfer to restore ankle dorsiflexion [29] and foot supination and to correct toe drop.

Several techniques to achieve these ends have been described, and should be adapted on a case-by-case basis, especially according to severity of paralysis and fibular muscle involvement. Most reports use the tibialis posterior muscle with trans-membrane transfer to restore ankle dorsiflexion [18,29,30]. A second transfer can be associated, using the flexor digitorum longus, also by trans-membrane transfer with end-to-edge suture onto the extensor digitorum longus and extensor hallucis longus [28].

Technically, four incisions are needed for trans-membrane transfer of the tibialis posterior muscle. The first is on the medial side of the navicular. The plantar expansions of the tibialis posterior are sectioned and the tendon is harvested with the adjacent peristeum. A second incision is made in the distal third of the limb just behind the posteromedial edge of the tibia, to pick up the tendon and release the muscle body after opening the deep aponeurosis. A third, anterior, incision is made just above the tibiofibular angle; retracting the extensor digitorum longus exposes the interosseous membrane, which is widely resected. The tendon is picked up from this approach, using a blunt instrument such as Kelly forceps. A fourth incision is made on the back of the foot adjacent to the transfer fixation site. The transfer can then be passed through the retinaculum of the extensors or else subcutaneously.

3.6.1. Tendon-tendon fixation

Bone fixation of the posterior tibial tendon may be hindered by insufficient tendon length, inducing a tenodesis effect more than an active transfer. To get round this, certain authors have described tendon-tendon fixation of various sorts: division of the
4. Conclusion

Before deciding on tendon transfer, alternatives less costly in terms of function should be considered. Neural repair, if possible, should be preferred as first-line attitude. Tenodesis or arthrodesis should also be considered. If transfer is finally indicated, strict respect of the rules usually allows preoperative goals to be achieved.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

Tendon lengthening


Tendon transfer

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