Functioning free muscle transplantation for restoring upper extremity function

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ABSTRACT

Functioning free muscle transplantation (FFMT) is now an important procedure in several fields of reconstructive surgery. In this article, the progress of FFMT in restoring upper extremity function, including essential aspects like indications, preoperative examination, donor muscle selection, donor nerve selection, operative technique, tension of muscle at suturing, postoperative functional assessment, and changes of the transferred muscle after operation are discussed in detail.

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Functioning free muscle transplantation (FFMT) involves the transfer of a skeletal muscle from one site to another with complete separation from the donor site. Circulation is maintained by microvascular anastomosis of the artery and vein of the muscle to suitable vessels in the recipient site. Reinnervation and active muscle contraction are produced by suturing an undamaged motor nerve in the recipient site to the motor nerve of the transplanted muscle. Reinnervation distinguishes this procedure from muscle transplantation carried out solely to provide soft tissue coverage and bulk. In 1970, Tamai et al[1] reported successful muscle transplantation by microneurovascular techniques in dogs. In 1978, Terzis et al[2] provided the first functional assessment of muscle transplantation in laboratory animals. Clinical experience began in 1973 when surgeons of the Shanghai Sixth People's Hospital[3] carried out the first successful transplantation of a portion of the ipsilateral pectoralis major muscle to restore finger flexion after Volkmann's contracture. In the same year, Axer et al,[4] transplanted the latissimus dorsi to restore elbow and finger flexion. Subsequently, many successful clinical cases were reported, and now FFMT has become an important technique for restoring the function of the lost muscle.

Indications for FFMT. Major muscle function loss may be primarily due to chronic nerve palsy, such as brachial plexus injury,[5] high levels of median, ulnar, or radial nerve injury,[6] ischemic injury (such as Volkmann's palsy),[7] or trauma itself such as traction avulsion amputation,[8] or malignant limb tumor resection.[9] Various functional muscle compartments can be involved, such as the elbow flexors (biceps and brachialis), and elbow extensors (triceps), forearm flexors, or extensor compartments. Lin et al[10] pointed out that the indications for FFMT for severe traumatic major muscle loss in the upper extremity include 1. complete loss of arm flexors (biceps and brachialis) with disruption of musculocutaneous nerve; 2. complete loss of forearm flexors or extensors with disruption of the innervating nerves, and where no local muscle or tendon is available for transfer. Functioning free muscle transplantation has become an available or perhaps the last reconstructive option for such difficult cases. It provides motor function, wound coverage, infection control, and limb contour.

Clinical examination. All structures involved in the transplant must be carefully evaluated. If the vasculature of the upper extremity is not established clearly, a preoperative arteriogram is required to select a suitable artery for either end-to-side or end-to-end anastomosis. Adequate veins may be found as either venae comitantes or superficial forearm veins. The history and physical examination should indicate which motor nerve branches are likely to be presented, usually an electromyogram examination is needed. In some cases, preliminary exploration is carried out to establish the status of the motor nerve. The presence and location of tendons can usually be determined from the physical examination. Good skin flap coverage must be available over the distal half of the forearm to allow tendon gliding at the junction between the muscle and the flexor tendons. Application of a skin flap may be required before the transplant or the muscle may be taken as a myocutaneous flap.

Muscles for FFMT to restore the function of upper extremity. The most suitable donor muscle is selected on the basis of its ability to fit the defect and to match the available nerve and tendons in the arm. The donor muscle for reconstruction of the upper extremity is selected according to its length in patients suffering from brachial plexus or trauma and according to its volume and the size of the overlying skin flap following tumor resection.Kobayashi et al[11] described the 4 preoperative conditions that must be met when selecting the donor muscle: 1. the involved joint must be supple, 2. the proximal and distal joints must be stable with balanced muscles, 3. the size, strength, and excursion of the transferred muscle must be comparable with the muscles to be replaced, and 4. appropriate arteries, veins, and motor nerves must be available at the recipient site. In the past, gracilis, latissimus dorsi muscle, pectoralis major, and rectus femoris were all used as donor muscles to restore the function of the upper extremity. But now, it is recommended that gracilis is the first choice as a donor muscle for reconstruction of the forearm, then the latissimus dorsi. For the arm, both the gracilis and latissimus dorsi are suitable.

Operative technique. The operative technique applied to the forearm is different for different people in different circumstances, but the principles are the same for functioning free muscle transplantation.

1. Preparation of the recipient site. The forearm incision should adequately expose all structures and create a suitable skin flap for coverage of the distal portion of the muscle and muscle tendon junction. If a myocutaneous flap is desired, its design should be incorporated into the incision. Frequently, a split-thickness skin graft over the proximal portion of the muscle will provide adequate muscle coverage and retain sensation in the skin.[12] For trauma patients, the necrotic tissue, including skin, muscle, and bone, should be treated with a wide debridement until clean and fresh tissue is seen, thus providing a healthy bed for the anastomosed nerve.[13] Vessels, nerves, and tendons are prepared for transplantation by meticulous dissection under tourniquet control. If an end-to-end anastomosis is planned, the artery should be divided, and the force of the blood spurt evaluated. If it is not normal, a more proximal site on the artery must be attempted or another artery is selected. To make direct coaptation between the selected recipient motor nerve and the motor nerve of the transferred muscle, the need for a vein graft to elongate the recipient artery or vein for vessel anastomoses or an arterial end-to-side anastomoses is often encountered. In selecting the recipient vessel, the first choice for biceps replacement in the arm is the lateral thoracic vessel or the thoracodorsal vessel (artery and vein). In the forearm, a branch of the ulnar artery at the elbow (anterior or posterior interosseous artery, or anterior or posterior ulnar recurrent artery) and nearby vein is chosen for flexor digitorum profundus (FDP) replacement. The radial artery and nearby vein is the first choice when using an FFMT for extensor digitorum comunis (EDC) replacement. Nerves should be divided under the microscope, and the funicular pattern noted. Intraneural fibrosis requires the removal of additional nerve slices until the undamaged nerve is identified. Intraoperative measurement of choline acetyltransferase activity is used for evaluation of the functional status of donor nerves during functioning free muscle transfer[14] when selecting the recipient motor nerve. The first choice in the arm for biceps replacement is the proximal stump of the musculocutaneous nerve, followed by the intercostals nerve, then the spinal accessory nerve.[15] In the forearm, the anterior interosseous nerve is the first choice for FDP replacement, or the posterior interosseous nerve for EDC replacement. When a discrepancy between nerve diameters is encountered, usually, the recipient motor nerve is bigger than the motor nerve of the transferred muscle. In that case, half of the recipient motor nerve may coapt to the motor nerve of the transferred muscle and the other half may be embedded in the transferred muscle directly or indirectly via nerve graft elongation. The medial epicondyle and fascia of the common flexor origin are exposed and prepared for fixation of the muscle's origin. The FDP tendons and flexor pollicis longus (FPL) must be exposed in the proximal wrist. Their gliding ability must be assessed by applying traction on their ends to determine if tenolysis will be required as a secondary procedure.

2. Preparation of the muscle. The muscle to be transplanted must be dissected carefully under tourniquet control. The neurovascular bundle entering the muscle should first be divided and presented. Multiple side branches on the vascular bundle need to be ligated. After the tendon of one side is circumferentially freed and transverse incised, mobilization of the muscle proceeds to the other side, ligating the minor vascular pedicle as they are encountered. Once the muscle remains attached by only a single pedicle, its color, contractility and bleeding should be observed to confirm muscle viability. The recent explosion of endoscopic techniques in plastic surgery has led to the successful harvest of a number of useful muscle flaps. The gracilis,[16,17] latissimus dorsi,[18,19] and rectus femoris[20] can all be harvested safely and reproducibly using endoscopic techniques. Cho et al[18] reported the largest latissimus dorsi muscle with the use of endoscopic technique was 15 x 25 cm in size, and compared with the conventional open procedure, there was no significant time increase. Spiegel et al[17] performed successful endoscopic harvest of gracilis muscle for free tissue transfer, then they pointed out that the primary benefit was a substantial reduction in the incision length from the average 32 cm in open procedure to 7 cm. Compared with traditional techniques, the endoscopic technique decreased pain and morbidity for the patient, resulting in a quicker recovery and aesthetic effect.[20] The principles of endoscopic muscle harvest include an incision long enough to remove the muscle; placed in at least conspicuous area that is within the reach of the instrumentation; retraction to optimize the optical cavity or visual working area; and use of video monitors to allow for coordinated assistance.

3) Muscle transplantation. Once removed from the donor site, the muscle should be positioned in the forearm so that the motor nerve is as close to the neuromuscular junction as possible. This will minimize reinnervation time. (i) Revascularization: Technically perfect anastomoses are important, as revision of thrombosed anastomoses is particularly undesirable in this procedure. Although a single artery is suitable in all gracilis transplants, it may be necessary to anastomose 2 veins if the venae comitantes are smaller than the artery of the muscle. Immediately after completion of the anastomoses, the muscle should become bright red and should bleed from the perimysium. The distal few centimeters of the muscle may take a few minutes to develop this color change. (ii) Reinnervation: The nerve repair should be carried out as close as possible to the neuromuscular junction, usually within 2 cm. Since the motor nerve contains considerable fatty connective tissue, it is necessary to separate the individual fascicles from their connective tissue and do a fascicular repair with interrupted 11-0 nylon suture. (iii) Tendon adjustment: Tendon fixation is accomplished by weaving the tendon into the grafted muscle or tendon. The tension at which they are sewn must be evaluated carefully to provide good muscle balance and optimal strength. For biceps replacement, the first choice of site for fixation of the proximal end of the transferred muscle is the coracoid process of the scapula, followed by the clavicle bone or the second rib. For distal end fixation, the distal tendon of the transferred muscle is preferred over the radius or ulna. For FDP replacement in the forearm, the medial epicondyle of the humerus and 4 conjoined tendons of the FDP are the choices for muscle fixation. To produce a balanced grip, the 4 profundus tendons of the FDP should be cut at the musculotendinous junction and sutured together as a conjoined tendon, which then is sutured to the transferred muscle by interweaving, so that the fingers can flex in unison. The position of the wrist while performing tension adjustment depends upon how powerful the wrist extension is. If the wrist extension is normally powerful, without injury, the wrist is kept in full extension and the fingers in flexion when making the tension adjustment between the transferred muscle and the FDP, being sure it is neither too tight nor too loose. If extension of the wrist is limited, the wrist should be kept in less extension or in neutral position for tension adjustment.

For EDC replacement, the transferred muscle-end fixations are the lateral epicondyle of the humerus proximally and the 4 conjoined tendons of the EDC, similar to that in FDP replacement. If the wrist extensors and EDC are paralyzed, the EDC tendon should be moved superficial to the extensor retinaculum, not kept deep to it. This change provides a bowstring effect for wrist extension and some tenodesis effect for finger extension. 1. Optimum muscle tension: The objective is to provide tension in the muscle so that it will provide full finger flexion and extension in any wrist position and provide maximum contractile strength. It is important to apply enough tension for the muscle to achieve its functional potential. Some authors fear this may produce ischemia,[21] but we have had no problem with this. Skeletal muscles are normally under significant tension at rest yet remain well perfused. 2. Flap coverage: The distal forearm must have good flap coverage to allow tendon gliding, otherwise, a secondary tenolysis, if required, will be difficult. We presently cover the proximal portion of the muscle with a split-thickness skin graft.

Assessment of FFMT. Patients should be evaluated for survival of the transferred muscle and electromyographic evidence of reinnervation in the transferred muscle before discharge. Objective criteria to assess the muscle transplant must be applicable to different anatomic locations and must relate to the functional replacement of the missing muscle. Ideally, a successful muscle transplant would provide 1. a contractile excursion that moves the involved joints through their full range of motion and 2. a contractile force, under precise and volitional control, equal to that which has been lost. However, almost all patients cannot achieve this. Therefore, Chuang[15] defines the success of FFMT based on whether the transferred muscles have the power to function against resistance (namely, M4 muscle strength in the Medical Research Council Scale system that can resist at least the examiner's one finger of resistance, or at least 1 kg of resistance). During the period of follow-up, the parameters that are evaluated include the strength of the transferred muscles, the range of active motion of the elbow and finger joints, sensory recovery, the ability to perform activities of daily living, and restoration of prehension. Serletti et al[22] used the Enneking Outcome Measurement Scale to evaluate the long-term functional outcome of patients who have required functioning free muscle transplants when undergoing limb preservation surgery for sarcoma. Patients were examined for range of motion, deformity, stability, pain level, strength, functional activity, and emotional acceptance and assigned a numerical score for each category. Based on this, an overall rating of excellent, good, fair, or poor was assigned. The result showed this method could reflect the late functional outcome objectively and reliably, and could be used in evaluating all patients under functioning free muscle transplantation.

Changes of the transferred muscle after FFMT. Whether or not the function of a freely transplanted muscle is completely restored depends not only on the extent of reinnervation, but also on the damage sustained by the muscle parenchyma during transplantation and ischemia.[23] Vessels, nerves, and tendons must be meticulously dissected and anastomosed when doing FFMT, so it is inevitable to take a long time for the transferred muscle to get the blood supply again. If the duration of ischemia is not longer than 2 hours, the muscle parenchyma sustains only minor and reversible damage on transfer. But, when muscles are transplanted by microneurovascular anastomosis, they suffer denervated degeneration at the new circumstance first, and then regenerate as reinnervation occurs. Hence, a lot of changes happen in the muscle after FFMT.

a) Morphologic change. The thickness and volume of the transferred muscle increases postoperatively.[24] A significant swelling peaked at 2 weeks, and then started to subside linearly. The signs of muscular atrophy were detectable in the third postoperative week and were considerably more distinct by the eighth postoperative week. After 9 months, the muscle had attained its initial thickness,[25] but large muscle bulk loss was accompanied by excessive scarring.[26] Magnetic resonance imaging studies revealed a decrease of transplanted muscle tissue and an increased proportion of fat in free flaps 6 months after surgery.[27] A significant type 1-specific atrophy and an increasing proportion of type 2 fibers were observed in free microvascular flaps 9 months after surgery.[28] The extent of fatty charge and fibrosis correlated to muscle atrophy.

b) Muscle metabolism. Ischemia lasting one hour affected the energy metabolism of the muscle cell as evidenced by a 50% reduction in creatine phosphate (PCr), a 20% reduction in adenosine triphosphate (ATP) and in the energy charge, a 100% increase in inosine monophosphate, and a 700% increase in hypoxanthine and xanthine.[29] Lundberg et al[30] found an accumulation of glucose-6-phosphate (G-6-P) during the ischemic period. There were no distinct changes in the pH values and inorganic phosphatase. When perfusion is begun after anastomosis, the production of energy-rich metabolites (PCr, ATP) rapidly increased, and surpassed the original level. But several minutes later it began to reduce, and reached less than 60% after one hour of reperfusion, 50% 24 hour postoperatively, then maintained this level during the first postoperative week.[23] Therefore, metabolism is energy-rich immediately after transplantation, then returns to a low level, this may be due to the denervated muscle losing active movement. The pH values and inorganic phosphatase remained almost unchanged, indicating good oxygen supply in the muscle. Therefore, Elander et al[29] points out that skeletal muscle can tolerate ischemia for up to 2 hours in the clinical situation without permanent damage to the tissues.

c) Electromyogram. Spontaneous action potentials first were seen approximately 10 days after muscle transplantation.[28] At 4 months after transplantation, spontaneous action potentials began to disappear with reinnervation of the grafted muscle, and practically none could be observed within 10 months. Eight weeks after transplantation, the number of axons in the nerve was sufficient to record a polyphase potential.[23] Voluntary action potentials of transplanted muscles could be recorded as early as 5 months postoperatively,[24] on average, 8 months after transplantation.[31] It took a long period (approximately one year after initial recording) for action potentials to attain a stable state.

d) Reinnervation. The speed of reinnervation of the transplanted muscle depended on the choice of recipient nerve, the patient's age and the occurrence of postoperative vascular complications.[32] In general, it will take at least 3 months after the surgery before it can be detected. Doi et al[33] reported the Tinel's sign advanced at a mean rate of 1.3 millimeters per day after reinnervate free muscle transplantation, Kauhanen et al[25] studied nerve fibers of the grafted muscle after 3-4 years, and found some fibers had the complete structure of a mature nerve, but some fibers are still denervated. No correlation between innervation and clinical factors was found. Yoshimura et al[34] found that in clinically transplanted muscles, some fibers appeared to remain denervated even 2-14 years after transplantation. It is concluded that, in microneurovascular human muscle transfers, there is a wide variation in the time required to obtain reinnervation for individual muscle fibers.

e) Neuromuscular junction. Hua et al[35] studied the changes at the neuromuscular junction after free muscle transfer. Under light microscopy, the neuromuscular junction showed changes of degeneration with withdrawal of the innervating axon terminal followed by regeneration and reconstitution of the neuromuscular junction. The newly formed neuromuscular junction was localized almost in the same region of the degenerated neuromuscular junctions, but their sizes were smaller and they still lacked the structural detail seen in the normal control neuromuscular junction even after 30 weeks. With the electron microscope, mitochondrial swelling and clumping of the synaptic vesicles were followed by withdrawal of the axon terminal from the muscle membrane on denervation. With reinnervation, the ultrastructure of the junction was only partially reestablished with poorly reconstituted primary and secondary folds of the muscle membrane 30 weeks after the transfer. Therefore, failure of complete reformation of the ultrastructure of the neuromuscular junction may provide another explanation for failure of full recovery of skeletal muscle function after free muscle transfer.[36]

Treatment recommendation. On the basis of many successful experiences in performing FFMT, the following recommendations are offered to help guide treatment and achieve useful elbow and hand function. 1. In complete avulsion of the brachial plexus: Double free muscle transplantation described by Doi et al[37] was a reliable and useful method in the restoration of hand and elbow function. The first free muscle used to restore elbow flexion and finger extension is transferred and reinnervated by the spinal accessory nerve. The second free muscle, transferred to restore finger flexion, is reinnervated by the fifth and sixth intercostal nerves. 2. In severe Volkmann's ischemia: FFMT may be performed 3-6 months after fasciotomy, and no progressive rehabilitation was made. If both flexor and extensor musculatures have been lost, the extensor replacement should be carried out first, then the flexors as a second stage. 3. In trauma and major soft-tissue loss: FFMT is usually recommended as a secondary procedure after the complete healing of bone or soft tissue. Chuang et al[32] reported 2 of 3 primarily transferred FFMTs resulted in failure, despite tenolysis following FFMT. The transferred muscle survived but the functional strength was poor. The possible cause of failure was assumed to be either scar adhesion, or unhealthy donor motor nerve selection. Although FFMT can provide motor function in addition to wound coverage, it should be used primarily for functional restoration and not for wound coverage. It is therefore suitable for elective, well-prepared cases following adequate coverage of skin defects, not for acute, contaminated cases as a primary procedure. 4. Following wide excision of sarcoma we recommend performing FFMT at the time of the tumor extirpation, because immediate reconstruction avoids scar tissue and soft-tissue contracture, re-creating the boundaries of the defect, and multiple operative procedures, and the functional results compared with delayed construction was not significantly different. Before reconstruction, preoperative hyperbaric treatment is a useful method to reduce complications with postoperative radiation. 5. Following arm or forearm replantation: Functioning free muscle transplantation would be carried out only when the nerve is reconstructed at the time of replacement, but the motor function below the elbow need at least one year of rehabilitation to recover.[6] Secondary reconstructive procedures, such as wrist fusion, arthrodesis of the carpometacarpal joint of the thumb, and tenolysis of the transferred muscle and the distal tendons, may be required to improve the functional outcome.

Prospect. Replacing the function of a destroyed or chronically denervated muscle or muscle group is a tremendous challenge to the reconstructive surgeon. With the use of microvascular techniques, FFMT has become an available or perhaps the preferable method to treat the damaged extremity. Endoscopic techniques in plastic surgery have reduced donor site morbidity and improved the aesthetic effect, in the future, it will become more popular for FFMT.

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