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Contemporary Review

Principles and Biomechanics of Muscle Tendon Unit Transfer: Application in Temporalis Muscle Tendon Transposition for Smile Improvement in Facial Paralysis

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Muscle tendon unit (MTU) transfer is a common procedure performed to restore hand function after peripheral nerve or spinal cord injury. The principles of MTU transfer established for hand surgery can be adopted to optimize the dynamic excursion of the temporalis tendon transfer procedure for facial reanimation. Additionally, the force generating ability of a transferred MTU depends on the ideal length-tension relationship of the donor muscle. There are unclear guideline for selecting the ideal tension at which a transferred MTU will generate maximum force and excursion and current practice often leads to overstretch and suboptimal actin myosin interaction. The use of intraoperative electrical stimulation is an option for determining the ideal tension to optimize excursion of transferred temporalis tendon units in simile restoration. Understanding the biomechanics and principles of MTU and applying it to the temporalis tendon transfer procedure is necessary to improve its use in facial reanimation.
Key Words: Temporalis tendon transfer, facial paralysis, Length-tension relationship, biomechanics of muscle tendon unit transfer, principles of muscle tendon transfer.

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INTRODUCTION

The primary goal in reanimating the paralyzed face is to restore facial tone, symmetry, and dynamic movement that is synergistic and controlled. This is best achieved when the injured facial nerve is directly repaired, grafted, or substituted with other cranial nerves in a timely manner. When re-establishing neural input is not feasible, or when the facial muscles are irreversibly injured or congenitally absent, transfer of functional muscle tendon units (MTUs) offer the potential for restoring some facial tone, symmetry, and motion after a single-stage procedure. In MTU transfer, the tendon of a functioning muscle is detached, mobilized, and then reattached to another tendon or bone to substitute for the action of a nonfunctioning muscle.[1] MTU transfer differs from a free functional muscle transfer such as a gracillis or the pectoralis minor transfer in that the neurovascular pedicle in MTUs remains uninterrupted. MTU was first developed to restore ambulation in patients suffering from poliomyelitis and was later refined to treat traumatic injuries during the first and second world wars. MTU has been further developed for multiple peripheral nerve paralyses, including median, ulnar, and radial nerve palsies. For example, the flexor carpi ulnaris tendon transfer is a common procedure performed in patients with radial nerve palsy.[2–5] In 1952, McLaughlin introduced the concept and technique of mobilization and transposing the temporalis tendon for facial suspension.[6] The more traditional temporalis muscle transfer later replaced this technique until it was recently reintroduced by several authors.[7–9] Transfer of the digastric muscle tendon for correction of marginal facial nerve branch injury is another example of MTU transfer in the head and neck.[10] Even though newer techniques of functional microvascular transfer of muscles have added new dimensions to facial reanimation, tendon transfer remains a viable option in facial paralysis management.

Through the vast experience gained in extremity surgery over the past century, the basic principles for MTU transfer procedures have been established and refined (Table I).[1] Adopting these principles may be helpful in advancing and refining the technique and outcome of MTU in the reanimation of the paralyzed face. The goal of this article was to explore the principles and biomechanics of MTU transfer established for extremity

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TABLE I.
The Principles of MTU Transfer.

Fundamental principles of MTU transfer
The muscle selected as an MTU donor must be expendable and functioning
Adequate soft tissue bed for the transfer tendon
Full passive range of motion of the involved joints (no fixed deformity)
Adequate excursion and length of donor tendon
Direct line of pull
Suitable insertion technique and firm fixation
Synergy of transfer
Single function for each transferred tendon

MTU = muscle tendon unit.

surgery and its application in the temporalis tendon transfer procedure for facial reanimation.

PRINCIPLES OF MTU TRANSFER IN EXTREMITY SURGERY

Table I outlines the fundamental principles of MTU transfer procedures. Although these principles were developed mainly as a result of experience with MTU in extremity surgery, the basic tenets may be applicable to all types of functional muscle transfer procedures including the temporalis muscle tendon transfer.

Selected Donor Muscle Must Be Expendable and Functioning

The success of muscle tendon transfer surgery depends on the proper selection of a donor muscle. First, the MTU selected as a potential donor must be expendable in that sacrificing its function should not cause significant morbidity. In the temporalis MTU procedure, the effect of the temporalis muscle on the mandible is completely lost on the side of the transfer. The temporalis muscle works in conjunction with the masseter muscle to raise the mandible during jaw closure. Clinically, one or both temporalis tendons can be transferred without significant functional deficits. The donor muscle selected for MTU transfer should also be functional. Muscles that have previously lost function and have recovered are not ideal donors for MTU transfer. The function of the temporalis muscle can be tested clinically by observing and palpating for contraction of the muscle in the temple area when the patient is asked to bite down. Intraoperatively, the temporalis muscle can also be stimulated with surface electrodes to detect jaw contractions. Preoperative testing of the temporalis muscle function is particularly important in patients with multiple cranial nerve injuries, Möbius syndrome, or a history of previous cranial surgery where the temporalis muscle was divided. Patients who have previously undergone the traditional temporalis muscle transfer procedure may still be good candidates for the temporalis MTU procedure if strong contraction of the remnant muscle can be elicited.

Selection of Muscle of Adequate Strength and Excursion

When replacing the function of a deficient muscle with that of a donor MTU, the donor muscle should have adequate strength and excursion that is comparable to that of the paralyzed muscle. Choosing a donor muscle with a comparable contraction velocity is also desirable. The strength of a muscle depends on the maximal force it can generate. The maximal force a muscle is capable of producing is proportional to its physiological cross-sectional area and its excursion range to the length of the muscle fibers.[11] The length of the sarcomeres is a major determinant for both force and excursion range. The speed of muscle fiber contraction is largely determined by the heavy chain of the myosin molecule, which in turn determines the muscle type. Muscle fibers are traditionally classified into three groups depending on their physiological behavior. Type I fibers are slow contracting, fatigue resistant, and generate small forces, type IIA fibers are fast contracting, fatigue resistant, and generate larger forces, and type IIB fibers are fast contracting, fatigue resistant, and generate the largest forces. Freilinger et al. distinguished the function of the facial muscles based on the proportion of muscle fiber type.[12] The muscles that attach to the oral commissure for lip elevation (zygomaticus major, levator labii superioris) are intermediate phasic muscles with a mixture or type I and type II fibers suited for sustained tone and fast phasic movement seen in facial expression. The temporalis muscle is made predominantly of type I fibers with about 13% type II fibers.[13] This muscle fiber profile should allow sustained tone to support the paralyzed cheek and lip, and a moderate speed of contraction to elevate the oral commissure during smile. The temporalis muscle has a larger physiologic cross-sectional area than the lip elevators combined and generates significant contraction force during biting and chewing.

Suitable Soft Tissue Bed for Transfer

For unrestricted tendon movement, the transferred MTU should pass through a healthy soft tissue bed that is free from inflammation, edema, and scar. This is necessary to allow the tendon to glide freely untethered by adhesions and scar. In 1919, Steindler advocated achieving soft-tissue equilibrium, in which edema is resolved, joints are supple, and scars are soft, before proceeding with tendon transfer surgery.[14] In a 1988 article, Brand discussed the mechanical properties of the peritendinous scars that determine the final success of a tendon transfer.[15] When handled meticulously, the buccal space fat pad provides an ideal soft tissue bed for the transposed temporalis tendon. The buccal fat pad fills the masticator space and consists of a main body and four extensions: buccal, pterygoid, superficial, and deep temporal.[16] The deep temporal extension of the buccal fat pad lies directly over the temporalis muscle and its tendon separating it from the zygomatic arch. Disruption of the deep temporal fat pad risks scaring of the muscle fibers and tendon to zygomatic arch and disruption of its smooth contraction.

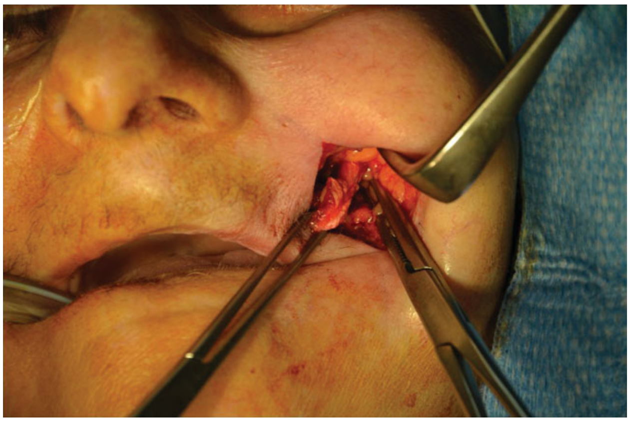

Fig. 1. The buccal fat provides a mobile bed through which the transposed temporalis tendon can glide. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

The buccal extension of the buccal fat pad passes anterior to the masseter and overlies the buccinator muscle as it courses to the lip musculature. The transposed temporalis tendon passes through the buccal extension to reach the melolabial crease and modiolus. To maintain a gliding path for optimal tendon movement, an adequate cushion of vascularized fat should be preserved on all sides of the tendon (Fig. 1). In addition, early mobilization of the transferred temporalis MTU is important to minimize tendinous adhesions and restrictive scar formation.

Full Passive Range of Motion of the Involved Joint (No Fixed Deformity)

A tendon transfer procedure will fail if the joint across which the transferred muscle is acting is stiff and immobile. Unlike extremity muscle, the facial muscles do not cross any joints so joint fixation in not applicable. However, for the purpose of smile restoration, oral commissure excursion may be compared to joint movement in extremity MTU. Scars and fibrosis around the lip, chin, and cheek, and additional forces that can oppose the free excursion on the oral commissure, can negatively affect the outcome of the temporalis tendon transfer. When present, these restrictive forces should be actively managed prior to the tendon transfer procedure.

Direct Line of Pull

Tendon transfer procedures are most effective when the vector of force is along a straight line. Changing the line of pull will result in a significant loss of force. The anterior fibers of the temporalis muscle are strongly activated during biting and have a vector of pull that compares favorably with the vector of the zygomaticus major. The insertion site of the transposed temporalis tendon should be selected to match the line of contraction of the contralateral zygomaticus major muscle (Fig. 2).

Suitable Insertion Technique and Firm Fixation

Hand surgeons have recognized the importance of firm tendon fixation techniques in the success of MTU procedures. Factors that have influenced techniques in tendon repair can be summarized by the statement by Strickland, "It now seems irrefutable that the most effective method of returning strength and excursion to repaired tendons involves the use of strong, gap resistant suture techniques followed by the frequent application of controlled motion stress."[17] Similar to tendon repair in hand surgery, a firm, stable, and gap-resistant fixation of the transposed temporalis tendon to the modiolus is important. In clinical practice, leaving a small piece of the coronoid attached to the temporalis tendon provides a stable platform for anchoring sutures. Holes can also be drilled through the coronoid for firm suture placement. Controlled motion stress in the form of early mobilization has been shown to reduce range of motion loss, increase blood supply, and reduce the degree of muscle atrophy that typically occurs after tendon repair.[18] Early mobilization of the transposed temporalis tendon should be encouraged for the above reasons. Patients can be placed on soft diet for 2 weeks and quickly advanced to actively engage the temporalis muscle in oral commissure excursion.

Synergy

Synergism occurs when muscles contract simultaneously to augment the effectiveness of each muscle in a given function. The zygomaticus major and levator labii superioris perform synergistic movements to elevate the

Fig. 2. A straight line vector of transfer maximizes the effectiveness of the transposed muscle tendon unit. The temporalis tendon should be inserted to match the vector of contraction of the contralateral zygomaticus major muscle. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

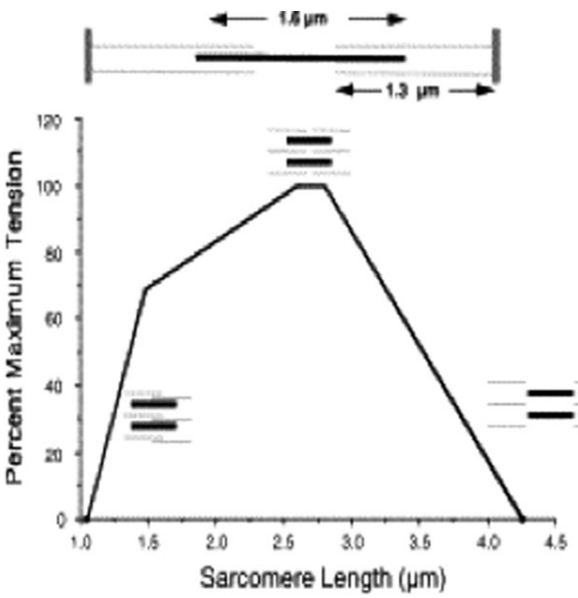

Fig. 3. Length–tension curve obtained using human filament lengths and assuming the sliding filament mechanism proposed by Gordon et al.[20] (Top) Schematic of filament lengths. Schematic myofibrillar filament overlaps at three different sarcomere lengths are illustrated along the length–tension curve.

upper lip and oral commissure during smile. On the contrary, the function of the zygomatic major and depressor anguli oris muscle are not synergistic. Thus, the temporalis MTU procedure should not be combined with a digastric tendon transfer to the oral commissure to mimic the function of the depressor anguli oris, as the new function of the transposed muscles will not be synergistic.

Single Function for Each Transferred Tendon

The final principle is that a single tendon should be used to restore a single function. Transfer of one muscle-tendon unit to restore multiple functions will result in compromised strength and movement. This principle is more relevant to hand surgery but applicable in MTU transfers for facial reanimation. As an example, the temporalis muscle has been used to provide dynamic support of the paralyzed eyelids, but combining this procedure with the tendon transfer to the modiolus will be contrary to the above principle and may result in reduced excursion and mass movement.

BIOMECHANICS OF MTU TRANSFER

Length–Tension Relationship and Consequence of Overstretch

One critical length–tension relationship and consequence of overstretch factor that influences movement around a joint is the force generating ability of the muscle.[19] The biomechanical determinant of active muscle force after transfer is the classic Blix curve that depicts the relationship between active force, passive force, and muscle length.[20] The sarcomere length–tension relationship illustrates that active muscle force increases as myofilament overlap increases, and passive muscle force increases as sarcomere length increases (Fig. 3). To achieve maximum force, the MTU must be set at the optimum sarcomere length–tension relationship for actin–myosin interaction. However, there are no clear intraoperative guidelines in determining the ideal sarcomere length and tension to insert a transferred muscle. Freehafer et al. suggested inserting the MTU as close as possible to its preoperative resting tension.[21] Overstretching of the MTU results in low-active force generation. Thus, although it is commonly believed that inserting a muscle in the stretched position may be beneficial because the repair site may slip or stress-relax, it would be unwise to rely on this unknown factor to optimize an overstretched transfer.[22] The routine practice of overcorrection to make up for anticipated slippage or stress relaxation may result in overstress and suboptimal excursion.[22] In hand MTU surgery, intraoperative sarcomere length measurements using laser diffraction have been shown to be a valuable tool for setting correct tension for tendon transfers.[23] To determine an optimal length–tension of the transpose temporalis tendon, the temporalis muscle can be stimulated intraoperatively once the tendon has been released. Varying the tension exerted on the tendon while stimulating the muscle can help determine the ideal length for insertion (supporting video). The stimulator should provide a biphasic current of approximately 20 mA at 20 Hz with variable pulse width. Pulse widths of 100 to 200 ms applied to the neuromuscular junction generally maximize the contraction of the muscle. In the majority of cases, the temporalis tendon can be mobilized to reach the melolabial crease and oral commissure and inserted slightly over the passive length. In cases of inadequate tendon length, overstretch can be avoided by using a tendon extension. The effect of tendon extension on muscle force was studied by Brunner.[24] If functional length changes, a muscle adapts by altering the number of sarcomeres in a series. If the tendon is elongated without changing the functional range of motion at which the muscle is active on the joint, the passive tension is decreased. As a result, the number of sarcomeres in a series is reduced. The muscle produces less force and the range of active force production is narrowed. If by elongating the tendon, however, the functional range of motion of the muscle at the joint is moved and the tension remains unchanged, the muscle force can be preserved. Therefore, during an MTU procedure, judging the optimal tension for insertion to maintain functional range of motion becomes even more important in the temporalis tendon transfer procedure when a tendon extender is used. To gain tendon reach to the melolabial fold, Labbé described the temporalis tendon lengthening myoplasty procedure.[7] In his original description, the temporalis muscle is exposed through a scalp incision, and the posterior third of the muscle is released and elevated from its periosteal attachment. By sliding the released muscle inferiorly, the muscle fibers are redistributed and fixated inferiorly, thereby allowing the released coronoid with the attached temporalis tendon to reach the lip. When

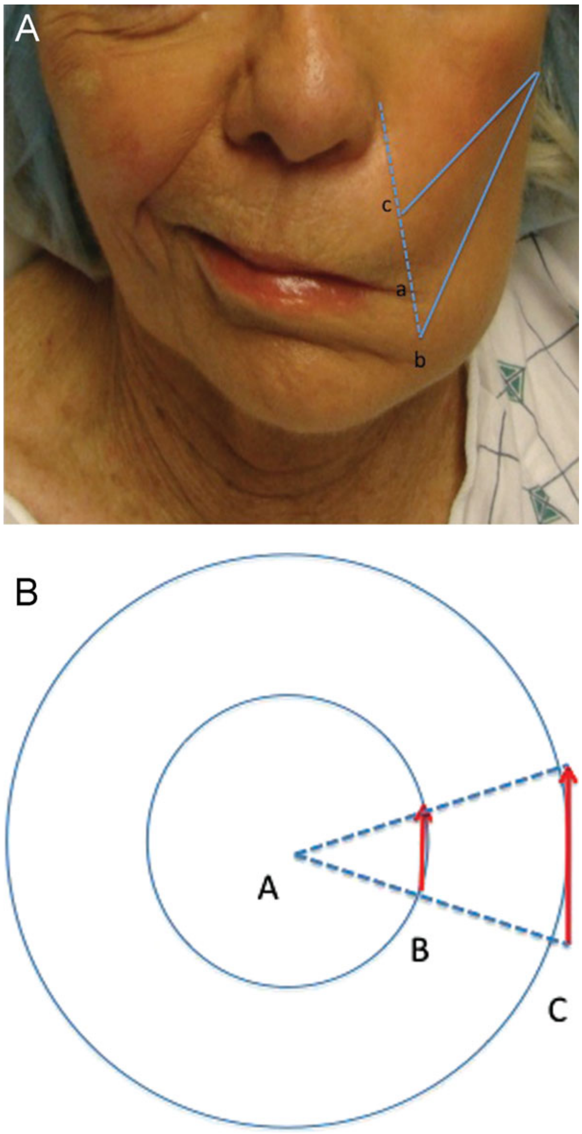

Fig. 4. The relationship between a muscle's moment arm and excursion is an important biomechanical factor to consider in the design of the muscle tendon unit. The length of a muscle's moment arm affects the excursion that results from a contraction. The further away the tendon is inserted (AC > AB) from the line of action (A), the higher the moment arm. Movement through an angle requires more contraction and shortening in a muscle with a long moment arm than in a muscle with a short moment arm. Tendons inserted closer to the oral commissure are more effective in commissure excursion. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

releasing the temporalis muscle, care should be taken to avoid injury to the neurovascular supply deep to the muscle. In addition, the released muscle should be refixated at the appropriate tension.

Moment Arm

The moment arm of a tendon transfer is an important biomechanical determinant of how much movement will occur.[15] The moment arm is a product of the force generated by the muscle and the perpendicular distance of its line of action from the axis of rotation (Fig. 4). The force generated by the muscle is dependent on the physiologic cross-sectional area of the donor muscle. The moment arm can be surgically varied depending on how far away the tendon is inserted from the axis of rotation. The closer the tendon line of action is to the axis of rotation, the smaller the moment arm but more muscle excursion and axis motion is achieved. Conversely, the larger the moment arm, the smaller the excursion. Because the facial mimetic muscles do not work across any joints, the relevance of moment arms in the temporalis MTU is not immediately apparent (Fig. 4). Nonetheless, this principle holds some value in the design of the temporalis MTU procedure. It is the author's clinical experience that the further away from the oral commissure along the melolabial crease the temporalis tendon is inserted (higher moment arm), the less effective excursion for smile restoration is realized.

TIMING AND INDICATION FOR TEMPORALIS TENDON TRANSFER

In 1974, Burkhalter reported the indications for MTU in extremity injury that are applicable to the temporalis tendon transfer.[25] These were: 1) the transfer can act as a substitute during regrowth of the nerve, which will thereby reduce the time of function loss; 2) the transfer can act as a helper and add power to normal reinnervated muscle function; and 3) the transfer can act as a substitute when, statistically, the recovery after neurorrhaphy or nerve repair is poor. When presented with facial paralysis, the clinician should make the determination if the paralysis is reversible. Reversible paralysis is that which may recover spontaneously (Seddon grade 1 or 2) or with intervention directed toward the nerve. Timely nerve grafting or nerve substitution to reinnervate a reversibly deinervated facial muscle yields superior results to muscle tendon procedures. Electromyography studies in combination with clinical history can help establish the reversibility of the paralyzed facial muscle. In cases were the repaired nerve is expected to recover partially or may take long to yield significant results, the temporalis MTU procedure can be performed as an adjunct while waiting for regrowth of the nerve, thereby reducing the time of function loss. A typical example is a patient who after a radical parotidectomy where the nerve was resected is also scheduled to undergo postoperative radiotherapy. Although the facial nerve is grafted, a temporalis MTU can be performed at the same time to provide lower facial support. In such situations, care should be taken to avoid disrupting the facial nerve branches during the MTU procedure. The temporalis MTU transfer procedure can also be considered as an option to upgrade partial facial paralysis that is either congenital or acquired.

PHYSIOTHERAPY

Muscle-retraining exercises are essential in optimizing the outcome of any muscle training procedure. In the preoperative period, patients visit a physical therapist who plans out specific exercises to strengthen the temporalis muscle and to identify isolated jaw movements that will be essential in contracting the temporalis muscle. Patients should be motivated to direct their rehabilitation. After the first 2 postoperative weeks, active mobilization of the transposed temporalis MTU should be initiated. This should be followed by muscle strengthening exercises. The main goal of the therapy is to systematically rehabilitate smiling function by transferring labial and jugal functions to the transferred temporal muscle. Lambert-Prou describes several phases of therapy to acquire a temporal smile.[26] The first phase, termed the mandibular smile, involves mobilization of the mandible by contraction of the transferred temporalis muscle and inducing an elevation of the commissura labiorum. The second phase, the voluntary temporal smile, is attained by contracting of the temporal is muscle without mandibular movement, which remains under voluntary control. The smile produced should become as symmetrical as possible. Finally, the last phase focuses on achieving a spontaneous smile independent of mandibular movement, the spontaneous temporal smile. Temporal contraction should produce a real expressive smile and good-quality articulate speech, saliva evacuation, and labial junction. Biofeedback methods are helpful in this process. The role of electrical stimulation is unclear. As demonstrated by Coulson and colleagues, repeated exercises and practice with the aid of video feedback loops of the best symmetric smile can be powerful tools to achieve a spontaneous smile adapted for social settings.[27]

CONCLUSION

Several factors are essential for the success of tendon transfers procedures. Based on an understanding of muscle physiology and biomechanics of muscle contraction, many of principles of MTU transfer in extremity surgery can be applied to the temporalis tendon unit transfer for facial reanimation. Although adhering to these principles does not guarantee success, ignoring them invites failure. Intraoperative assessment with electrical stimulation or more sophisticated tools to determine the ideal tension–length of the MTU is necessary to improve the outcome of the temporalis MTU transfer surgery in smile restoration.

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