Tendon transfers commonly are used to restore arm and hand function after injury to the main motor nerves or after spinal cord injury. Surgeons traditionally use passive tension to determine the length at which a muscle should be attached during tendon transfer. The principles used to choose the length at which the transferred muscle should be attached are relatively vague and have not been examined thoroughly. Misunderstanding of the sarcomere length-passive tension relationship can result in severe overstretch of the muscle and poor function. Upper extremity muscles have operating ranges that vary between synergists and antagonists, and recent architectural and biochemical data suggest that upper extremity muscles are designed to provide optimal control of joint position and stability. It is hypothesized that a significant functional improvement will be realized when muscles are reattached during tendon transfer procedures at the appropriate length and tension.

To substitute lost muscle function, the distal tendons of intact muscles often are transferred from one position to another, a procedure that is known as a tendon transfer or more appropriately muscle-tendon transfer. It is reasonable to select a donor muscle with architectural properties that are similar to the original muscle to do the original muscle’s function. Skeletal muscle architecture has been defined as “the arrangement of muscle fibers within a muscle relative to the axis of force generation.” Many other factors also influence donor muscle selection, including donor muscle availability, donor muscle morbidity, preoperative strength, integrity, expendability, synergism, transfer route and direction, and surgical experience and preference.

The ultimate outcome is a transfer generating maximal strength at a desired joint angle. To achieve that goal, muscle physiologic and biomechanical implications essential for the success of tendon transfers need to be considered: (1) implications of architectural matching between donor and recipient muscles; (2) implications of passive mechanical tensile properties; (3) implications of in vivo sarcomere lengths; and (4) implications of muscle adaptation.

Implications of Architectural Matching Between Donor and Recipient Muscles

Muscle architecture is an important factor when selecting donor muscles in tendon transfer procedures. The choice must, therefore, be based on matching between the donor mus-
cle’s and original muscle’s force and excursion potentials. An example of divergent architecture between synergists and consequently a risk for selection of the wrong donor depending on desired function is seen in the long and short radial extensors of the human wrist, the extensor carpi radialis longus and extensor carpi radialis brevis. The extensor carpi radialis longus muscle is the shorter muscle of the two but contains longer muscle fibers. The fiber length/muscle length ratio is relatively high and the physiologic cross-sectional area is relatively low leading to the assertion that the extensor carpi radialis longus is a muscle designed for high excursion or velocity. The extensor carpi radialis brevis, however, is a longer muscle with shorter fibers and, therefore, a much lower fiber length/muscle length ratio but has a higher physiologic cross-sectional area compared with the extensor carpi radialis longus. These data suggest that the extensor carpi radialis brevis is designed preferentially for high force production. Using rigid body kinematics, Loren et al quantified the moment arms of both muscles acting in wrist extension. The purpose was to determine whether architectural differences between muscles might be compensated for by changes in wrist moment arm. Lieber and coworkers measured the sarcomere length change in each muscle during wrist rotation in patients having surgery for tennis elbow. Sarcomere length change during joint rotation is a direct reflection of the relative ratio of the fiber length/moment arm ratio in a musculoskeletal system. Interestingly, the skeletal kinematics actually accentuated architectural differences between muscles. The extensor moment arm of the extensor carpi radialis brevis was much greater throughout the range of motion (ROM) compared with that of the extensor carpi radialis longus. Therefore, muscle fiber length change with joint rotation was expected to be greater in the extensor carpi radialis brevis compared with the extensor carpi radialis longus. This was confirmed by the intraoperative sarcomere length measurements that showed twice as large sarcomere length change per degree wrist joint rotation for extensor carpi radialis brevis compared with extensor carpi radialis longus. Based on these data, it is wiser to select the extensor carpi radialis longus than the extensor carpi radialis brevis, as the donor muscle to replace deep finger flexors whose excursion are many centimeters depending on the several joints they cross (Fig. 1).

Transfer of the posterior portion of the deltoid muscle into the triceps tendon has been reported to provide adequate strength and excursion for elbow extension in patients with spinal cord injuries (Fig. 2). In a recent anatomic and biomechanical investigation, the detailed architectural properties of the posterior deltoid and triceps muscles were measured in cadaveric specimens and the posterior deltoid-to-triceps tendon transfer was modeled mathematically. This was done to determine whether this is an architecturally appropriate transfer and whether the transfer is vulnerable to tendon slippage. In an earlier study, it was observed that a slippage of as much as 23 mm could occur during the immobilization and rehabilitation period, which could affect the force generating properties of this muscle (Fig. 3). Fridén and Lieber found...
that muscle fiber bundle length varied significantly among the deltoid (123.1 ± 7.8 mm) medial (64.5 ± 3.8 mm), lateral (66.5 ± 5.4), and long heads (85.3 ± 9.5) of the triceps. The physiologic cross-sectional area of the posterior deltoid was significantly less than the total triceps area (p < 0.001) and was predicted to provide only approximately 20% of the maximum isometric tension of the combined triceps heads (Fig 4). These data indicate that the excursion of the posterior deltoid greatly exceeds that of any of the triceps heads. The second important architectural property, cross-sectional area, is a good predictor of maximum muscle force generation. These data show that the long fibers of the posterior deltoid make it a suitable transfer to provide elbow extension because of its tremendous excursion and also show that it is difficult to set the deltoid muscle to an improper length. The study also emphasizes the need for additional biochemical study to test the suitability of the tendon transfer procedures used today.

**Fig 2A–C.** The posterior deltoid to triceps transfer is shown. (A) The posterior deltoid border is mobilized and the interval between middle and posterior deltoid is identified. (B) A tendon graft is harvested from the tibialis anterior muscle and via a subcutaneous tunnel is sutured to the distal deltoid insertion and to the distal triceps tendon via a dorsal incision at the level of olecranon. (C) Detail of the mobilization of the posterior deltoid from the middle portion is shown. Care is taken to identify the posterior deltoid insertion that subsequently is detached along with the associated periosteum. The tibialis anterior tendon graft is attached to the distal portion of posterior deltoid with an overlap of 5 cm and sutured to each other using 4–0 Ti-Cron® (Sherwood Davis & Geck, St Louis, MO) running sutures along the sides of the graft and host tendons.
Implications of Passive Mechanical Tensile Properties

Practical intraoperative experience does not always mirror the theoretical predictions of architectural measurements. For example, the brachioradialis muscle is reported to have a fiber length (>12 cm) that would predict a functional range of at least 6 cm, but intraoperative experience with this muscle indicates that this is not the case. Brachioradialis excursion rarely exceeds 1 cm after release of the distal insertion or 4 cm after the entire forearm component is released. Still, the brachioradialis is an attractive donor muscle used to replace lost hand function after median nerve or spinal cord injury. It is used widely because it is an auxiliary elbow flexor and because it does not cross the fingers or wrists and therefore is expendable.

In a mechanical cadaveric experiment, Fridén et al. simulated the effect of an assistant holding a tendon as a surgeon released the brachioradialis from surrounding tissue. The brachioradialis insertion was released from radial styloid. This tendon stump was attached to a servomotor that could be operated under length or force control. A constant load of 4.9 N was applied to the tendon, whereas the distal tendon was released surgically from the surrounding tissue in 3-cm increments. The study showed that a release of approximately 3 cm was necessary to linearly load the muscle-tendon unit. Subsequent releases, as much as 9 cm proximal from the insertion, provided minimal additional mobility (Fig 5). As the release progressed toward the elbow, large increases in mobility were measured. These large increases were obtained at the point of muscle-muscle contact compared to the...
with the earlier connections, which were tendon-bone and tendon-surrounding connective tissue contacts. Anatomically, the first muscle-muscle connection to be severed was that between the brachioradialis and the extensor carpi radialis longus muscle, which share a common fascial connection with the brachioradialis. Successive release of the brachioradialis-pronator teres and brachioradialis-flexor carpi radialis connections provided increased excursions (Fig 6).

To provide a reasonable comparison between the excursion values reported here and the intraoperative condition, it is necessary to add the excursion values to the release distances to obtain the total excursion of the muscle-tendon unit after surgical release in vivo. This value would be approximately 32 mm, which represents the average sum of the release distances (22 mm) added to the excursion value under load (10 mm). In these cadaveric specimens, because the muscles did not provide a restoring force after release, the excursion values measured only represent the connective tissue component of excursion, without taking into account the muscle fibers’ intrinsic restoring force.

Combining the architecture data with the mechanical data provides insights into the factors that limit brachioradialis mobility. If the average brachioradialis fiber length is taken to be approximately 150 mm (Fig 4), approximately 75 mm of active contraction distance would be expected. This is based on the fact that sarcomere lengths in humans can be as long as 4.25 μm and probably as short as 2.2 μm during active contraction. It should be kept in mind that the intraoperative excursion measurement represents the length corresponding to the maximum passive tension minus the length with the muscle under no tension. This would be less than the active range over which the muscle could contract. This type of argument provides strong evidence that muscle fiber length does not limit excursion in the brachioradialis muscle.

**Implications of In Vivo Sarcomere Lengths**

It is not possible to predict the relationship between passive tension and muscle length because of variation in fiber length within upper extremity muscles and because sarcomere length at rest varies between muscles in a...
way that has not been established clearly. Fridén and Lieber measured the physiologic length of muscles after transfer about the wrist. This was done to predict the functional outcome of the procedures and to understand the basis for selection of these lengths. They found that the average sarcomere length after transfer was 3.78 μm. A muscle at this sarcomere length generates approximately 30% of maximum tetanic tension. These transfers were done using traditional guidelines whereby normal wrist and finger posture was restored after the transfer and an appropriate muscle was selected to power the transfer. The goal was to insert the transferred muscle near optimal length (2.6–2.8 μm, where myofilament overlap is maximal). These results indicate that none of the muscles studied develop sufficient passive tension at optimal length. Therefore, there is a problem in using passive tension to make this type of decision intraoperatively because a fixed relationship between active and passive force generation in mammalian skeletal muscle does not exist. If these data generally are applicable and each of the muscles studied has approximately the same sarcomere length-tension relationship, Fridén and Lieber postulate that muscles were placed at a relatively high passive tension and would generate only a relatively low active force (Fig 7). This could provide an explanation for the statement that a transferred muscle loses one strength grade.

Implications of Muscle Adaptation

Muscle fiber length at the macroscopic level is a reflection of the number of serial sarcomeres arranged along the fiber at the microscopic
level and this sarcomere number has been shown to be adaptable in response to chronic length changes. Results from an immobilization study have been extrapolated to indicate that the number of muscle serial sarcomeres will adapt any time a muscle length is changed so that the resulting sarcomere length will be optimized for that joint angle of activity to maximize force production. To study muscle adaptation after tendon transfer, the change in the number of sarcomeres was investigated in an animal model. Different sarcomere lengths were set at the time of transfer and varied continuously across the range from approximately 3.5 \mu m to approximately 5.5 \mu m with the average sarcomere length being 4.50 \pm 0.21 \mu m. The number of sarcomeres in series measured after transfer and immobilization showed a strong dependence on degree of stretch at the time of transfer (Fig 8). If the muscle were to adapt by restoring sarcomere length to a constant value, the number of sarcomeres would have been the greatest for muscles that were stretched the most. Surprisingly, the opposite result was obtained, that is, the number of sarcomeres was significantly and negatively correlated to the sarcomere length at the time of transfer (Fig 8). The transferred muscles had sarcomere numbers greater than and less than control values indicating serial sarcomere number addition and sarcomere number subtraction. Because muscle fiber length directly determines muscle excursion, alterations in serial sarcomere number will affect the range over which a muscle can contract. This alteration in range will directly affect the joint ROM that the patient will be able to attain after surgery. Because greater muscle stretch may result in smaller sarcomere number change presents a challenge to many surgeons have been taught that a substantial degree of passive stretch can be, or even should be applied to a transferred muscle tendon unit. Conflicting recommendations exist regarding the specific magnitude of passive tension at which a transferred muscle should be reattached. Development and application of an intraoperative sarcomere length measurement device is thought to aid the surgeon’s decision-making in the near future.

References
9. Fridén J, Lieber RL: Quantitative evaluation of the post-


