PRINCIPLES OF TENDON TRANSFERS

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Tendon is the integral part of the muscle-tendon complex which provides direct connection to bone, transmits force, and provides movement. The primary purpose of a tendon transfer is to restore the balance of power, or more precisely, to approximate the normal functional characteristics of the dysfunctional muscle or limb without adversely sacrificing function.

ANATOMY

Tendons are inelastic, non-contractive collagen fibers which run longitudinally from muscle to bone. Tendons are composed of fasciculi which are condensed collagen fibers surrounded by the endotenon. (Figure 1) Fascicles combine to form a tendon that is surrounded by the epitenon, a fibroelastic and synovial membrane. A tendon which follows a straight course is surrounded by a loose elastic areolar tissue known as paratenon. The paratenon nourishes the tendon and allows for smooth, gliding action of the tendon through the subcutaneous tissue.

As a tendon changes direction and friction is increased, the tendon is enclosed in a tendon sheath. The sheath is an enclosed structure which prevents bow stringing across a joint, and also produces a synovial fluid for smooth gliding motion.

The paratenon ends at the margins of the sheath in a fold of tissue called the plica. (Figures 2, 3) There are several folds of the plica on the proximal side of the sheath to accommodate the greater excursion found in the distal end of the sheath.

The tendon is nourished from within the sheath by synovial fluid and blood vessels of the mesotendon. The mesotendon is a bifoliate elastic membrane found on the convex or friction-free surface of the sheath and is richly supplied with blood vessels and lymphatics. Occasionally, the mesotendon is absent and is condensed into a cord-like vincula which performs the mesotendon's function. (Figures 4, 5)

At a tendon's attachment to bone, periosteum is absent and there is a gradual transition from tendon collagen to fibrocartilage to organized bone. Tendon circulation is primarily from paratenon but there is some contribution from muscle and less from bone. The peritenon is a general term referring to all connective tissues associated with tendons.

PHYSIOLOGY

Although the tendon being transferred is relatively non-metabolic, it is connected to a dynamic contractile structure, muscle. Certain aspects of muscle physiology must be appreciated so that appro-

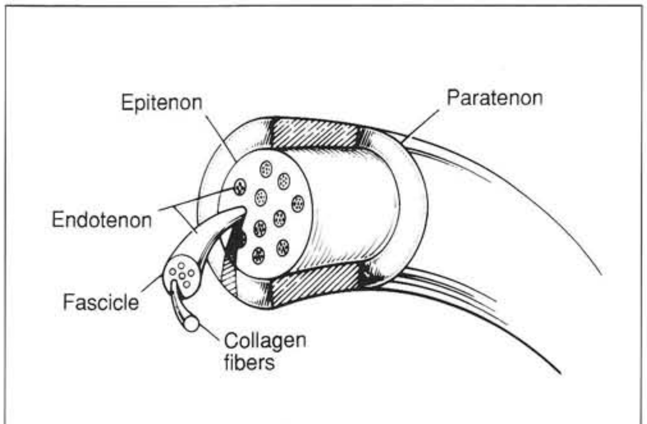

Figure 1. Anatomy of the tendon demonstrating the peritendonous structures.

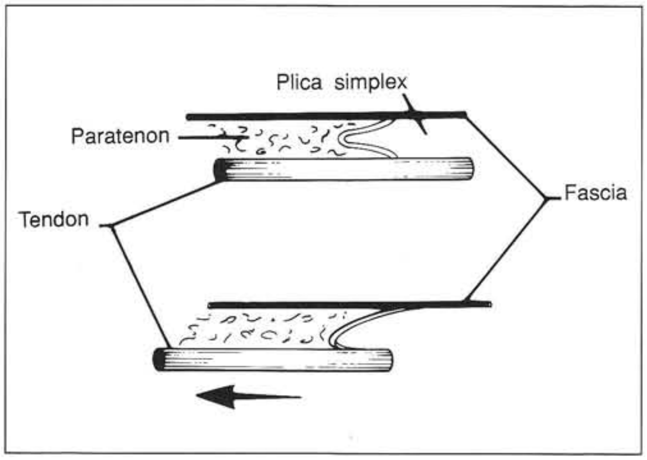

Figure 2. Plica is a fold of tissue which separates paratenon from the tendon sheath. Multiple folds in the plica are found when increased motion is anticipated. As the tendon moves, the plica unfolds to accommodate motion.

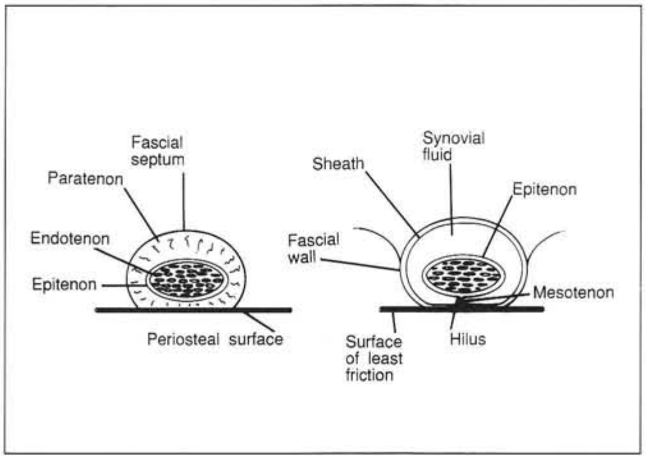

Figure 3. Cross sectional anatomy of a tendon sheath. Note the paratenon is not present within the tendon sheath.

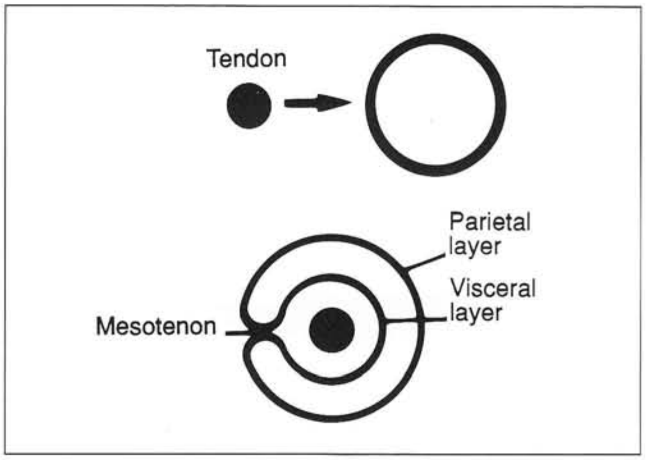

Figure 4. Demonstration of how a tendon sheath is formed.

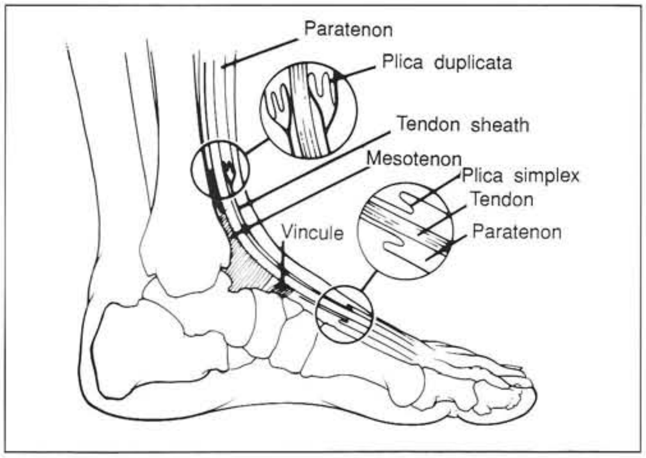

Figure 5. Sagittal view of a tendon crossing the ankle. Increased tendon gliding in the proximal aspect of the sheath is reflected by multiple folds of plica, as compared to the distal end of the sheath.

priate patient evaluation and technique can be performed.

Strength is determined roughly by the cross-sectional area of the muscle belly. The relationships of relative strength of various muscles remains constant from individual to individual regardless of the absolute strength of the muscle. (Figure 6)

The ability of a muscle to produce tension is directly related to the length of the muscle. When the muscle fiber is stretched to 120% of the resting length, maximum strength is obtained. (Figure 7)

All muscles undergo a fixed degree of excursion with each full contracture up to 57% of its resting length. At this point, no further tension can be generated. Since muscle fiber length is constantly proportional, muscle excursion or amplitude can be quantified.

Muscles of the lower extremity are classified as either stance phase (posterior group) or swing phase (anterior group). Muscles which are transferred out of phase (ie. tibialis posterior to dorsum of the foot), can undergo phasic conversion. However, in spite of aggressive rehabilitation therapy, phasic conversion is still unlikely. The overall success of the transfer though, is not diminished. A tethering effect as well as the myotactic reflex will make the procedure successful. The muscle most likely to undergo phasic conversion is the peroneus brevis. Otologically, the peroneus brevis develops with the anterior group muscles (extensors), then is the last muscle to rotate posteriorly.

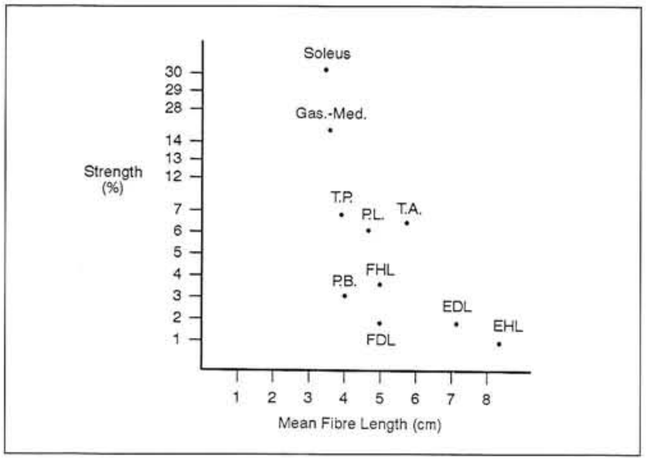

Figure 6. Relative strength and excursion of the muscles of the leg.

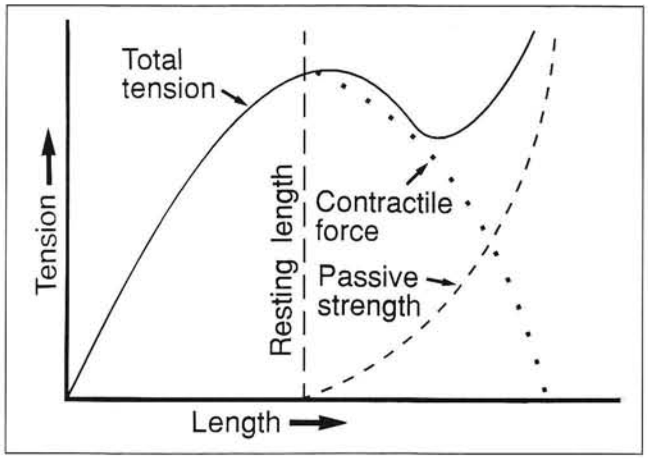

Figure 7. Blix curve demonstrates maximum contractile force is generated when the muscle fiber length is stretched to 120% of its resting length. Deviation in either direction produces a marked decrease in tension.

Tendon is relatively avascular and acellular, therefore, its ability to heal is in a large part dependent on the peritendonous structures. It takes about four weeks before healing is sufficient to allow a gradual return to activity. (Table 1)

BIOPHYSICS

One does not have to be an engineer to understand the basic mechanics of tendon transfers. Tendons produce motion by acting on joints. The distance from a joint axis to the tendon is the lever arm. The longer the lever arm, the greater the amount of power a muscle can generate. (Figure 8) If a muscle passes through a joint axis, its lever arm is zero and it will generate no power. So while a muscle's strength remains constant, its power can be altered by changing its relation to the joint axis. The level of insertion of a tendon has no bearing on the muscle's function, since the relationship of the tendon to the joint axis determines the muscle's power. (Figure 9)

A muscle is 100% efficient when it passes perpendicular to a joint axis. A muscle passing parallel to the joint axis will have no effect upon that joint. A tendon passing oblique to a joint axis will have its power proportionately diminished by the number of degrees it deviates from the perpendicular. (Figures 10, 11)

A straight line pull of a tendon is optimal. Changes in direction of contracture reduce the maximum effectiveness of the muscle. Muscles transferred subcutaneously, above the retinaculum, have a relatively straight line pull and demonstrate increased power as the muscle bowstrings and the lever arm is lengthened. This occurs at the expense of joint excursion. A muscle

TABLE 1

CHRONOLOGY OF TENDON HEALING

TIME	HISTOLOGICAL PROCESS	STRENGTH	TREATMENT
Week one	Softening. Production of jelly-like "fibroblastic splint"	Suture	Immobilize
Week two	Increased vascularity and proliferation of fibroblasts	Suture	Immobilize
Week three	Vigorous production of collagen fibers	Moderate bond strength	Gentle motion or isometric exercise
Week four	Collagen fiber alignment; cleavage from local tissues	Gradual return to not quite full strength	Progressive muscle force

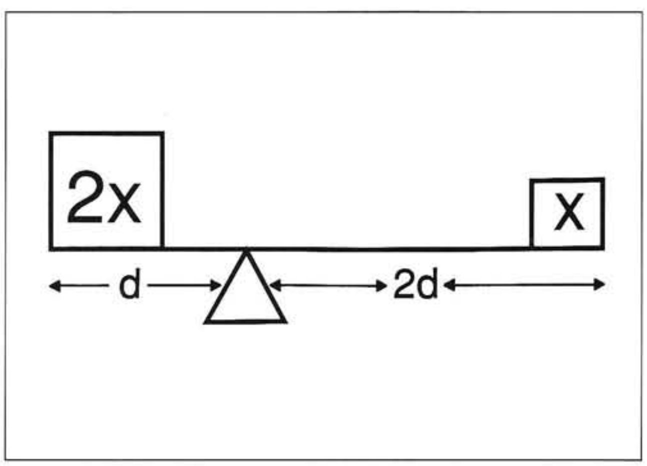

Figure 8. As the length of the lever arm increases, the power generated by the muscle proportionately increases.

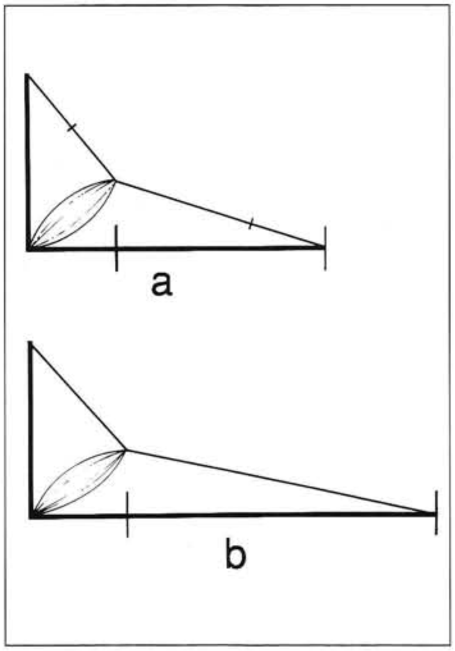

Figure 9. The level of insertion does not influence the tendon's relationship to the joint axis. Therefore, the quality of motion is unaffected.

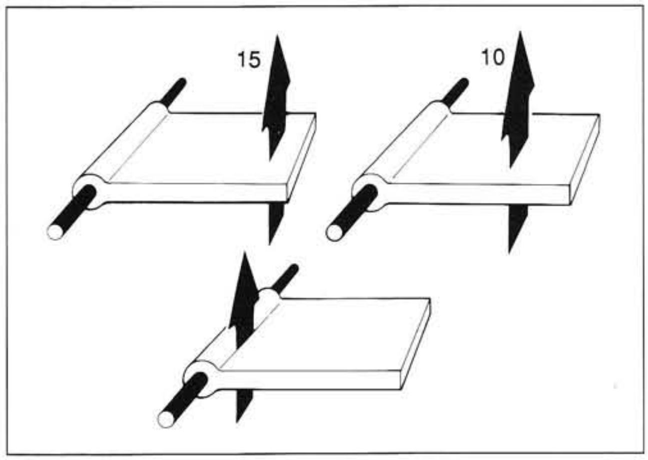

Figure 10. A force directed through an axis will produce no movement. The same force will support increasing amounts of weight as the distance from the joint axis is increased.

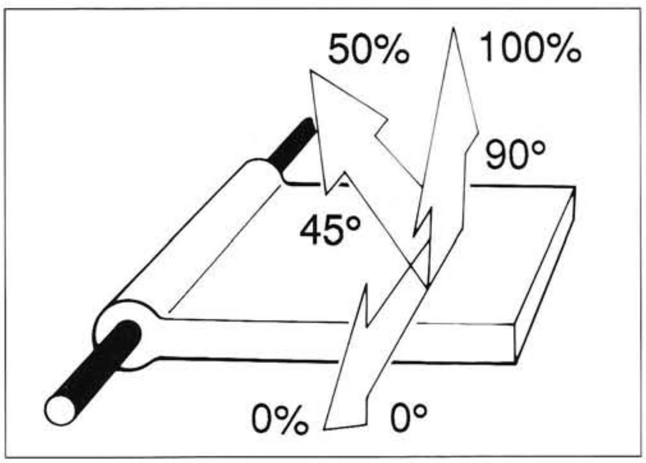

Figure 11. A force directed perpendicular to a joint axis is 100% efficient, but only 50% efficient when directed at a 45 degree angle.

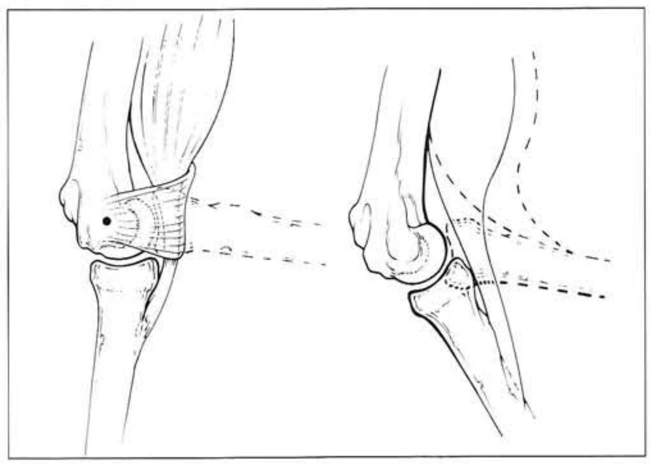

Figure 12A. A tendon transferred under the retinaculum exerts a constant force across the joint. Joint excursion is great. A tendon transferred above the retinaculum has a greater mechanical advantage at the expense of decreased excursion.

transferred underneath a retinaculum has an increased angular pull, but the lever arm remains constant and maximum joint excursion is obtained. (Figure 12)

SURGICAL LIMITATIONS AND CONSIDERATIONS

Tendon transfer surgery requires careful planning and evaluation. Physiologic and biomechanic factors limit the usefulness and practicality of tendon transfers. Muscle strength may decrease by 1/2 to 1 full grade with transfer, so a thorough preoperative evaluation must be performed. Muscle strength is determined by the examiner placing the foot in the position produced by maximum contraction of the muscle, have the patient contract the muscle, then apply resistance. To eliminate the effects of gravity during testing, have the patient lie on his/her side. A muscle should at least be a 3+ for transfer. (Table 2)

The excursion, amplitude or range of contraction of the muscle should be sufficient to perform the task required. For example, the tibialis

TABLE 2

MUSCLE GRADING

POLIO FOUNDATION	LOVETT	KENDALL	
5	normal	100%	vs. full resistance
4	good	75%	vs. partial resistance
3	fair	50%	vs. gravity
2	poor	25%	with gravity removed
1	trace	10%	contracture without movement
0	absent	0%	none

posterior has adequate strength for ankle dorsiflexion, but limited excursion. Following anterior transfer of the tibialis posterior, a limitus in ankle joint plantarflexion will be observed.

For the tendon to function properly, it must be affixed to a stable segment. A tibialis posterior transfer, anteriorly to the cuneiform would be ineffective if the midtarsal joints were unstable. As the muscle would contract, the MTJ would dorsiflex before the ankle. Since the excursion of the tibialis posterior is small, no additional motion would be available for the ankle.

Finally, a joint must have motion available for the transfer to function. Antagonist tendon lengthening and/or capsulotomies are useful adjunctive procedures. To ensure a successful result, gliding function of the tendon must be preserved. Skin incisions, when possible, should not be placed along the course of the transfer. The tendon must be gently handled and kept moist at all times. The paratenon should not be stripped from the tendon or adhesions will form. The tendon should be passed through existing sheaths when possible. Be sure an adequate channel is made for tendon passage.

To obtain maximum contractile strength, the tendon should be reattached at its physiologic length under minimal or no tension. Under general anesthesia, the foot is placed in a position produced by maximum contractures of the transferred tendon, then remove all slack from the tendon.

Tendon can be attached to either bone or another tendon. Since the paratenon provides gliding and prevents adhesions, it must be stripped and the tendon cross-hatched with a knife to ensure tenodesis. Multiple methods have been described including the newer tendon anchors. Tendon attachment is best made to a single point. When dual insertions are preformed, motion will result at whichever insertion is tighter. Postoperative immobilization in a cast is required for a minimum of 3 to 4 weeks.

SPLIT TIBIALIS ANTERIOR TENDON TRANSFER (STATT)

The tibialis anterior is split in half and the lateral slip is transposed laterally beneath the retinaculum and attached to the peroneus tertius. The rebalancing of power is complex and effects multiple joint axes. Preoperatively, the tibialis anterior is oblique to the ankle joint axis making it an inefficient dorsiflexor. Once the tendon is split, the resulting force vector is perpendicular to the joint axis, a more effective dorsiflexor. (Figure 13)

The transposition also causes the tibialis anterior to become a swing phase pronator of the STJ and the MTJ, making the STATT a useful adjunct in cavus foot surgery (Figure 14).

JONES TENDON SUSPENSION

The EHL is detached from the hallux and routed through a drill hole into the neck of the 1st metatarsal. It is indicated when a cocked hallux results from an overpowering of the EHL. Removing the deforming force on the hallux will secondarily result in 1st metatarsal dorsiflexion. The EHL does not actively dorsiflex the 1st metatarsal because the long extensor crosses the 1st metatarsal joint axis in the midfoot and is unaffected by the transfer. Therefore, for the procedure to be a success, there must be flexibility of the first ray and release of retrograde pressure from the extensor position of the hallux will allow the first metatarsal to dorsiflex.

A simplified approach to the surgery can be accomplished by tenodeses of the EHL to the neck of the metatarsal without distal detachment. The first ray is manually dorsiflexed and the hallux is relocated at the MPJ. The EHL is then attached to the 1st metatarsal with suture or internal fixation. (Figure 15) Fusion of the hallux IPJ may also be indicated in the Jones suspension in order to correct hallux malleus or prevent its occurrence.

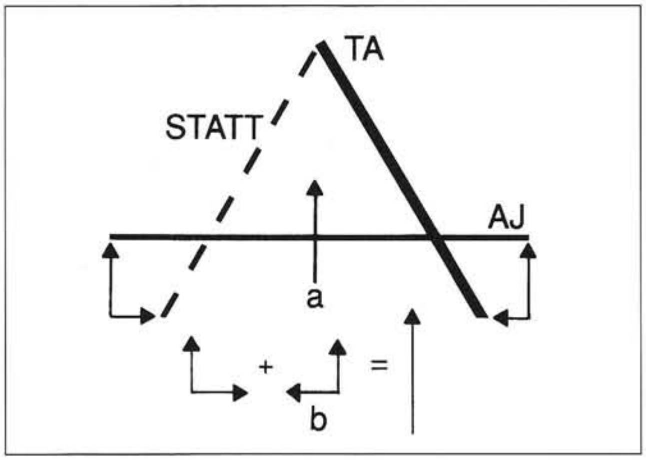

Figure 13. Tibialis anterior passes medial to the ankle joint axis producing an oblique force vector. Splitting the tendon and passing half laterally also produces an obliqua force vector. Summation of the force vectors produces an increased vector perpendicular to one joint axis.

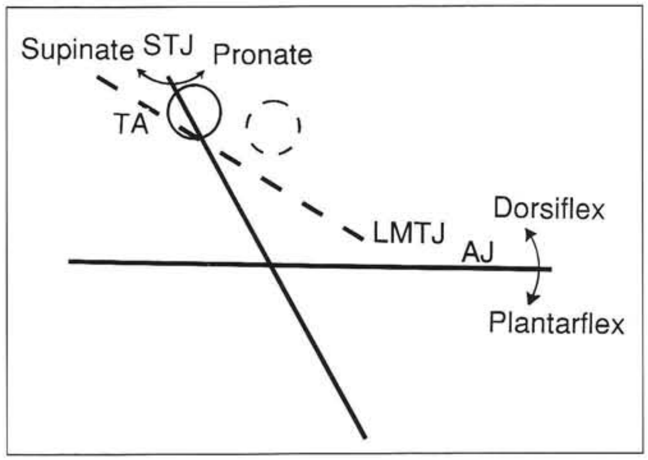

Figure 14. The tibialis anterior will normally not effect the STJ or the longitudinal axis of the MTJ. The STATT procedure (dotted tendon) causes the tibialis anterior to become a swing phase pronator of the STJ and LMTJ.

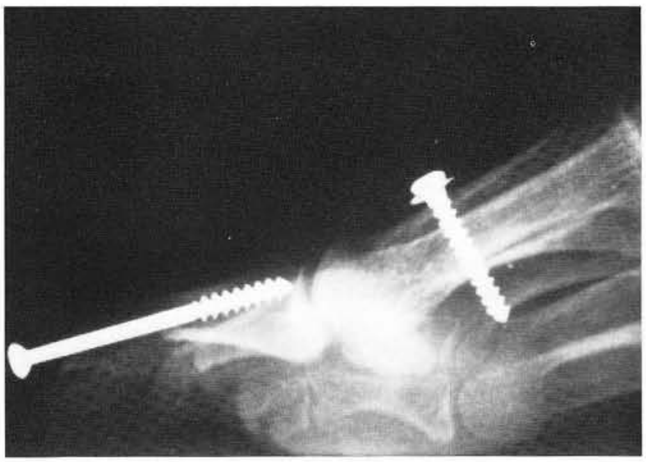

Figure 15. Postoperative x-ray of the author's modifications of the Jones tendon transfer. The tendon was left in place and tenodesed to the metatarsal with internal fixation.

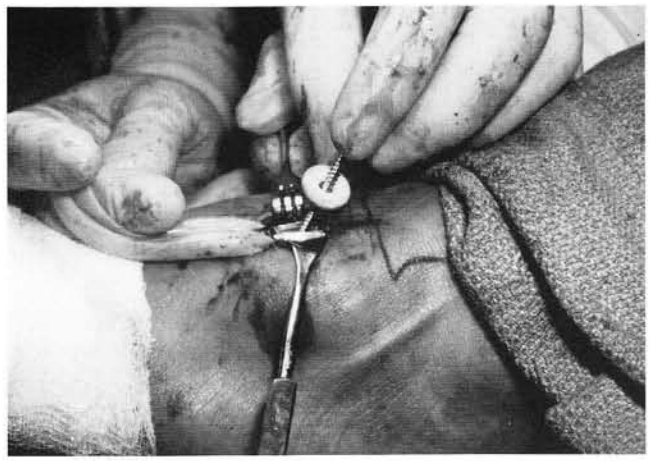

Figure 16. The author's modification of the Hibbs tendon transfer. The tendons are bound in suture and tenodesed to the lateral cuneiform with internal fixation. The tendon is not detached distally.

HIBBS TENDON SUSPENSION

In this procedure, the EDL is attached proximally to the cuneiform. It is indicated in the patient with a flexible anterior cavus and flexible hammertoes created by extensor overpowering. By transferring the insertion of the EDL proximally, the deforming force on the toes is removed and the forefoot will dorsiflex once the retrograde force of the digits has been eliminated. Surgery on the digits is not necessary if no static deformity exists.

As in the Jones procedure, the EDL does not dorsiflex the forefoot because its relationship and lever arm to the MPJ axis is unchanged. An additional benefit of this procedure is increased effectiveness as an ankle joint dorsiflexor. In the preoperative condition, the EDL is primarily a dorsiflexor of the MPJ's and the ankle secondarily. Following the Hibbs, the EDL is a primary ankle joint dorsiflexor.

As originally described, the Hibb's procedure involves extensive dissection across the entire dorsum of the foot. The author simplifies the procedure by placing a 3 cm incision over the lateral cuneiform. The tendon slips are stripped of paratenon and bundled with suture. With the toes held in plantarflexion and the foot at a right angle to the leg, the tendon is tenodesed to bone. (Figure 16)

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