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Gliding Resistance and Modifications of Gliding Surface of Tendon:

Clinical Perspectives

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The normal human digital flexor tendon in its sheath has a coefficient of friction similar to articular cartilage, which is maintained not only by synovial fluid lubrication but also by lubricants bound to the tendon surface, including hyaluronic acid, phospholipids, and a lubricating proteoglycan, lubricin. This system can be disrupted by degenerative conditions such as trigger finger, or by trauma. Restoration of a functioning gliding surface after injury can be helped by using low-friction, high-strength suture designs; therapy that enables gliding; and, at least experimentally, the addition of lubricants that can be fixed to the tendon surface covalently.¹ Such lubricants may be especially helpful when tendon grafts are needed, because the lubricants can significantly reduce the normal high friction of extrasynovial tendons,¹ which are the most common tendon graft donors.

The flexor tendon and digital sheath system is a marvel of nature's tissue engineering. The precise fit, lubrication, strength, motion, and mechanics are all designed to optimize efficiency, strength, and motion. This article reviews the relevant anatomy, mechanics, and biology, particularly as they affect the gliding surface.

NORMAL TENDON

Gliding Surface: The Tendon Skin

The tendon surface in the finger is specially adapted for gliding. The typical extrasynovial tendon is surrounded by an areolar paratenon (Fig. 1A),^{2–5} which provides for good gliding, but, when this system is disrupted by injury, fibrosis and adhesions are the common result.^{6,7} In contrast, the intrasynovial tendon has a different gliding system, with a coefficient of friction that is similar to articular cartilage,^{8–11} and a gliding surface (see Fig. 1B) that includes the lubricating elements of hyaluronic acid, phospholipids, and a unique proteoglycan, lubricin.^{10,12–14} This surface is durable, protecting the underlying collagen fibril network from abrasion after repetitive motion, not only in vivo but also in harsh in vitro conditions (Fig. 2).¹⁵ This protective, low-friction surface serves as a barrier to tissue ingrowth, most likely as a result of the lubricin that is present, because lubricin is known to have anti-cell adhesion properties.^{16–18} In many ways, the gliding surface of the flexor

tendon in the digital sheath functions as a protective barrier, protecting the tendon much the way skin protects the organism.

Gliding Resistance

The gliding resistance of the tendon/pulley interface is affected by at least 3 factors: the coefficient of friction of the interface, which is normally very low; the load on the tendon; and the angle of the arc the tendon makes with the pulley.¹⁹ The second and third factors combine to determine the perpendicular force between the tendon and pulley. The greater the angle of the arc of contact for a given tendon load, the greater the perpendicular force between tendon and pulley, and therefore the greater the frictional force. Mechanical principles emphasize that frictional force is not, in general, related to the size of the contact area, although the size and shape of the surface does play a role in fluid-lubricated situations, which is relevant to tendons, which are lubricated by synovial fluid within the tendon sheath.¹⁰ Lubricants such as synovial fluid reduce friction between dry surfaces by separating the surfaces with a thin film of fluid, so that microscopic irregularities on the opposing surfaces do not touch one another. However, the motion of this lubricating fluid creates its own source of friction, called drag, which is related to the velocity of motion and the viscosity of the lubricant.¹⁹ In total, the net effect of the boundary lubrication mechanism of tendon and pulley results in a coefficient of friction of around 0.02 to 0.03,^{9,15} about the same as that between cartilage surfaces, and about an order of magnitude less than ice on ice.²⁰

Differences Between Extrasynovial and Intrasynovial Tendons

As noted earlier, the gliding mechanisms of extrasynovial and intrasynovial tendons are different. The latter surface is optimized for gliding at low friction, and has a protective skin; the former does not. The result is obvious in repetitive loading testing, as noted in Fig. 2; the extrasynovial tendon abrades at a faster rate and becomes rougher under repetitive loads, which may explain, at least in part, the poor results of grafting using extrasynovial tendons to replace intrasynovial tendons clinically,^{21–27} and in animal studies in vivo (Fig. 3).^{5,7}

Differences Between Regions of Intrasynovial Tendons: Microenvironments

In addition to the differences between extrasynovial and intrasynovial tendons, there are also microenvironments within tendons that affect gliding ability. Most notably, within the tendon sheath are vincular vessels to the profundus and superficialis tendons, which may act as tethers to some extent. Most importantly, these vessels provide segmental vascular nutrition to the tendons,^{28–30} and their integrity is important to tendon healing.³¹

TENDONS IN PATHOLOGIC CONDITIONS

Trigger Finger

The cause of trigger finger is not fully understood, but it is generally considered to be a degenerative condition of the flexor tendon, as also occurs in other species with intrasynovial tendons.^{32,33} The tendon in trigger fingers may show microscopic calcification or other signs of degeneration.^{34–37} Although the gliding resistance of trigger fingers is unknown, the clinical presentation suggests that it must be increased. Lubricants have been used successfully to treat stenosing tenosynovitis in animals,³⁸ and has been suggested for humans as well.³⁹ However, the only available clinical study³⁹ compared steroid plus hyaluronate with surgery, with results in the nonsurgical group similar to those reported historically for trigger finger alone.^{40–44}

Laceration

The gliding of tendons that have been lacerated is impaired, regardless of whether the laceration is complete⁴⁵ or partial,⁴⁶ or whether the injury is sutured⁸ or, if partial, left unrepaired.⁴⁷ It is also clear from laboratory and clinical studies that both the gliding and healing of partially lacerated tendons (unless these are near complete) is better with trimming than with repair.^{47,48}

EFFECTS OF TREATMENT ON TENDON GLIDING

Suture Type

The design of the tendon core suture is important to the ability of the tendon to glide. Low-profile repairs, such as the modified Kessler and its variants (Fig. 4A), have little suture material on the anterior tendon surface.^{45,49–52} These repairs have low friction, and result in healing with fewer adhesions in animal models. In contrast, repairs with suture loops on the tendon surface, such as the MGH/Becker repair, have higher friction and result in more adhesions (see Fig. 4B). With regard to the epitendinous suture used to finish the repair in zone 2 injuries, all current designs have multiple loops on the tendon surface. Whether these loops are locked or not seems to have little impact on friction,⁵³ although one report did note increased resistance to the Lin technique of locking.⁵⁴ Because locking loops provide better gap resistance, these should be preferred, with the possible exception of the Lin method.⁵⁴

Knot Location

The location of the knot is critically important to the amount of friction generated by a tendon repair. Knots on the tendon's anterior surface generate more friction than lateral knots, or knots inside the repair site.^{52,55} Thus, for example, if the Tsuge repair is preferred, a double Tsuge method with the knots on the lateral tendon surface might be preferable to a more classic Tsuge repair, with the knots placed anteriorly.

Suture Materials

The suture material also has an effect on friction. Although it might be assumed that monofilament sutures have lower friction than braided sutures, the answer is more complex, because often monofilament sutures are made of different materials than braided ones, and braided sutures are more likely to have friction-lowering components such as polytetrafluoroethylene, polybutylate, or silicone included. In our tests, the suture material with the lowest friction has been braided polyester/monofilament polyethylene composite (FiberWire, Arthrex, Naples, FL).⁵⁶ However, these lower friction sutures also tend to hold a knot less well,⁵⁷ and the effect of suture material on the friction of the overall tendon repair is small.⁵⁶ In addition, although braided polyester/monofilament polyethylene composite sutures are stronger than some other commonly used materials, such as polypropylene, nylon, or braided polyester,^{56,58} surgeons should be aware of size differences: for example, size 4-0 braided polyester/monofilament polyethylene composite has a greater cross-sectional diameter than 3-0 sutures made of other materials.⁵⁸ Thus, although suture materials vary in frictional coefficient, the effect of suture material on the overall friction of the suture construct is small, and surgeons should be aware of differences in cross section between sutures of nominally similar size.

TRIMMING OF PARTIALLY LACERATED TENDON

The surgical literature is clear that partially lacerated tendons heal better when trimmed than when sutured, unless the partial laceration is nearly complete.⁵⁹ Trimmed tendons also have less friction, and less tendency to trigger.⁴⁷ Thus, it has been my preference to trim partial lacerations and make a smooth divot in the tendon when the partial injury is less than 50%

of the tendon diameter (Fig. 5). For larger injuries (up to 75%–90% lacerations; often it is difficult to accurately estimate the degree of partial injury visually, and so it may be better to err on the side of prudence and add a suture when in doubt), a running locked peripheral 6-0 finishing suture can be used. If the partial laceration is nearly complete, then I treat such injuries as complete lacerations.

Therapy

The effect of therapy on tendon gliding is related to the amount of loading that is applied to the tendon. Active motion programs ensure that the tendon is moving, but the load applied by the patient is difficult to control, and, if the load exceeds the holding power of the tendon suture (usually just a few kilograms in the early phases), the repair may break.^{58,59} Passive motion and synergistic motion programs can provide more measured loads, but the familiar problem of trying to push a tendon through a pulley often limits gliding in the flexion direction.⁶⁰ Tanaka and colleagues⁶¹ recently developed a modified synergistic method that provides some loading (roughly 100 g) in the proximal direction by maintaining metacarpophalangeal joint extension in both the flexion and extension phases of the synergistic program (Fig. 6). Place-and-hold methods are another way to provide a more gentle proximal pull on the tendon.^{60,62}

Barriers

Mechanical adhesion barriers have been used for years in an attempt to improve the results of tendon repair.^{38,63–71} However, although many agents have shown promise in animal models, few have proved to be reliably effective clinically.^{72,73}

Hyaluronic Acid

Hyaluronic acid has been used as a barrier to adhesion formation for many years. Its use is based on the clinical observation that wounds bathed in synovial fluid often do not heal.⁷⁴ However, more recent studies suggest that the inhibitory effect is caused by another component of synovial fluid, lubricin.

Nonetheless, hyaluronic acid has been shown to be an effective barrier to adhesion formation in animal models, especially in highly cross-linked versions, which tend to have greater tissue resident time.⁷⁵ Methods are also available to fix cross-linked hyaluronic acid to the tendon surface with covalent bonds; such methods result in even longer residence time and, in animal models, reduced friction and fewer adhesions.⁷⁶ As suggested by the adhesion-inhibiting effect of lubricin, adding lubricin to the hyaluronic acid mixture results in even further adhesion prevention, although at the cost of increased rates of tendon rupture in animal models.⁷¹

Antimetabolites

The use of antimetabolites in tendon repair has advantages and disadvantages. Unless they are highly targeted, drugs that reduce DNA or collagen synthesis not only block adhesions; they block healing. Beta-aminopropionitrile blocks collagen cross linking; it has been used experimentally to block adhesions since the 1960s, and is effective,⁷⁷ but because its potential side effects include aneurysm formation,⁷⁸ it has never engendered much enthusiasm with regard to clinical use. The cancer chemotherapeutic agent 5-fluorouracil blocks DNA synthesis, and has a short duration of action when applied topically; it has been tried in tendon repair, and does reduce adhesions and improve tendon gliding,^{79,80} but it may have a greater role in tenolysis, in which tendon integrity may be less of an issue.

THE FUTURE: TISSUE ENGINEERING OF THE GLIDING SURFACE

As noted earlier, the beneficial effects of hyaluronic acid on adhesion reduction and tendon lubrication can be extended by using 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide to covalently bond carboxyl groups on hyaluronic acid molecules to amine groups on proteins on the tendon surface.^{81,82} The addition of gelatin (denatured collagen) and N-hydroxysuccinimide improve the efficiency of the reaction.⁸² With this treatment, the hyaluronic acid remains on the tendon surface for weeks rather than days.⁷⁶ We have used this reaction in our research to reduce the friction associated with both tendon repair and tendon grafting, in vitro and in vivo.^{71,76,83,84} When lubricin is added, the results in terms of lubrication are even better, and a high friction extrasynovial tendon such as a palmaris longus can be provided with the coefficient of friction of an intrasynovial tendon such as the flexor profundus.⁸⁵

In the future, it should be possible to improve the gliding and reduce the friction of human tendon repairs and, especially, tendon grafts, with such surface treatments. There could be a particular role for cases in which, because of other injuries (fracture, replantation, polytrauma), the patient is unable to participate in the usual early motion therapy program. In such cases, the use of attached surface lubricants may allow a delay in the initiating rehabilitation, while still minimizing adhesion formation. Our recently published preliminary data in an animal model show that this may be possible.¹

SUMMARY

The smooth gliding of the normal human digital flexor is maintained not only by synovial fluid lubrication but also by lubricants bound to the tendon surface, including hyaluronic acid, phospholipids, and a lubricating proteoglycan, lubricin. This system can be disrupted by degenerative conditions such as trigger finger, or by trauma. The resistance to tendon gliding after surgical repair of the lacerated digital flexor tendon relates to location of suture knots, exposure of suture materials, and type of surgical repair and materials. Restoration of a functioning gliding surface after injury can be helped by using low-friction, high-strength suture designs; therapy that enables gliding; and, at least experimentally, the addition of lubricants that can be fixed to the tendon surface covalently. Such lubricants may be especially helpful when tendon grafts are needed, because the lubricants can significantly reduce the high friction of extrasynovial tendons.

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KEY POINTS

- The tendon surface in zone 2 is specially adapted for gliding; the lubricated surface forms a protective skinlike layer with a coefficient of friction similar to cartilage on cartilage, or ice on ice.
- Repair techniques that minimize friction have better results in animal models of tendon repair.
- Therapy that enables gliding yields better results in animal models and clinically.
- It is possible to modify the gliding surface to reduce friction through tissue engineering; such modifications result in fewer adhesions after tendon repair in animal models and, in some reports, clinically.
- Modification of the gliding surface of tendon grafts can convert an extrasynovial graft into the functional equivalent of an intrasynovial graft, with improved results in animal models.

Fig. 1. (A) Typical extrasyovial tendon is surrounded by an areolar paratenon ($\times 400$). (B) intrasyovial tendon has no paratenon ($\times 400$).

Fig. 2.

(A) Extrasynovial surface after 1000 cycles of repetitive motion against a pulley (scanning electron microscope [SEM], $\times 20$). (B) Intrasynovial surface after 1000 cycles of repetitive motion against a pulley (SEM, $\times 25$).

Fig. 3.
Typical appearance of an extrasynovial tendon graft in a canine model in vivo after 6 weeks.
Note extensive adhesions.

Fig. 4.
(*Top*) A high-profile repair: MGH/Becker. Note exposed core suture on the palmar tendon surface. (*Bottom*) A low profile repair: modified Kessler. Note absence of exposed core suture on the palmar tendon surface.

Fig. 5.
Tendon trimming after partial tendon laceration.

Fig. 6. Modified synergistic motion. (*A*) Wrist flexion phase, (*B*) wrist extension phase. (*Data from Tanaka T, Amadio PC, Zhao C, et al. Flexor digitorum profundus tendon tension during finger manipulation. J Hand Ther 2005;18:330–8.*)