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Tendon excursion and gliding: Clinical impacts from humble concepts

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Abstract

As integral components of the musculoskeletal system, the primary function is transmission of muscle forces to the skeletal system. Proper excursion and gliding of the tendon determine the efficiency of this function. Studies of the tendon excursion and gliding based on two simple mechanical concepts have resulted in several significant clinical implications.

Keywords: Tendon; Gliding; Excursion; Friction

1. Introduction

As integral components of the musculoskeletal system, the primary function of tendons is transmission of muscle forces to the skeletal system. Proper excursion and gliding of the tendon will determine the efficiency of this function. Studies of the tendon excursion and gliding based on two simple mechanical concepts have resulted in several significant clinical implications. In this article, the illustration of the concepts and examples of applications will be based on a limited number of publications of the author rather than an exhaustive review of the literature.

2. Excursion

Tendon excursion takes place as the muscle contracts and the joint rotates. The amount of tendon excursion is related to the amount of the joint rotation. A pulley-type constraint keeps the tendon path close to the bone when the tendon crosses a joint. In normal anatomy, there is an intimate relationship between tendon excursion and joint rotation that maintains the mechanical advantage of the tendon while preserving the passive and active muscle tension during joint motion. The instantaneous moment arm (r) or mechanical advantage of a tendon can be related to the tendon excursion (E) and the joint rotation (φ) as

$$r = \mathrm{d}E/\mathrm{d}\varphi.$$

This simple concept has been confirmed analytically for various scenarios of tendons crossing the joint (Fig. 1) (An et al., 1979, 1983). The major advantage of assessing the moment arm of a given tendon around the joint using this approach is that the measurement does not rely on the geometric information of the tendon insertions across the joint and the location of the center of joint rotation does not have to be defined during the measurement (An et al., 1983, 1984). This geometric information is sometimes difficult to define and is subject to potential errors (Hughes, et al., 1998). Experimentally, the tendon excursion has been measured using linear or rotary potentiometers in vitro or ultrasound imaging in vivo. Joint rotations have been monitored using goniometers, magnetic tracking devices, and imaging systems.

This simple concept relating the joint rotation to the tendon excursion by the moment arm or mechanical advantage has been used to better understand the functional anatomy of the muscle and joint mechanics

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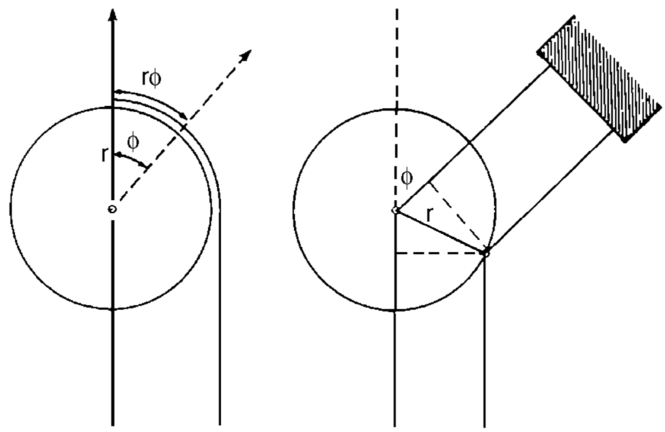

Fig. 1. Simple relationship between instantaneous moment arm of a tendon and tendon excursion and joint rotation was applicable to each of the models simulating the tendon crossing the joint (Reprinted from An, K.N., Chao, E.Y., Cooney, III W.P., Linscheid, R.L., 1979. Normative model of human hand for biomechanical analysis. Journal of Biomechanics 12, 775–788; Elsevier).

(An et al., 1983; Smutz et al., 1998; Kuechle et al., 1997). In one study, the tendon excursions during rotation of individual index fingers were recorded continuously throughout the joints' ranges of motion (An et al., 1983). Both, intrinsic and extrinsic muscles were studied during flexion–extension and abduction–adduction movements. The precise roles of the two extrinsic extensor communis and extensor indicis in abduction and adduction function, respectively, were validated for the first time. In addition, the variations of the intrinsic muscles to the flexion function of metacarpophalangeal joint were clearly depicted. For the function of the thumb joint (Smutz et al., 1998), the flexor pollicis longus was a pure flexor while flexor pollicis brevis was an adductor as well as a flexor, the extensor pollicis longus was an extensor and an adductor, extensor pollicis brevis was an extensor and a mild abductor, the abductor pollicis longus was an extensor as well as an abductor, the abductor pollicis brevis was mainly an abductor, the adductor pollicis was a major flexor as well as an adductor, and the opponents pollicis was a flexor and an abductor. This information was used in the design of tendon transfer for restoring the thumb function.

This moment arm-tendon excursion principle has been used to compare various surgical reconstructive procedures and the options for tendon transfer and tendon reattachment (Liu et al., 1998; Nakajima et al., 1999). During the repair of some rotator-cuff tears, the torn tendon cannot be freed up adequately to permit reattachment at its original anatomical site of insertion. An option is to advance the site of insertion medially and reattach the tendon to a trough in the sulcus or to the humeral head. The biomechanical effects of such medial advancement on the moment arm of the supraspinatus muscle during glenohumeral elevation were studied. Three and 10 mm of medial advancement of the tendon for attachment in the sulcus had a minimum effect on the moment arm during elevation compared with the value determined for the intact condition. However, 17 mm of medial advancement was found to reduce the moment arm significantly.

For a tendon spanning more than one joint, the excursion taking place at adjacent joints influences the total excursion and thus the joint rotation is a kinetic chain relationship. The tenodesis phenomenon is well recognized among the tendons of the extrinsic muscles of the hand (Fig. 2). Usually, the flexors and extensors of the finger and thumbs span the joints of digits as well as the wrist joint. Therefore, the wrist position or rotation would influence the tension of these tendons during finger movement; in return, the movement of the wrist joint would influence the digit motion as well. The coordinated motion between the finger and wrist joints resulting from passive tension of the muscles while performing synergistic wrist motion was investigated (Su et al., 2005). Moving the wrist from flexion into extension induced synergistic finger joint motion as follows: the distal interphalangeal joint angles changed from an average of 12° of flexion to 31°; proximal–interphalangeal joint angles changed from 19° to 70°; and metacarpal phalangeal joints changed from 27° to 63° of flexion. For the postoperative treatment of flexor tendon injury, it has been demonstrated that synergistic wrist motion could eliminate tendon slackness in the palm and improve tendon excursion during passive finger joint motion (Cooney et al., 1989; Horii et al., 1992).

The effect of tendon excursion in two joint muscles also helped explains why the mechanism of co-contraction of quadriceps and hamstrings at the knee joint during closed-kinetic-chain exercises resulted in favorable tension in the anterior cruciate ligament after reconstruction (Lutz et al., 1993). The closed-kinetic-chain exercise produced significantly less posterior shear force at all angles when compared with the

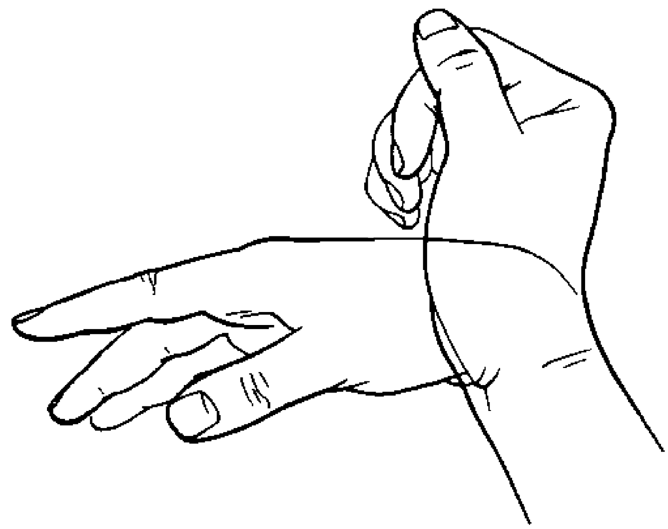

Fig. 2. The interaction among the adjacent joints due to the excursion of multi joint tendon could be demonstrated by this tenodesis effect (Reprinted from Horii, E., Lin, G.T., Cooney, W.P., Linscheid, R.L., An, K.N., May 1992. Comparative flexor tendon excursion after passive mobilization. An in vitro study. Journal of Hand Surgery 17A(3), 559–566, Elsevier).

open-kinetic-chain extension exercise. In addition, the closed-kinetic-chain exercise produced significantly less anterior shear force when compared with the open-kinetic-chain flexion exercise.

Due to the length-tension interaction during muscle contraction, the potential tension generated by the muscle will be influenced by the joint position and tendon excursion (An et al., 1989; Kaufman et al., 1989). In vivo determination of the physiological and anatomical parameters of muscle contraction is difficult, but not impossible. The optimum muscle length and muscle stress of three major elbow flexors, the biceps brachii, the brachialis, and the brachioradialis were determined (Chang et al., 1999). The elbow flexion torques in eight different joint were measured first, then the mathematical model was used to estimate the tendon excursion and thus muscle fiber lengths at those given elbow positions. The optimum muscle lengths were finally determined using an optimization method. The calculated muscle stress for each subject was on average $109\,\mathrm{N/cm^2}$, while the optimum muscle length for the biceps brachii, the brachialis, and the brachioradialis was on average 14.05, 6.53, 17.24 cm, respectively. The joint angles corresponding to these optimum muscle lengths are 110°, 100° and 50° of elbow flexion, respectively. The estimate of optimum muscle length is important for muscle modeling and tendon transfer surgery by taking advantage of the length-tension relationship of individual muscles.

The muscle length–tension relationship consideration is important in the treatment of massive rotator cuff tear. Advance of the retracted tendon will affect the relationship throughout the range of arm elevation, especially for subscapularis and supraspinatus muscles where the muscles are operating at the peaks of the length tension curve. Any elongation of muscle would shift the operating range to the descending part of the curve and thus reduce the force generation potential. Therefore, gapping the tear with a patch or graft would make sense, theoretically. On the other hand, the infraspinatus muscle is operating in the ascending part of the length–tension curve. Advance the retracted tendon where the muscle will be elongated would not reduce the potential force generation. In this situation, the consideration of graft material to fill the gap may not be that critical.

3. Gliding

A tendon gliding through the pulley is analogous to a belt wrapped around a fixed mechanical pulley (Fig. 3) (An et al., 1993). As the tendon moves proximally, the tensions in the tendon proximal and distal to the pulley (F_p and F_d) are related to the angle (θ) of the tendon segments across the pulley or arc of contact, and the friction coefficient (μ):

$$F_p = F_d e^{\theta\mu},$$

$$f = \text{friction} = F_p - F_d.$$

This simple relationship clearly demonstrates the importance of angle of contact and the friction coefficient. It explains why avoiding awkward joint postures is important in ergonomic consideration to reduce the repetitive injury of soft tissue. In-depth investigations of the mechanism of lubrication associated with the tendon gliding provided insight related to the potential etiology of soft tissue disorders including carpal tunnel syndrome and tendonitis.

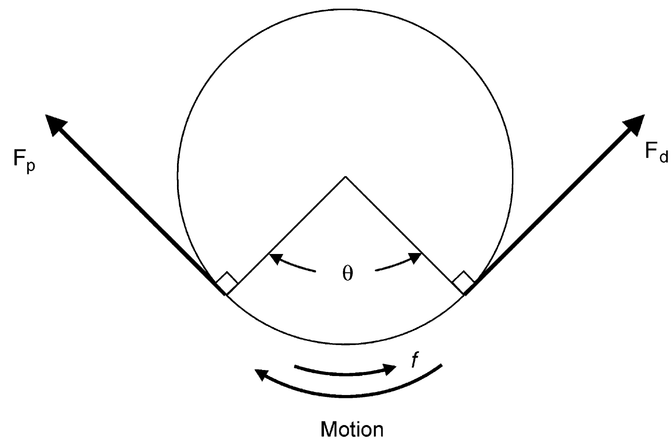

Fig. 3. The friction between the tendon and pulley is related to the arc of contact (θ), and the friction coefficient (μ).

Clinically, significant improvements have been made in the surgical and rehabilitation modalities for treating tendon injuries.

An experimental system was developed and validated that allows direct measurement of friction at the tendon–pulley interface (An et al., 1993; Uchiyama et al., 1995). The friction force between the flexor tendon and the A2 pulley was then measured to be in the range of 0.021–0.31 N when 4.9 N tendon tension was applied. Furthermore, the friction coefficients were also estimated by measuring the friction force at various arcs of contact and calculating the slopes of the plot of the natural log of F_p/F_d versus the angles. The friction coefficient between flexor tendon and A2 pulley ranged from 0.022 to 0.063 which is higher than those that have been determined for the articular surface in diarthrodial joints (0.003–0.04).

To better understand the characteristic of tendon gliding resistance, the gliding abilities of the flexor digitorum profundus tendon (intrasynovial) and the palmaris longus tendon (extrasynovial) through the A2 pulley were compared (Uchiyama et al., 1997a). The average gliding resistance at the interface between the palmaris longus tendon and the A2 pulley was found to be greater than that between the flexor digitorum profundus tendon and the A2 pulley under similar loading conditions. Both intra- and extra-synovial tendons had been considered as sources of clinical tendon grafts. The flexor digitorum profundus and superficialis tendons, the extensor indicis proprius tendon and the palmaris longus tendon were studied. The intrasynovial tendons produced less excursion resistance than the extrasynovial tendons (Nishida et al., 1999).

The tendon lubrication mechanism was investigated in vitro. The gliding resistance increased significantly after the tendon had been treated with a hyaluronidase solution (Uchiyama et al., 1997a). Alcian-blue staining of the surface of the tendon before and after it was treated with hyaluronidase suggested the presence of hyaluronate complex. Alcian blue-positive and hyaluronidase-sensitive materials, such as hyaluronate or proteoglycan, in the synovial membrane and the matrix of the tendon, may act as a boundary lubricant, facilitating the gliding and reducing the resistance between the tendon and the pulley. Subsequently, other lubricants including lubricin and phospholipids have been identified and are under extensive investigation.

The study of the lubrication mechanisms provides great opportunities for tissue engineering the tendon graft for the purpose of reconstructive procedures. Several approaches of surface modification were developed which could reduce the friction of an extrasynovial tendon for the consideration of tendon graft (Sun et al., 2004). For example, after 500 cycles, the gliding resistance of normal PL tendon increased 10-fold, while the gliding resistance of tendons coated with carbodiimide derivatized gelatin (cd-gelatin) or carbodiimide derivatized gelatin/HA (cd-gelatin–HA) did not increase significantly (Fig. 4). Scanning electron microscopy after 500 cycles of motion showed that the tendon surface in the group treated with cd-gelatin–HA appeared smoother than tendons in the other groups.

Gliding resistance after tendon repair influences the outcome of the surgical procedure. Gliding resistance was measured for the intact FDP tendon and for the same tendon after it was cut transversely and repaired with a 4/0 Ticron core suture and a 6/0 running epitendinous nylon suture (Coert et al., 1995). The breaking strength and gliding resistance between the pulley and flexor tendon was measured for various suture techniques including modified Kessler, Tsuge, augmented Becker and Cruciate (Momose et al., 2001). After repair, the gliding pattern of the tendon through the A2 pulley changed significantly. The resistances were approximately doubled. As expected, the repair strength increases as the number of strands crossing the repair increases. It was also found that these stronger repairs

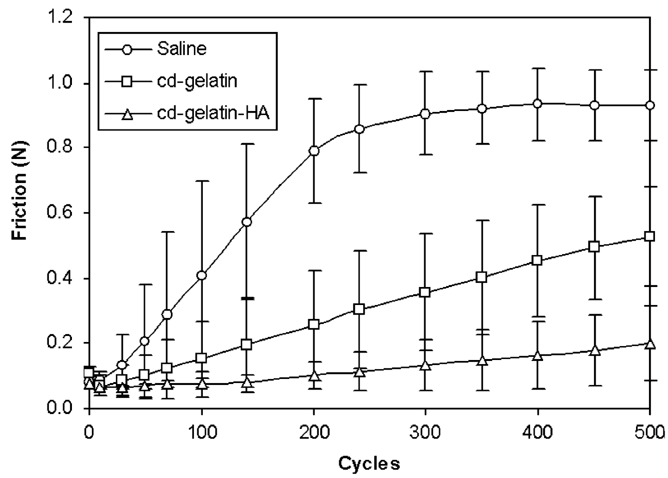

Fig. 4. Gliding resistance of peroneus longus tendons treated with saline, 10% gelatin/0.25% EDC/0.25% NHS (cd-gelatin) or 10% gelatin/1% HA/0.25% EDC/0.25% NHS (cd-gelatin–HA) at different cycles of simulated flexion/extension: (Reprinted from Sun, Y.L., Yang, C., Amadio, P.C., Zhao, C., Zobitz, M.E., An, K.N., 2004. Reducing friction by chemically modifying the surface of extrasynovial tendon grafts. Journal of Orthopaedic Research 22, 984–989, Elsevier).

need not produce higher gliding resistance than less robust repairs. Suture techniques with a multi-strand core suture, with knots located outside the tendon surface, and with multiple-loops on the tendon surface may result in increased gliding resistance between the tendon and pulley system after tendon repair (Zhao et al., 2001).

Maintaining a smooth lubricated surface between the flexor tendon and sheath after tendon repair is very important for restoration of digit function. The mechanics of the post-operative rehabilitation were studied in a canine model in vivo. One hundred and twenty flexor digitorum profundus tendons were partially lacerated and repaired with either a modified Kessler or Becker repair. The postoperative therapeutic regimen was either synergistic wrist and digit motion or passive digit flexion and extension with the wrist fixed in 45° of flexion. Compared to intact tendons, friction was significantly increased immediately after tendon repair. The gliding excursion of the repaired tendons treated with synergistic wrist and finger motion therapy was significantly greater than that of tendons rehabilitated with the wrist fixation therapy, suggesting that wrist extension generates force that can pull the repair site through the pulley, thereby increasing passive excursion of the tendon (Zhao et al., 2002a). As a result of increased tendon excursion, synergistic therapy may improve the clinical outcome after repair of partial tendon lacerations. The synergistic motion group had a significantly lower adhesion grade and significantly less adhesion breaking strength than the wrist fixation group at 3 and 6 weeks (Zhao et al., 2002b).

The characteristics of tendon gliding have led us to hypothesize its relationship to the development of various types of repetitive trauma disorders of tendon. The etiology of spontaneous extensor pollicis longus (EPL) tendon rupture is still largely unknown. It is possible that friction within the sheath may play a role. We found that the gliding resistance of the EPL tendon was significantly higher than that of the extensor digitorum communis tendon of the index finger (EDC II). There was also a significant effect on gliding resistance due to wrist position. Positioning the wrist close to neutral flexion/extension and in some ulnar deviation minimizes the friction within the EPL sheath. Such positions may be advantageous for splinting patients at risk for EPL rupture (Kutsumi et al., 2004). While the etiology of de Quervain's disease is unknown, repetitive motion coupled with awkward wrist position and septation within the first dorsal compartment are considered causative factors. In our study, it is noted that a combination of septation and wrist position significantly affected extensor pollicis brevis tendon gliding resistance in this cadaver model. These factors may contribute to the development of de Quervain's disease (Kutsumi et al., 2005). The gliding resistance and potential micro-trauma of the subsynovial connective tissue were investigated and hypothesized for initiating the cascade leading to carpal tunnel syndrome. Excessive or abnormal gliding within the bicipital groove could potentially lead to the bicep tendonitis (Heers et al., 2003). A similar hypothesis is currently being investigated for posterior tibial tendon dysfunction.

4. Summary

More than two decades of investigating tendon function based on two simple biomechanical concepts have provided unique insight and opened the doors to exciting future research topics. Some of the fundamental information of tendon joint interaction and the characteristics of tendon gliding seem to be relatively useful in improving outcome of the patient treatments.

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