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REVIEW

Achilles Tendon Rupture: Avoiding Tendon Lengthening during Surgical Repair and Rehabilitation

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Achilles tendon rupture is a serious injury for which the best treatment is still controversial. Its primary goal should be to restore normal length and tension, thus obtaining an optimal function. Tendon elongation correlates significantly with clinical outcome; lengthening is an important cause of morbidity and may produce permanent functional impairment. In this article, we review all factors that may influence the repair, including the type of surgical technique, suture material, and rehabilitation program, among many others.

INTRODUCTION

The Achilles tendon (AT†) is the strongest and thickest tendon in the human body. It serves a basic function of connecting the soleus and gastrocnemius muscles to the calcaneus bone to allow plantar flexion about the ankle joint. By virtue of its biomechanical properties, the AT influences the capacity of many human movements [1].

Since first described by Ambroise Paré in 1575 and reported in the literature in 1633, rupture of the AT has received increasing attention regarding treatment. This attention is based on the fact that rupture of the AT is both a serious injury and one of the most common tendinous lesions, affecting approximately 18 in 100,000 people, typically males between 30 and 50 years of age [2]. The common site for AT rupture is 2 to 6 cm from the calcaneal insertion. That region has a smaller cross sectional area than the rest of the tendon [3]. For a reason yet unknown, the insertional area is able to withstand higher strains than the rest of the tendon without failing.

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†Abbreviations: AT, Achilles tendon; N, Newtons; ROM, range of motion.

Treatment of AT rupture remains controversial [4]. Several scientific articles have addressed the best therapeutic option for this injury, including open surgical repair, conservative treatment, and percutaneous surgery, among others. However, the clinical relevance of achieving an optimal length and tension during surgical repair of the AT may be somewhat underestimated by surgeons and physical therapists, with only few mentions in the medical literature [5,6,7].

Several research studies have made a significant contribution to different areas of tendon treatment. It is crucial to know how the current concepts on tendon mechanical behavior, surgery, and rehabilitation interact and may contribute to reach an optimal clinical outcome. The objective of this article is to review all factors that may affect the optimal length and tension restoration after AT rupture.

MECHANICAL BEHAVIOR OF TENDONS

Some basic concepts of the mechanical behavior of tendons may be useful for surgeons in charge of repairing AT ruptures.

The basic function of the tendons is to transmit the force created in the muscle to the bone, thus making joint and limb movement possible. To do this effectively, tendons must be capable of resisting high tensile forces with limited elongation [8]. Tendons transmit loads with minimal energy loss and deformation. Tendons are viscoelastic materials and display sensitivity to different strain rates. A tendon is perfectly elastic as long as the strain does not exceed 4 percent, after which the viscous range commences. Elasticity is a time-independent phenomenon, while viscosity is a time-dependent phenomenon against force. At low rates of loading, tendons are more viscous; therefore, they absorb more energy, which is less effective at moving loads. At high rates of loading, tendons become more brittle with high strength but low toughness and therefore absorb less energy and are more effective at moving heavy loads [9].

Force and deformation are two critical mechanical properties that are commonly measured when testing tendon structures. Force and deformation provide information about the quantitative mechanical behavior of a structure without regard to its length and size, while stress and strain account for the dimensions of the structure and thereby provide information about its qualitative properties. The mechanical properties of isolated tendons are normally determined by *in vitro* tensile tests. The tissue is elongated to failure at a prescribed rate, while the changes in force are recorded. The force is plotted against time, but since a constant strain rate is normally used, the time axis is proportional to elongation. The parameters that are measurable from this force-elongation curve include stiffness (slope in the linear region), maximum load, strain (time) to maximum load, strain to failure, and energy to failure (area beneath the curve). Mechanically, tension is the magnitude of the pulling force exerted on an object. It is the opposite of compression, and it is measured in Newtons (N). Stiffness is an important constituent of tendon mechanical properties; it is defined as the resistance of tendons to an increase in length and is calculated as muscle force/length. Stiffness has a significant influence on force transmission, muscle power, and energy absorption and release during locomotion. An optimal level of tendon stiffness is critical for effective muscle-tendon interactions and minimizing the energetic costs of locomotion.

Under mechanical stress, tendons undergo *stress-relaxation*, *creep*, and hysteresis. *Force relaxation* means that with the same degree of extension, the load required to maintain extension decreases over time [9,10]. *Creep* means that with a constant load, length (deformation) increases over time. *Hysteresis loop* is a measure of the energy that is dissipated or lost during the loading and unloading test of the tendon; therefore, it is an indicator of the viscous properties of the tissue. It is crucial to understand the creep phenomenon because it is responsible for the tension loss occurring during the initial phase of the postoperative period. Creep decreases exponentially with increase in the initial strain [3]; therefore, we

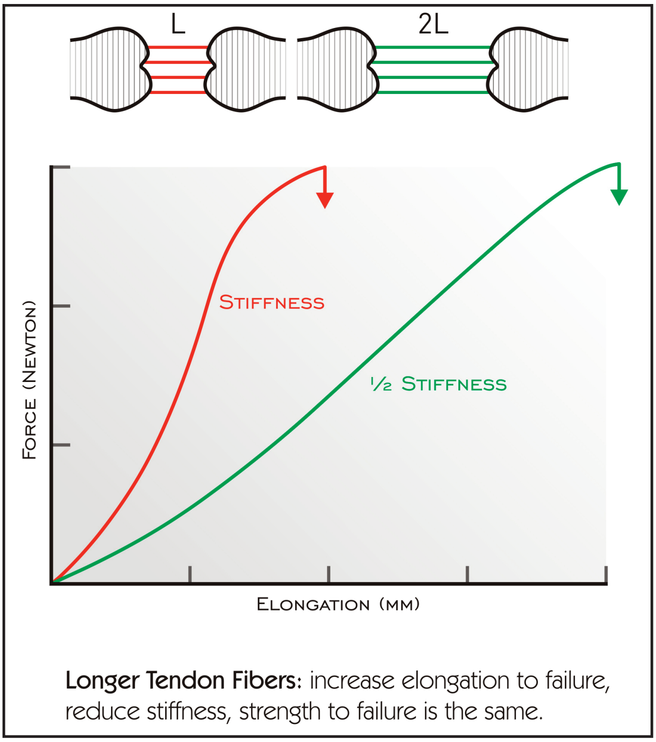

Figure 1. The effect of original length of tendon on the shape of the force elongation curve. (adapted from Curwin SL. The aetiology and treatment of tendinitis. In: Harries M, Williams C, Stanish WD, Micheli LJ, editors. Oxford Textbook of Sports Medicine. New York: Oxford University Press; 1994, p 516).

recommend performing the repair with high amount of tension.

Tendon is a remarkably strong tissue. Its *in vitro* tensile strength is about 50-100 N/mm^2. The cross-sectional area and the length of the tendon affect their mechanical behavior. The greater the tendon cross-sectional area, the larger loads can be applied prior to failure (increased tendon strength and stiffness). The longer the tissue fibers, the greater the fiber elongation before failure (decreased tendon stiffness with unaltered tendon strength) [11] (Figure 1). Thus, a tendon with a cross-section area of 1 cm^2 is capable of supporting a weight of 500-1,000 kg. Athletes who subject their AT to repetitive loads as habitual runners have shown larger AT cross-sectional area than control subjects [12,13]. An increased tendon cross-sectional area would reduce the average stress of the tendon, thereby decreasing the risk of acute tensile tendon rupture.

Strain is the mechanical parameter that most directly influences tendon damage accumulation and injury [3]. Forces that place highest stress on the muscle-tendon unit occur during the eccentric muscle contractions [10]. The AT experiences high *in vivo* stresses (approximately 5 percent vs. 1.5-3 percent strains expected for most tendons at 40MPa), so it is prone to suffer high incidence of injuries. The human AT has a safety factor of 1.5, whereas most tendons have a safety factor of 4 or greater [14].

Another relevant property of tendon repairs is the *gapping resistance*, which can be evaluated through cyclic loading studies.

SELECTING APPROPRIATE TREATMENT FOR ACHILLES TENDON RUPTURES

There is no consensus on the best therapy for AT ruptures; however, a complete discussion of all treatment alternatives for this injury is beyond the scope of this article.

Which option should the orthopedic surgeon select? When deciding the treatment, it is of utmost importance to consider the nature of the rupture, the time until diagnosis, whether it is primary or recurrent, the age and health of the patient, and whether the injury occurs in high-level, recreational, or non-athletic population.

Although non-operative treatment can give satisfactory results, recent studies have suggested that operative repair of the AT may have advantages such as decreased ankle stiffness and calf atrophy, fewer cutaneous adhesions, and lower risk of trombophlebitis. For the purpose of this review, it is important to highlight that non-operative treatment cannot avoid tendon lengthening [7].

In a meta-analysis conducted by Khan et al., including 12 randomized control trials and 800 patients, open surgery was associated with lower risk of re-rupture than non-operative treatment but higher risk of other complications, especially wound problems [15].

Surgical treatment seems to be the method of choice for young people, athletes, and delayed ruptures. There is no single, uniformly accepted surgical technique, and the options include open repair, with or without augmentation, and percutaneous techniques.

Minimally invasive and percutaneous techniques have been mentioned as valid therapeutic alternatives for AT ruptures. Khan et al. found that percutaneous surgery was associated with lower risk of complications than open surgery [15]. However, that technique does not allow the surgeon to visualize the ruptured tendon ends and achieve appropriate tendon tensioning [16]. Furthermore, imaging studies have reported that 100 percent of AT repaired by percutaneous technique showed residual gap on MRI at four weeks postoperative [17].

New minimally invasive modalities for AT repair may allow direct visualization of the two ends and have been reported satisfactory clinical results [16]. However, further clinical studies are needed to validate these techniques.

TENDON LENGTHENING AFTER ACHILLES TENDON REPAIR

Lengthening of the AT after surgical repair is due to two main factors: lack of proper tension at the time of surgery and progressive tendon lengthening during the postoperative period [18]. Lengthening is an important cause of morbidity after AT rupture [19] and may produce permanent functional impairment.

Separation of AT ends has been clearly demonstrated after repair [18]. Lee et al. also reported that AT tendon elongation correlated significantly with clinical outcome; the less elongation occurred, the better outcome scores. This elongation was not correlated with isokinetic calf muscle strength, body mass index, or age. Furthermore, weakness in the end-range plantar flexion of AT repair has been attributed to an excessive tendon lengthening during muscle contraction. Together, these studies indicate the need for stronger Achilles tendon repair [18].

AT lengthening is difficult to measure directly. An increase in ankle dorsiflexion has been used as a surrogate measure of the length of the musculotendinous unit of the calf. The AT, as the prime ankle plantarflexor, is the factor that limits dorsiflexion. Cadaveric models have shown that other regional soft tissues structures do not influence the maximal dorsiflexion; when the AT is sectioned, the limiting factor becomes the impingement of the talar neck upon the anterior aspect of the tibia [19]. It can therefore be assumed that the AT remains the key determinant of maximal ankle dorsiflexion even when the tendon is lengthened [19]. The same study reported that maximal ankle dorsiflexion increased by a mean of 12º for each 10 mm increase in length.

SURGICAL FACTORS INFLUENCING TENDON TENSION REPAIR

Secure soft-tissue fixation is essential to many clinical applications, from direct tendon repair to tendon transfers to ligament and tendon reconstructions. It allows for early rehabilitation before biological healing, which is critical to many procedures. Minimizing elongation of the sutured tendon construct is a critical aspect of soft tissue fixation because elongation of the graft may be associated with functional construct failure [20].

Table 1. Summary of recommendations to reduce tendon lengthening during Achilles tendon repair.

1. Free proximal and distal adhesions
2. Use large caliber (≥ #2) non-absorbable braided suture materials (i.e. polyblend)
3. Use locking suture techniques (i.e. Krackow)
4. Sutures should be place at approximately 2.5 cm from the rupture site
5. Knots should be tied away from the rupture site (i.e. “gift-box technique”)
6. Epitendinous suture augmentation is recommended

Biomechanical characteristics of the tendon repair depend mainly on three factors: the quality of the tissue, the strength of the knot, and the strength of the suture material itself.

The quality of the tissue affects the “coefficient of friction,” which is the holding capacity of the suture within the tendon. This is an important concept because the failure of the tendon repair usually occurs due to pull-out of the suture material within the tendon; knot failing was also observed, while suture breakage is uncommon [21]. Recommendations to reduce tendon lengthening during Achilles tendon repair are summarized in Table 1.

Suture Material

Surgical fixation of tendon is mostly accomplished with sutures, but there is no universal consensus on which is the best type of suture for AT repair. Suture techniques show differences from one continent to another. European surgeons tend to use strong monofilament or braided absorbable materials, whereas Americans prefer mechanically strong stitches with braided non-absorbable sutures.

Suture caliber definitively influences the repair; a biomechanical study using flexor tendons revealed that increasing suture caliber increased repair strength [22].

Harrell et al. [23] studied the mechanical properties of different tension bands and found that four loops of No. 5 braided polyester withstood similar failure load to stainless steel wire.

Synthetic polyblend sutures have been introduced for tendon repairs with reportedly greater strength than polyester suture. Benthien et al. [24] found that polyblend sutures repair resulted in a 260 percent higher load to failure and 33 percent less gap formation at the repair site after 3,000 loading cycles; all repairs failed at the knot.

Suture Technique

There are a variety of suture techniques described for grasping and holding soft tissues. The Kessler and Bunnel stitches are well-known for their holding power and are often used when repairing tendons. In 1986, Krackow et al. [25] described a new locking suture for fixing ligaments and tendons. The classic Krackow stitch involves three or more locking loops placed along each side of the tendon. Watson et al. [26] demonstrated that the Krackow locking repair is stronger than Bunnel and Kessler technique, establishing that the Krackow technique is the benchmark biomechanically. Additional studies confirmed the superior pull-out strength of locking loop techniques. McKeon et al. [27] found that load to failure is greatly increased by adding a second interlocking Krackow stitch placed 90º to the first. They also reported that adding more than two locking loops did not increase load to failure or consistently change elongation. Using only two locking loops not only saves valuable operative time but also avoids potential necrosis and injury of the tendon constricted by the loops of the suture. Additional unnecessary suture loops will add more links in the chain, more nonlinear sutures, and perhaps increase the risk of lengthening through slippage.

The site where the knot is tied is also of importance when considering tension restoration. Two different studies have reported higher repair strength when the knot is tied away from the rupture site. Jaakkola et al. [28] found that the triple bundle is nearly three-fold stronger in tension that the

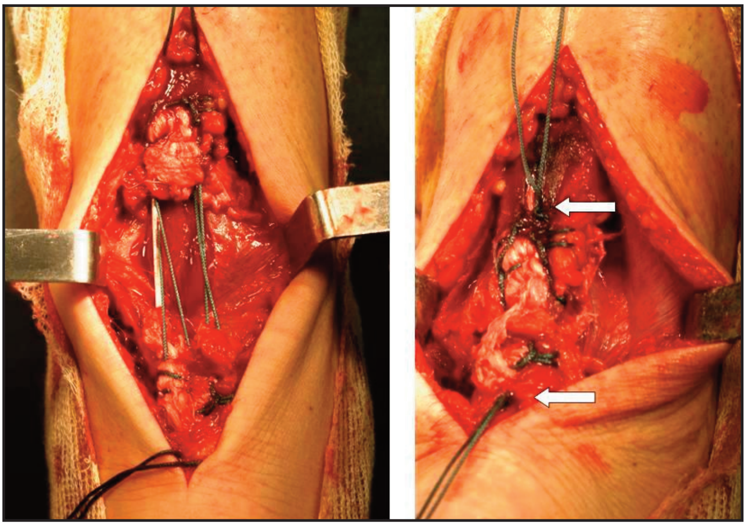

Figure 2. The "Gift-box" technique for Achilles tendon repair. Sutures are tied away from the rupture site (arrows).

Krackow locking loop; this difference is mainly due to the increased number of strands crossing the rupture site. Another factor in this difference is that the knot was tied away from the rupture site in the triple bundle technique, whereas in the Krackow technique, the knot is tied at the rupture site. Having the knot at the rupture site could set up a stress riser on the suture at the rupture site, and subsequent tension on the suture could result in early failure at the knot. More recently, Labib et al. [29] tested a modification of the Krackow technique in which the knots of the suture were tied over the cross-limb of the counter suture ("gift-box" technique) (Figure 2) and found that the load to failure increases more than two-fold. The authors considered that the "gift-box" technique is a simple a relatively quick method without constricting additional tissue during the repair as reported in the "triple bundle technique."

Finally, positioning the ankle in plantarflexion for knot tying would help to reduce tendon lengthening and to achieve a stiffer repair.

Suture Augmentation

Several augmentation techniques for AT repair have been published in the orthopedic literature. Epitendinous suture augmentation has been shown to increase gap resistance and overall strength in flexor tendon repairs of the hand. Lee et al. [18] found that cross stitch augmentation of Achilles tendon repair yields a stronger and stiffer repair with greater resistance to gapping. The augmentations were performed so that the suture grabbed not only the epitendon but also tendon tissue approximately 2.5 cm away from the rupture site, using No. 0 polydioxanone sutures. Augmented Krackow repair can withstand early range of motion rehabilitation and immediate weight bearing with a 1-inch heel lift.

The authors recommended that, as skin closure can be problematic, suture bulk should be kept to a minimum if possible. On the other hand, fascia flap augmentation using a turned down 10-mm-wide central gastrocnemius aponeurosis flap, did not show any advantage over simple end-to-end repair [30].

IMPLICATIONS OF THE REHABILITATION PROGRAM ON TENDON LENGTHENING

Achilles tendon rupture is most commonly managed with open surgical repair; however, there is no clear consensus regarding the optimal postoperative rehabilitation protocol for this injury after surgery [4]. The trend has been to accelerate the rehabilitation protocol after AT tendon repair, including earlier weight bearing, range of motion, and strengthening exercises, as well as shorter immobilization times and faster re-

Table 2. Estimated forces at the Achilles tendon during different activities [32,33,34,35,36].

Task	Forces at AT (Newtons)
Ankle Immobilized Neutral	370
Passive ROM	400
Walking + Boot Neutral	590
Cycling	1000
Walking	1500-2000
CMJ	1900
Squat Jumping	2200
Repetitive Hopping	3790
Running	9000

turn to sports [31,32]. However, this protocol does not have much scientific support.

During weight bearing, the AT transmits the largest force of any tendon in the body. Published reports on the strength of suture of cadaveric AT indicate that these repairs are extremely weak compared to forces that AT is exposed during walking. Common repairs may fail at forces from 45 to 250 N. Strongest techniques are the "3-bundle" (453 N) and "augmented 4-strand Krackow" (323 N). Thus, it would be surprising that the reported re-rupture rates following surgical repair would not be higher. While it is certainly important to maximize the strength of our repair, it is probably more clinically relevant to create repairs that increase gapping resistance.

It is important to consider the estimated forces applied to the AT during most common exercises and activities during the rehabilitation period (Table 2).

We put together the current knowledge on several factors of the postoperatively regimen, which may affect the rupture repair, in order to establish sound and safe guidelines.

Cyclic Loading and Gapping Resistance

The repair resistance to gap formation is of great importance. If there is a gap at the repair, increased granulation tissue, adhesions, and delayed collagen maturation will result. As the gap becomes larger, healing is delayed and the result is a weaker, more attenuated repair. Increased resistance to gapping is probably just as important as increased strength and stiffness. Gapping greater than 5 mm is considered to be a clinical failure.

Separation of AT ends after rupture repair has been investigated by several authors. Lee et al. [18] found that significant amount of gapping is typically present when testing different sutures prior to ultimate failure. Nystrom et al. [37] reported that separation of the AT ends followed a biphasic course, with an initial separation at 0-7 days, no separation between 8-12 days, and late separation at 22-35 days. On the other hand, Kangas et al. [38] found that elongation curves first rose at 6 weeks and then slowly fell.

In order to minimize gap formation, calf muscle stretching exercises should be avoided until the initiation of the remodeling phase of the healing period (approximately 6 weeks after surgery).

Ankle Position

When the ankle is immobilized, stress on the AT during gait is determined by the degree of plantar flexion and the contractile activity of the plantar flexors [33]. The greater the degree of plantar flexion in which the ankle is immobilized the greater will be the subsequent atrophy [39]. The tension in the repaired tendon at neutral position is only a small percentage (6.4 percent) of the strength of the tendon when operatively repaired with a locking loop suture technique [40]. On the other hand, contractile activity during weight bearing on the immobilized ankle may result in undesirable stress on the Achilles tendon. The clinical dilemma is that no stress accelerates atrophy, whereas too much stress may jeopardize the repair. Akizuki et al. [33] reported that in normal ankles, there is still significant contractile activity in the plantar flexors with immobilization in neutral plantar flexion (79 percent of normal walking). However, the simple addition of a 1-inch heel lift is sufficient to reduce plantar flexors activity (57 percent of normal walking), representing 12 percent of MVC of plantar flexors. Although the 1-inch heel lift resulted in less than 10º of plantar flexion, it reduces plantar flexor activity by 22 percent, relative to immobilization in neural. Therefore, heel lifts can be used to reduce stress on the repair while the patient progresses in weight bearing status.

Early Motion and Weight Bearing

Several studies have suggested that early ankle joint range of motion (ROM) exercises during rehabilitation of AT repair may reduce the strength deficits commonly observed between limbs after rigid immobilization techniques. Early ROM exercises have been shown to improve the biomechanical behavior of *in vitro* tendons after rupture and may be a more optimal rehabilitation approach for patients recovering from Achilles tendon rupture. Animal studies have demonstrated the early tension and weight bearing on a repaired tendon improved tendon and calf muscle strength and tendon vascularity.

The relationship between early rehabilitation and tendon elongation is still controversial. Kangas et al. [35] and Mortensen et al. [41] measured AT elongation radiographically using metallic markers implanted after tendon repair at the time of surgery. Mortensen et al. [38] found more elongation in the early motion group, whereas Kangas et al. found less elongation in those patients and correlated with a better clinical outcome. The latter study provides further evidence that protected early motion in the postoperative regimen following open repair is not detrimental and is more likely to be beneficial [42]. Human prospective studies and randomized controlled trials have shown that, compared with cast immobilization, the use of early postoperative ROM and weight bearing showed significant improvement in health-related quality of life in the early post-operative period [43], posed no additional risks and demonstrated a trend toward a reduction in lost work days and an earlier return to sports.

The suture technique used during the surgical procedure will strongly affect the rehabilitation regimen. Biomechanical studies have reported that the strength of percutaneous repair is as much as 50 percent weaker than open repairs [44]. Furthermore, based on cyclic loading studies, Lee et al. [32] do not recommend starting early ROM protocol for patients repaired with percutaneuos techniques. Non-augmented Krackow repairs can withstand early range of motion rehabilitation but not immediate weight bearing with 1-inch heel lift. Augmented Krackow repairs appear the only method in that study to be able to withstand early range of motion and weight bearing with a 1-inch heel lift. It would not be advisable to start unprotected weight bearing in any of these groups.

Muscle Strength and Sarcomere Adaptation

The value of plantar flexion strength measurements after AT ruptures is much debated. It seems that plantar flexion strength is better regained after operative treatment. Loss of plantar flexion strength after non-operative treatment correlates with the calf atrophy. Furthermore, weakness in the end-range plantar flexion after AT repair recently has been attributed to an excessive tendon lengthening during muscle contraction [45].

Moreover, increases in plantar flexor muscle cross sectional area, passive stiffness, and the ability to absorb passive energy also increase [46]. Maintaining or increasing skeletal muscle mass is crucial to improve the ability of the triceps surae and AT to reduce the risk of injury.

Skeletal muscles have been shown to adapt to chronic length change by altering the serial sarcomere number to reset sarcomere length to its optimal length and, consequently, regulate force generation. In a recent animal study of tendon transfer, Takahashi et al. [47] found that muscle and tendon adapt dramatically to chronic length increase, albeit with asynchronous timing. The net result is a transient increase in the serial sarcomere number that appears to be reversed after the delayed adaptive response of the tendon. Apparently, the muscle adaptation "predicts" any tendon elongation, and, as a result, the muscle "readjusts" by substraction of sarcomeres. The authors concluded that understanding the time course of muscle tendon unit adaptation can provide surgeons with information to guide postoperative care following tendon surgery [47].

TREATMENT FOR THE LENGTHENED ACHILLES TENDON

Once tendon lengthening has become permanent, its clinical management is often difficult. Emphasis should be placed on strengthening of primary and secondary plantar flexor muscles. Contractions in the shortest position of the triceps surae muscles ("inner range exercises") are advisable, in an attempt to restore normal length muscle. Eccentric activity combined with "inner range" exercises have shown to generate improved serial sarcomere adaptation.

The exercise program should also include ankle proprioception training because proprioception influences functional movements and bilateral deficits in ankle proprioception have been found in patients after AT rupture [48].

Greater muscle strength is associated with a stiffer tendon [49]. It is suggested that the AT of subjects with greater muscle strength does not impair the potential of storing elastic energy in tendons and may be able to deliver the greater force supplied by a stronger muscle more efficiently.

Finally, is operative shortening an adequate therapy in case of excessive elongation after Achilles tendon rupture? Unfortunately, there is limited information on this topic. Bohnsack et al. [50] reported eight cases of surgical treatment after failed conservative treatment for Achilles tendon rupture in which shortening decreased gait disturbances, improved activity, but lack of plantarflexion strength persisted. The authors concluded that early decision for Achilles tendon shortening might prevent those deficits.

PERSPECTIVES

Treatment of AT ruptures still constitutes a challenge for the orthopedic surgeon because, even with improved nonsurgical, surgical, and rehabilitation techniques, outcomes following tendon repair are inconsistent.

Primary repair seems to be the "gold standard" of care; however, surgically repaired tendons rarely recover functionality similar to the previous state [51]. Most patients with an Achilles tendon rupture seldom achieve full function at 2 years after surgery; moreover, only minor improvements occur after the first year [52]. Poor results have been related to alterations in the cellular organization within the tendon that occur at the time of injury and during the early healing stages [53].

In an effort to increase tendon repair quality, a better understanding of normal development may provide strategies to improve tissue engineering. The use of growth factors, mesenchymal stem cells, and biocompatible scaffolds could enhance tendon healing and regeneration [51]. For instance, recent cadaveric studies have reported promising results using extracellular matrix xenograft by decreasing gapping and increasing repair strength and stiffness after repair [53,54]. In recent years, tissue engineering has made great strides in understanding tendon healing. However, significant challenges remain in developing strategies that will lead to a clinically effective and commercially successful product.

SUMMARY

In summary, Achilles tendon rupture is a serious injury for which the best treatment is still controversial. The surgeon should evaluate a patient's functional requirements carefully and treatment should attempt an optimal restoration of tendon length, tension, and stiffness. Therefore, in trying to prevent excessive elongation of the tendon, which is associated with a poor clinical outcome, there is consensus that operative treatment is the preferred therapeutic alternative for the majority of patients, especially young athletes.

Secure tendon repair fixation is essential to prevent gapping and allow for an accelerated rehabilitation. Selection of the suture material and knotting technique is also crucial to prevent tendon repair separation. Locking-loop stitches using strong non-absorbable sutures, knot tying away from the rupture site, and epitendinous augmentation are highly recommended. Although there is no clear consensus regarding the optimal postoperative rehabilitation protocol for this injury, most physicians advocate for early range of motion exercises and weight bearing. In the future, tissue engineering may lead to improved management of these injuries.

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