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ORIGINAL RESEARCH

Addition of a Vertical Tensioned Locking Loop for Krackow Suture Fixation of Achilles Tendon Repairs: A Biomechanical Comparison

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ABSTRACT

Introduction: Acute Achilles tendon ruptures are common and controversy exists regarding treatment. Open Achilles tendon repair using a Krackow locking suture repair is a commonly utilized technique. We hypothesized that the addition of a vertical locking-loop stitch would increase the strength of the repair.
Methods: Ten matched pairs of human cadaveric Achilles tendons were transected to simulate acute rupture. In each pair, one side was repaired using a standard Krackow technique, while the other side was repaired using a Krackow technique augmented with a vertically oriented locking-loop suture. Five matched pairs were tested for stiffness and ultimate load to failure; the remaining matched pairs were assessed for gap formation at 100, 500, and 1,000 loading cycles.
Results: Mean stiffness and peak load were higher for the augmented Krackow repair than the standard Krackow repair groups (26.92±11.43 N/mm vs 9.41±2.99 N/mm, p=0.043; 497.55±134.44 N vs 202.61±94.34 N, p=0.043, respectively). Smaller gap formation was observed in the augmented repair at 500 cycles (p=0.042). No tendon failures occurred during cyclic loading in the augmented repair group, whereas four tendons failed in the standard repair group (p=0.032).
Discussion: The addition of a vertically oriented locking loop to a standard Krackow repair yielded higher stiffness, peak load, and resistance to gap formation. This repair option may allow early rehabilitation protocols with minimal additional operative time or morbidity for the patient.
Keywords: Achilles tendon rupture; Tendon repair; Krackow suture.

INTRODUCTION

Achilles tendon ruptures are common injuries that pose a treatment dilemma for the surgeon. The incidence of these injuries is 18 per 100,000 and is increasing [1-3]. The injury is more common in males than females, with the average age of 46.4 years [4]. The Achilles tendon is at risk for rupture during rapid, eccentric loading of the gastrocsoleus complex [5]. Achilles tendon ruptures are commonly sustained during athletic activity,

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and the mechanism of injury typically involves forceful push-off of the foot with an extended knee, unanticipated sudden forced ankle dorsiflexion, or violent dorsiflexion of a plantar flexed foot [6]. These injuries have great potential to have a continued negative impact on athletic performance and function even with currently accepted treatments. Recent studies have shown that 32% of National Football League players who suffered Achilles tendon rupture never returned to play [5] and only 44% of National Basketball Association players who suffered a complete rupture of the Achilles tendon and underwent surgical repair returned to play for longer than one season [7].

Debate remains regarding the most effective management of acute Achilles tendon rupture. Current treatment options include closed management, open operative repairs, and minimally invasive or percutaneous operative repairs. A recent meta-analysis of prospective, randomized, controlled trials comparing open operative repair of acute Achilles tendon rupture to nonoperative management demonstrated that open operative repair significantly reduces the risk for rerupture (3.6% vs 8.8%; odds ratio, 0.425; 95% confidence interval, 0.222-0.815) [3]. There are, however, higher incidences of deep infection, noncosmetic scar complaints, and sural nerve sensory disturbance in patients treated with open operative repair [3].

Early accelerated functional rehabilitation protocols have been demonstrated to accelerate healing and lead to improved patient outcomes in the treatment of acute Achilles tendon rupture [8-18]. Such protocols can prevent adhesion formation, joint stiffness, and muscle atrophy, and biomechanical studies have shown early mobilization and range of motion interventions during healing to improve tensile strength and tendon vascularity [19-21]. In vivo testing demonstrates that knee flexion does not significantly reduce force transmission across operatively repaired Achilles tendons, whereas in intact Achilles tendons there is a significant reduction in force with knee flexion of 45-50 deg [20]. The lack of significant reduction in tension seen with knee flexion in the repaired Achilles tendons was hypothesized to be due to tendon lengthening following the repair [20]. In a study by Benum et al., forces transmitted across repaired Achilles tendons were estimated to be 553 N during normal ambulation, 369 N immobilized in a walking cast with ankle at neutral, 282 N immobilized with a 0.5-in heel lift, and 191 N immobilized with a 1-in heel lift [22,23]. It is critical, therefore, in subjects allowed early rehabilitation that the repair technique demonstrate strength, stiffness, and resistance to gap formation capable of withstanding such a postoperative regimen.

Several biomechanical studies exist in the literature comparing the strengths of various suture repair configurations. The Krackow technique is very commonly utilized clinically and has been shown to increase load to failure compared with other suture repair techniques [24]. A biomechanical cadaveric study by Lee et al., however, demonstrated that non-augmented Krackow suture-repaired tendons failed during cyclic loading at a force of 190 N, which corresponds clinically to the force transmitted across the repair during weight bearing with a 1-in heel lift [1]. The researchers showed that a Krackow repair augmented with an epitendinous cross-stitch weave suture significantly increased the strength of the repair and resistance to gap formation, tolerating cyclic loading simulating clinical early rehabilitation protocols. An increased number of suture strands crossing the rupture site have been demonstrated to increase strength and minimize gap repair in biomechanical models [25,26]. Increasing suture caliber also increases repair strength [26]. Increasing the number of strands and suture caliber crossing the repair site risks further damage to the frayed tendon ends and can also impair healing by impeding circulation to the tendon; these risks must be weighed against their benefits by the surgeon performing the repair.

To decrease gap formation, minimize further tissue damage, and increase strength of the open suture repair construct, we tested another modification to a traditional locking-loop Krackow suture construct. The addition of a vertically oriented suture traversing over the second loop of the construct theoretically would protect the susceptible first loop/suture interface during stress across the repair. We hypothesized that the addition of this vertically oriented loop would serve to stiffen the entire construct by converting a two-strand construct to a four-strand construct, thereby increasing the strength and minimizing gap formation.

MATERIALS & METHODS

Ten matched human cadaver Achilles tendons with attached calcaneal bone blocks were harvested (donors aged 61-94 years, average age 75.8 years; eight males and two females), wrapped in saline-soaked gauze, and stored frozen until tested. The 10 pairs were assigned to two groups. Group A consisted of five matched pairs (donors aged 61-84 years, average age 68.4 years; four males and one female), which were examined using an ultimate load-to-failure protocol. Group B consisted of five matched pairs (donors aged 71-94 years, average age 83.2 years; four males and one female), which were examined using a cyclic loading protocol with measurement of gap formation.

Acute Achilles tendon rupture was simulated by sharp transection of the specimens 4 cm proximal to the distal insertion, as 75% of Achilles tendon ruptures are located 2-6 cm proximal to the insertion of the Achilles into the calcaneus [27]. One side of each pair was randomly assigned to receive the control repair, ie, traditional locking-loop Krackow suture fixation; the contralateral limb received the study repair, ie, addition of a vertically oriented locking loop to locking Krackow suture repair. No. 2 braided polyblend suture was used, as this material was shown to have the highest strength in several studies [28,29]. In the control group specimens, four locking loops placed 1 cm apart were placed in the proximal and distal aspects of the tendon defect (Figure 1), which has been demonstrated to have increased strength and resistance to pull out of the repair from the tendon [30]. The suture ends were tied with a square knot with five alternating throws and careful attention to provide appropriate tension to remove excess suture material from each locking loop, and which well approximates the severed tendon ends with the repair. The study repair consisted of a standard four locking-loop Krackow repair with the addition of a vertically oriented locking loop by using No.2 Fiberwire suture (Arthrex, Naples, FL). The tagged ends of the suture were passed proximally and distally between the second and third locking loops of the construct for both medial and lateral limbs using a free needle. The tagged ends passed through the locking loops were then tied

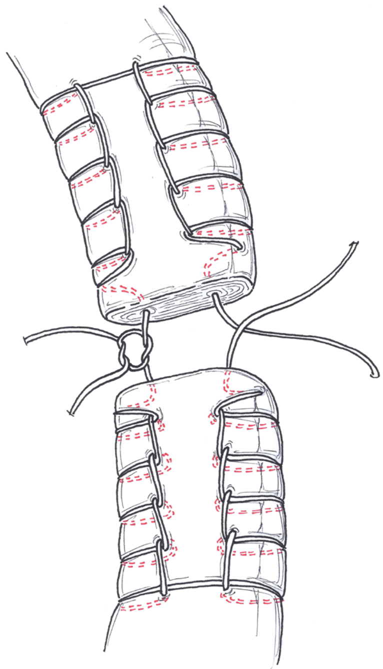

Figure 1. Krackow suture repair (control repair) of a sharply transected Achilles tendon. It was constructed with four locking loops spaced 1 cm apart, with two suture strands crossing the rupture site, and each limb tied with a square knot.

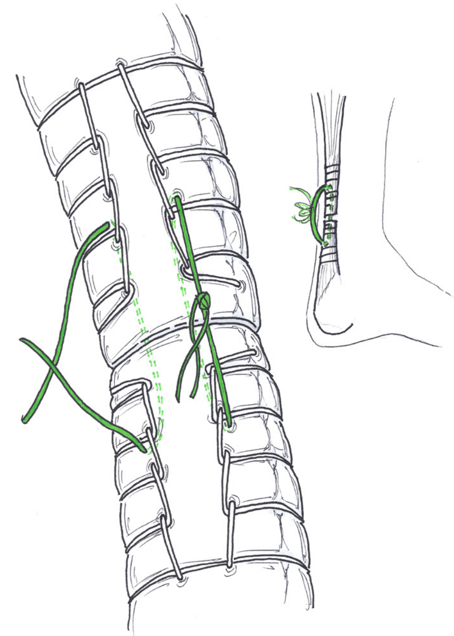

Figure 2. Study repair. Note the addition of the vertically oriented locking-loop stitch, placed between the second and third locking loops of both the medial and lateral limbs of the Krackow repair and secured with a square knot. The addition of these loops theoretically: 1) protects the susceptible first loop/suture interface; 2) converts the repair from a two- to a four-strand construct crossing the repair; 3) allows the surgeon to further dial in the final opposition of the ruptured tendon ends after completing the Krackow repair by tensioning each medial and lateral loop independently.

with a square knot with five alternating throws, allowing the surgeon to set the final opposition of the ruptured tendon ends with both the medial and lateral loops (Figure 2). This independent loop tensioning was performed to close any remaining gapping at the rupture site and ensure full opposition in both the sagittal and coronal aspects of the tendon.

The harvested Achilles tendon repairs were tested in a servo-hydraulic testing device (MTS 810, MTS Systems, Eden Prairie, MN) with a 2,224 N load cell for force transmission measurement. A soft tissue freeze clamp affixed at the level of the musculotendinous junction provided proximal stability to the construct. Two Steinmann pins placed orthogonal to each other transfixing the calcaneal bone block in a fenestrated aluminum housing provided distal fixation (Figure 3).

Group A specimens underwent monotonic loading to failure testing at 2 mm/s. Total failure was defined as a reduction of the load to 10% of the peak force. For each specimen, the peak force value was noted and recorded based on the force displacement curve. Stiffness was also calculated using the linear portion of the loading force displacement curve (N/mm) for both repair techniques [25,30].

Group B specimens were submitted to cyclic loading at 1 Hz, to simulate the rate of human locomotion [1], to forces of 0-100 N for 1,000 cycles. As demonstrated in the literature, the Achilles tendon repair construct must be able to withstand 100 N for passive ankle flexion range of motion [1,20,22,31]. Gap formation measurements were taken using Mitutoyo digital calipers (model CD-6 CS; Mitutoyo America, Aurora, IL) at intervals of 100, 500, and 1,000 cycles, and clinical failure was defined as gap formation of ≥5 mm [2,32,33]. If clinical failure did not occur before the 1000th cycle, the specimens were loaded to failure at 200 N/s and stiffness and peak load values were calculated.

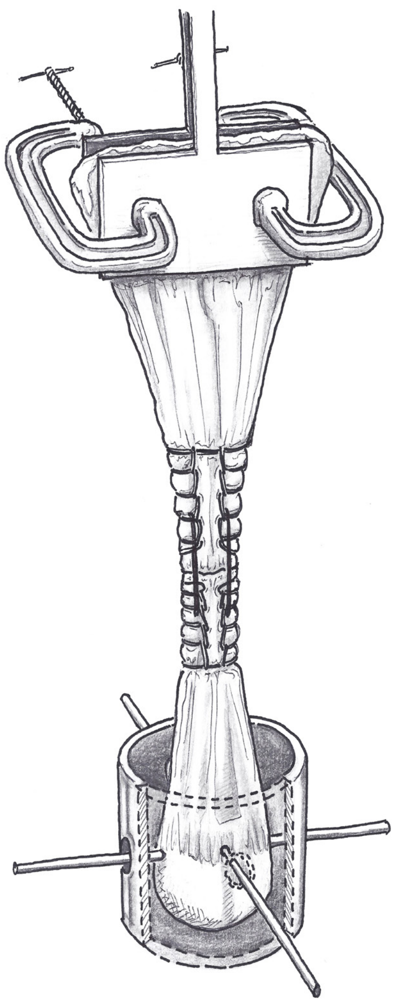

Figure 3. Depiction of study repair mounted in MTS machine as setup for this study. Proximally, a soft tissue freeze clamp is affixed at the level of the musculotendinous junction. Distally, two orthogonally placed Steinmann pins pass through the calcaneus bone block and are secured in a fenestrated aluminum housing.

Related-samples Wilcoxon signed rank or Mann-Whitney tests were performed to compare differences between the control and study tendon repairs. All statistical analyses were performed with SPSS Software (version 20; IBM Corporation, Armonk, NY) with statistical significance set at $P<0.05$.

RESULTS

The results for group A are presented in Table 1. In group A, the mean peak force was significantly higher in the study repair (augmented Krackow) specimens than the control repair (standard Krackow) specimens. The stiffness was also significantly higher in the study repair specimens. The results for group B are presented in Tables 2 and 3. In group B, a trend toward higher ultimate loads in the study repair group was found; however, this failed to reach statistical significance. The stiffness values of the control and study repair constructs were not significantly different. The stiffness values were higher in group B than in group A because the loading rate was 200 N/s, which was at least 2.5 times the loading rate used in group A.

Gap formation was measured using digital calipers at 100, 500, and 1,000 cycles. The formation of a 5-mm gap defined clinical failure. Gap formation was found to be significantly higher in the control group at 500 cycles. Of the control specimens, one of five failed by 100 cycles, and four of five failed by 500 cycles. One specimen in the control group had a gap of <5 mm by 1,000 cycles. In contrast, a 5-mm gap did not form in any of the study specimens in group B at any point during cyclic loading, which was a significant improvement over the control repair ($p=0.032$).

Table 1. Mean values for group A specimens (monotonic loading to failure).

Parameter	Control Repair	Study Repair	P Value
Stiffness (N/mm)	9.41 (2.99)	26.92 (11.43)	0.043
Peak Force (N)	202.61 (94.34)	497.55 (134.44)	0.043

Note: Standard deviations are given in parentheses.

Table 2. Mean values for group B specimens (cyclic loading followed by load to failure).

Parameter	Control Repair	Study Repair	P Value
Stiffness (N/mm)	53.54 (5.29)	54.90 (4.36)	0.5
Peak Force (N)	165.51 (67.08)	462.19 (215.12)	0.08
Gap at 100 cycles (mm)	3.25 (1.95)	0	0.066
Gap at 500 cycles (mm)	6.25 (2.56)	0	0.042
Gap at 1,000 cycles (mm)	7.77 (4.67)	0.4064 (0.91)	0.068

Note: Standard deviations are given in parentheses.

Table 3. Number of specimens with clinical failure (gap ≥5 mm at tendon repair site) or lack of clinical failure (gap <5 mm) for the specimens in group B (cyclic loading).

Parameter	Control Repair	Study Repair
Specimens with clinical failure at 100 cycles	1	0
Specimens with clinical failure at 500 cycles	3	0
Specimens with clinical failure at 1,000 cycles	0	0
Specimens with gap <5 mm after 1,000 cycles	1	5

DISCUSSION

Open Achilles tendon repair using a Krackow locking-suture repair technique is a well-described, commonly utilized technique for the treatment of Achilles tendon rupture. We have demonstrated that the addition of vertically tensioned locking-loop sutures to a locking Krackow suture repair increased the peak load and stiffness, and decreased gap formation in a cadaveric model of acute Achilles tendon rupture. Resistance to gap formation is an important variable because healing is delayed and the repair tissue is weaker as the gap increases [2]. Tendon lengthening following surgical repair of Achilles tendons leads to lower patient satisfaction scores, increased ankle dorsiflexion, increased co-activation of lower leg musculature, and decreased step length [9,34]. Emerging research findings and clinical understanding support early mobilization rehabilitation protocols to stimulate healing of the tendon and yield better clinical outcomes for patients [8-18,20]. The repair technique described in this study may allow such early mobilization rehabilitation protocols given its increased stiffness and resistance to gap formation, although further clinical research is required to confirm this possibility in clinical applications.

Numerous biomechanical studies exist in the literature comparing various open Achilles tendon suture repair techniques [35]. The Krackow technique has been demonstrated to have higher load to failure than the Bunnell and Kessler techniques [24]. The triple-bundle technique has a higher load to failure than the Krackow locking-loop stitch [36]. The addition of epitendinous sutures to Krackow suture repairs has been shown to increase the strength of Achilles repairs [32,37]. Epitendinous cross-stitch configuration stitches augmenting a Krackow repair had 53% greater failure strength, 3.1% higher initial stiffness, and 3.6% higher resistance to formation of a 2-mm gap formation than a simple running epitendinous stitch augmenting a Krackow repair [37].

The rehabilitation protocol is a critical factor in the treatment of Achilles tendon ruptures [2,18]. Early accelerated functional rehabilitation protocols have been demonstrated to accelerate healing and lead to improved patient outcomes in the treatment of acute Achilles tendon ruptures [1-18,38]. Positioning of the hindfoot in 20-25 deg of ankle plantar flexion has been demonstrated to effectively eliminate tension on the Achilles tendon regardless of knee position [31]. Gap formation of Achilles tendon repairs follows a time-dependent course: initial separation is seen at days 0-7, no separation is seen from 8-12 days, and late separation occurs at days 22-35 [2,39]. A multicenter, randomized trial by Willits et al. utilized an accelerated rehabilitation protocol that featured early weight bearing and early range of motion following operative or nonoperative management of acute Achilles tendon rupture [18]. The protocol began protected weight bearing 2 weeks following injury in the nonoperative group or repair in the operative group. This progressed to weight bearing as tolerated at 4 weeks, and each patient wore the functional brace for a total of 8 weeks. Bracing in this study utilized an Aircast removable, below-knee pneumatic walking brace (Aircast, Summit, NJ) with a 2-cm heel lift and approximately 20 deg of plantar flexion. There was no significant difference with regard to strength, range of motion, calf circumference, or Leppilahti score between the operative and nonoperative groups. Willits et al. concluded that their data supported accelerated functional rehabilitation and demonstrated that nonoperative treatment has acceptable and clinically similar results compared with operative repair [18].

Achilles tendon repairs need to be able to withstand the forces of the postoperative rehabilitation protocol used. The Achilles tendon is exposed to an average of 550 N during normal walking, 370 N when walking with the ankle immobilized at neutral, 280 N when walking with the ankle immobilized with a 0.5-in heel lift, and 190 N when walking with the ankle immobilized with a 1-in heel lift [1,22]. Passive ankle flexion range of motion exposes the Achilles tendon to 86-100 N of force [1,20,22,31]. Based on these values established in the literature, the addition of a vertically oriented locking loop to a traditional Krackow suture repair technique, as described in this study, would be able to withstand both passive ankle range of motion and walking with the ankle immobilized with a 1-in heel lift.

There were limitations in our study design. The age of the cadavers (average age 75.8 years) used for the study is greater than that of the population most vulnerable to this injury. As a result of increased age, the specimens in our study may not have had the same tissue characteristics as those from younger donors. Our stiffness and peak force values are similar to those in a study by Labib et al. [40], whose average donor age was 88 years, and to those in Lee et al. [32], whose average donor age was 52 years. This suggests that the donor age may not contribute to an important difference in results. The use of matched pairs further minimizes any influence age may have on study data. The simulated acute Achilles rupture in this study was created by sharp transection. In contrast, shredding and fraying of the tendon ends at the rupture site tends to occur in the clinical setting, thereby affecting the ability of the suture repair to achieve purchase in the tendon. A similar study attempted to create a traumatic tendon rupture in a cadaveric Achilles model and found that the "mop end" rupture encountered clinically could not be replicated, as the specimen failed at the tendon-clamp interface at forces greater than 900 N [32]. It would be difficult to reproduce the same degree of shredding and tissue damage in matched pairs, which may affect the data collected and therefore the statistical comparison of the investigational repair vs the control group.

Further areas for research include retrospective case review to determine the clinical re-rupture and complication rates of this technique. Another area of interest would be to evaluate the effect of rehabilitation protocols and early mobilization on the clinical outcomes of this repair in a prospective, randomized fashion.

CONCLUSIONS

Operative treatment of acute Achilles tendon ruptures has lower rates of re-rupture than nonoperative management. Early mobilization and rehabilitation protocols demonstrate improved outcomes in the treatment of acute Achilles tendon ruptures. The addition of a vertically oriented locking loop to a traditional Krackow suture repair technique increases stiffness, peak load, and resistance to gap formation of the construct when compared with the traditional Krackow. The addition of a vertical locking loop to a standard Krackow suture technique may allow early mobilization rehabilitation protocols given its increased stiffness and resistance to gap formation with minimal additional operative time or morbidity for the patient.

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REFERENCES

[1] Lee SJ, Sileo MJ, Kremenic IJ, Orishimo K, Ben-Avi S, Nicholas SJ, McHugh M. Cyclic loading of 3 Achilles tendon repairs simulating early postoperative forces. Am J Sports Med. 2009;37:786-90.

[2] Maquirriain J. Achilles tendon rupture: avoiding tendon lengthening during surgical repair and rehabilitation. Yale J Biol Med. 2011;84:289-300.

[3] Wilkins R, Bisson LJ. Operative versus nonoperative management of acute Achilles

tendon ruptures: a quantitative systematic review of randomized controlled trials. Am J Sports Med. 2012;40:2154-60.

[4] Raikin SM, Garras DN, Krapchev PV. Achilles tendon injuries in a United States population. Foot Ankle Int. 2013;34:475-80.

[5] Parekh SG, Wray WH 3rd, Brimmo O, Sennett BJ, Wapner KL. Epidemiology and outcomes of Achilles tendon ruptures in the National Football League. Foot Ankle Spec. 2009;2:283-6.

[6] Maffulli N. Rupture of the Achilles tendon. J Bone Joint Surg Am. 1999;81:1019-36.

[7] Amin NH, Old AB, Tabb LP, Garg R, Toossi N, Cerynik DL. Performance outcomes after repair of complete Achilles tendon ruptures in National Basketball Association players. Am J Sports Med. 2013;41:1864-8.

[8] Costa ML, MacMillan K, Halliday D, Chester R, Shepstone L, Robinson AH, Donell ST. Randomised controlled trials of immediate weight-bearing mobilisation for rupture of the tendo Achillis. J Bone Joint Surg Br. 2006;88:69-77.

[9] Kangas J, Pajala A, Ohtonen P, Leppilahti J. Achilles tendon elongation after rupture repair: a randomized comparison of 2 postoperative regimens. Am J Sports Med. 2007;35:59-64.

[10] Kangas J, Pajala A, Siira P, Hamalainen M, Leppilahti J. Early functional treatment versus early immobilization in tension of the musculotendinous unit after Achilles rupture repair: a prospective, randomized, clinical study. J Trauma. 2003;54:1171-80.

[11] Kearney RS, McGuinness KR, Achten J, Costa ML. A systematic review of early rehabilitation methods following a rupture of the Achilles tendon. Physiotherapy. 2012;98:24-32.

[12] Krapf D, Kaipel M, Majewski M. Structural and biomechanical characteristics after early mobilization in an Achilles tendon rupture model: operative versus nonoperative treatment. Orthopedics. 2012;35:1383-8.

[13] Maffulli N, Tallon C, Wong J, Lim KP, Bleakney R. Early weightbearing and ankle mobilization after open repair of acute midsubstance tears of the Achilles tendon. Am J Sports Med. 2003;31:692-700.

[14] Nilsson-Helander K, Silbernagel KG, Thomeé R, Faxén E, Olsson N, Eriksson BI, Karlsson J. Acute Achilles tendon rupture: a randomized, controlled study comparing surgical and nonsurgical treatments using validated outcome measures. Am J Sports Med. 2010;38:2186-93.

[15] Olsson N, Silbernagel KG, Eriksson BI, Sansone M, Brorsson A, Nilsson-Helander K, Karlsson J. Stable surgical repair with accelerated rehabilitation versus nonsurgical treatment for acute Achilles tendon ruptures: a randomized controlled study. Am J Sports Med. 2013;41:2867-76.

[16] Sorrenti SJ. Achilles tendon rupture: effect of early mobilization in rehabilitation after surgical repair. Foot Ankle Int. 2006;27:407-10.

[17] Suchak AA, Spooner C, Reid DC, Jomha NM. Postoperative rehabilitation protocols for Achilles tendon ruptures: a meta-analysis. Clin Orthop Relat Res. 2006;445:216-21.

[18] Willits K, Amendola A, Bryant D, Mohtadi NG, Giffin JR, Fowler P, Kean CO, Kirkley A. Operative versus nonoperative treatment of acute Achilles tendon ruptures: a multicenter randomized trial using accelerated functional rehabilitation. J Bone Joint Surg Am. 2010;92:2767-75.

[19] Enwemeka CS, Spielholz NI, Nelson AJ. The effect of early functional activities on experimentally tenotomized Achilles tendons in rats. Am J Phys Med Rehabil. 1988;67:264-9.

[20] Orishimo KF, Burstein G, Mullaney MJ, Kremenic IJ, Nesse M, McHugh MP, Lee SJ. Effect of knee flexion angle on Achilles tendon force and ankle joint plantarflexion moment during passive dorsiflexion. J Foot Ankle Surg. 2008;47:34-9.

[21] Pneumaticos SG, Noble PC, McGarvey WC, Mody DR, Trevino SG. The effects of early mobilization in the healing of Achilles tendon repair. Foot Ankle Int. 2000;21:551-7.

[22] Akizuki KH, Gartman EJ, Nisonson B, Ben-Avi S, McHugh MP. The relative stress on the Achilles tendon during ambulation in an ankle immobiliser: implications for rehabilitation after Achilles tendon repair. Br J Sports Med. 2001;35:329-33; discussion 33-4.

[23] Benum P, Berg V, Fretheim OJ. The strain on sutured Achilles tendons in walking cast. An EMG analysis. Eur Surg Res. 1984;16 Suppl 2:14-21.

[24] Watson TW, Jurist KA, Yang KH, Shen KL. The strength of Achilles tendon repair: an in vitro study of the biomechanical behavior in human cadaver tendons. Foot Ankle Int. 1995;16: 191-5.

[25] Hapa O, Erduran M, Havitçioğlu H, Çeçen B, Akşahin E, Güler S, Atalay K. Strength of different Krackow stitch configurations using high-strength suture. J Foot Ankle Surg. 2013;52:448-50.

[26] McKeon BP, Heming JF, Fulkerson J, Langeland R. The Krackow stitch: a biomechanical evaluation of changing the number of loops versus the number of sutures. Arthroscopy. 2006;22:33-7.

[27] Giza E, Frizzell L, Farac R, Williams J, Kim S. Augmented tendon Achilles repair using a tissue reinforcement scaffold: a biomechanical study. Foot Ankle Int. 2011;32:S545-9.

[28] Benthien RA, Aronow MS, Doran-Diaz V, Sullivan RJ, Naujoks R, Adams DJ. Cyclic loading of Achilles tendon repairs: a comparison of polyester and polyblend suture. Foot Ankle Int. 2006;27:512-8.

[29] Yamagami N, Mori R, Yotsumoto T, Hatanaka H, Uchio Y. Optimum suture material for locking technique in tendon repair: effects of suture friction in mobilization. Clin Biomech (Bristol, Avon). 2011;26:529-34.

[30] Jassem M, Rose AT, Meister K, Indelicato PA, Wheeler D. Biomechanical analysis of the effect of varying suture pitch in tendon graft fixation. Am J Sports Med. 2001;29:734-7.

[31] Davis WL Jr, Singerman R, Labropoulos PA, Victoroff B. Effect of ankle and knee position on tension in the Achilles tendon. Foot Ankle Int. 1999;20:126-31.

[32] Lee SJ, Goldsmith S, Nicholas SJ, McHugh M, Kremenic I, Ben-Avi S. Optimizing Achilles tendon repair: effect of epitendinous suture augmentation on the strength of Achilles

tendon repairs. Foot Ankle Int. 2008;29:427-32.

[33] Longo UG, Forriol F, Campi S, Maffulli N, Denaro V. A biomechanical comparison of the primary stability of two minimally invasive techniques for repair of ruptured Achilles tendon. Knee Surg Sports Traumatol Arthrosc. 2012;20:1392-7.

[34] Suydam SM, Buchanan TS, Manal K, Silbernagel KG. Compensatory muscle activation caused by tendon lengthening post-Achilles tendon rupture. Knee Surg Sports Traumatol Arthrosc. 2015;23:868-74.

[35] Sadoghi P, Rosso C, Valderrabano V, Leithner A, Vavken P. Initial Achilles tendon repair strength—synthesized biomechanical data from 196 cadaver repairs. Int Orthop. 2012;36:1947-51.

[36] Jaakkola JI, Hutton WC, Beskin JL, Lee GP. Achilles tendon rupture repair: biomechanical comparison of the triple bundle technique versus the Krakow locking loop technique. Foot Ankle Int. 2000;21:14-7.

[37] Shepard ME, Lindsey DP, Chou LB. Biomechanical comparison of the simple running and cross-stitch epitenon sutures in Achilles tendon repairs. Foot Ankle Int. 2008;29:513-7.

[38] Speck M, Klaue K. Early full weight-bearing and functional treatment after surgical repair of acute Achilles tendon rupture. Am J Sports Med. 1998;26:789-93.

[39] Nyström B, Holmlund D. Separation of tendon ends after suture of Achilles tendon. Acta Orthop Scand. 1983;54:620-1.

[40] Labib SA, Rolf R, Dacus R, Hutton WC. The “Giftbox” repair of the Achilles tendon: a modification of the Krackow technique. Foot Ankle Int. 2009;30:410-4.