Acta of Bioengineering and Biomechanics Original paper
Vol. 20, No. 1, 2018 DOI: 10.5277/ABB-01024-2017-03

Biomechanical evaluation of tendon connection with novel suture techniques

ZHE CHEN[1]*, JUN WANG[1], JIA-SEN WEI[1], ZHAO-YANG HOU[1], MIN LI[2], QI-XIN CHEN[3]

[1] Department of Orthopedics, The Second Affiliated Hospital of Zhejiang Chinese Medical University, Hangzhou, Zhejiang, China.
[2] Biomechanics Lab, Zhejiang Chinese Medical University, Hangzhou, Zhejiang, China.
[3] Department of Orthopedics, The Second Affiliated Hospital of Zhejiang University, Hangzhou, Zhejiang, China.

Purpose: Achilles tendon rupture is a severe injury with poor curative effect due to its anatomical characteristic and mechanical peculiarity. Internal fixation of limited loop (IFLL) with steel-wire has been applied on patients with tendon rupture to fix the broken ends before physical rehabilitation. The purpose of this study is to investigate the biomechanical property and radiological characteristic of such suture technique for the repairment of tendon rupture. *Methods:* Tendons of pigs' hint feet were separated for the biomechanical study. Suture surgery was performed according to the protocol of IFLL. Biomechanical Testing Machine was adopted to conduct the biomechanical tensile load examination. The maximal load, elastic modulus and tendon stiffness of the stitched tendons with or without reinforcement were examined. *Results:* The maximum tensile load of the stitched tendons using IFLL reached 1/4 of the uninjured tendon's maximum tensile load, indicating that such suture technique is capable of providing enough tension for the ruptured tendon. Surprisingly, tendons fixed with titanium wire showed the highest load tension, which was comparable to the undamaged tendon. Therefore, we found the biomechanical basis of using IFLL in effectively connecting the rupture ends of tendons. *Conclusions:* In conclusion, we provide biomechanical evidence for the use of IFLL in treatment of Achilles tendon rupture, by providing enough strength for the ankle function. Such suture technique could help the patients with better rehabilitation and reduced in-hospital stay after Achilles tendon injury.

Key words: *internal fixation with limited loop, Achilles tendon, biomechanics*

1. Introduction

Achilles tendon, 15 cm in length, which originates from the middle of the calf that consists of gastrocnemius muscle and soleus, is the strongest muscle tendon in human. Achilles tendon rupture is a common injury among sportsmen. However, it is difficult to repair, as the conservative treatment often result in re-rupture and the open surgery usually come with higher incision complications [22]. Angiography of Achilles tendon showed that the tendon is prone to local malnutrition and retrogression after injury, making conservative treatment inefficient for patients with Achilles tendon rupture [19]. Alternative therapies for tendon rupture are the conventional surgical methods, including tendon conjugation, plaster fixation and post-operative rehabilitation [12]. The traditional ways to connect broken tendons, including simple suture and staple joint, are not strong enough for the following rehabilitation [20]. On the other hand, long-term plaster fixation in plantar flexion position often induce deformity and rigidity of ankle joint [3]. Therefore, in order to avoid plaster fixation before physical rehabilitation after the surgery of Achilles tendon injury, identifying firm tendon fixation technique is an important step in the field of orthopedics and sport medicine.

A suture method has been designed, namely, the internal fixation of limited loop (IFLL), using suture line and steel-wire for the repair of early Achilles tendon rupture [5]. Our recent clinical results have

* Corresponding author: Zhe Chen, MD, Department of Orthopedics, The Second Affiliated Hospital of Zhejiang Chinese Medical University, Hangzhou, Zhejiang, 310005, China. Phone: 86-18958013615, e-mail address: 375523808@qq.com
Received: October 11th, 2017
Accepted for publication: January 15th, 2018

shown that fixation of the broken tendons with steel-wire limited loop is efficient to help the patients rebuild ankle function, with shorter recovery time and fewer complications, compared to other suture methods [5]. However, the biomechanical basis of such suture technique with different suture wires on model tendons have not been studied. To explore the biomechanical properties of the IFLL suture technique on tendon rupture, in the present study, we investigated whether IFLL can provide enough supporting strength for the rupture ends of Achilles tendon. Using 25% of the normal tendon maximum tensile load as a criterion [6], [18] for sufficient tension in physical exercises, we found that such fixation method is sufficient to provide enough strength for post-operative rehabilitation.

2. Materials and methods

2.1. Separation of the tendons

Pigs' hint feet, purchased from Hangzhou slaughterhouse, were used for separation of tendons in biomechanical study. Research materials were stored at 4 °C, except during suturing and biomechanical testing.

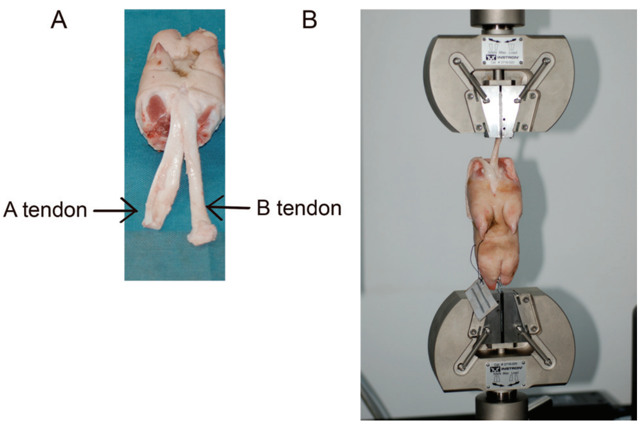

Fig. 1. Images of dissociated A tendon and B tendon (A) and universal testing systems for tension used in the experiment (B)

We chose porcine tendons because of their low cost, size similar to human Achilles tendons, and the immediate availability. Crus, skin in the rear side and deep fascia in the planta pedis were carefully dissected layer by layer until the superficial digital flexor tendon (B tendon) was seen. B tendon is thinner than the strong deep digital flexor tendon (A tendon). The A tendon was seen beneath the distal side of B tendon. The A tendon consists of one wide flat tendon and one small round tendon in the proximal end, these two parts merge into one large even-thickness tendon in the ankle joint. A tendon divided into 4 strands of tendon bundle at the place of 2~3 cm distance away from tiptoes, extending tiptoes (Fig. 1A).

To make bone tunnels, soft tissue was dissected and feet bones were sawed by a hacksaw at 5 cm distance away from tiptoe root of pigs' hint feet. Electric drill and 2.5 mm kirschner wire were used to drill vertical holes in the mid-distal part of the metatarsal majus. Two suitable thick and soft lead wires were threaded through the holes for preparation of biomechanical experiments.

2.2. Radiological observation

In order to observe the bony structure of pig's feet, the above specimens were sent to the Department of Radiology for X-ray DR films. During X-ray observation, subjects with too much damaged bone structure, inappropriate position of bone tunnel and steel wire, were excluded from biomechanical test due to their mechanical instability.

After the biomechanical experiments, X-ray films were taken again, to study the destruction of the bony structure, and the changes in the internal fixation materials.

2.3. Surgical operation

The No. 1 absorbable suture (Johnson & Johnson, ETHICON VICRYL*PLUS Vcp359) or the No.7 silk suture (Johnson & Johnson, ETHICON MERSILK SA86G (0) 3.5METRIC) was used for the 4-needle discontinuous suture to surround the two broken tendon ends in an end-to-end manner and 6 surgical knots were placed for each needle.

Single-strand steel-wire or titanium cable internal fixation (Figs. 2 and 3A)

Tendon was cut transversely in the distal end of tendon, 1 cm away from bifurcate of tendon. 1.0 cm long small longitudinal incisions were made in both sides of the proximal end of the metatarsal majus and vertical holes were drilled for constructing bone tunnels. The needle of No.1 steel wire (Johnson & Johnson, ETHICON* STEEL WIRE) or titanium cable with 1.3 mm in diameter (Guangci M.D) was threaded through the bone channel to the contra-side, finally went through the distal rupturing end of tendon after passing subcutaneous tissue and medial inferior part of ipsilateral hind feet. After crossing the distal end of tendon, the needle threaded through from the middle of the side sectional tendon bundle, then entered into the tendon bundle of the ipsilateral proximal rupturing end, finally went through the place 1.5 cm away from the section. After coiling 1/4 cross-section diameter, the needle entered the tendon and crossed the tendon diagonally until out of the contra-side. The above method was repeated for 3~4 times, till arriving the vertex of 12~13 cm distance away from the proximal end of the tendon, which was deemed as the proximal vertex of limited loop. The above method was operated repeatedly in negative direction for 3~4 times till

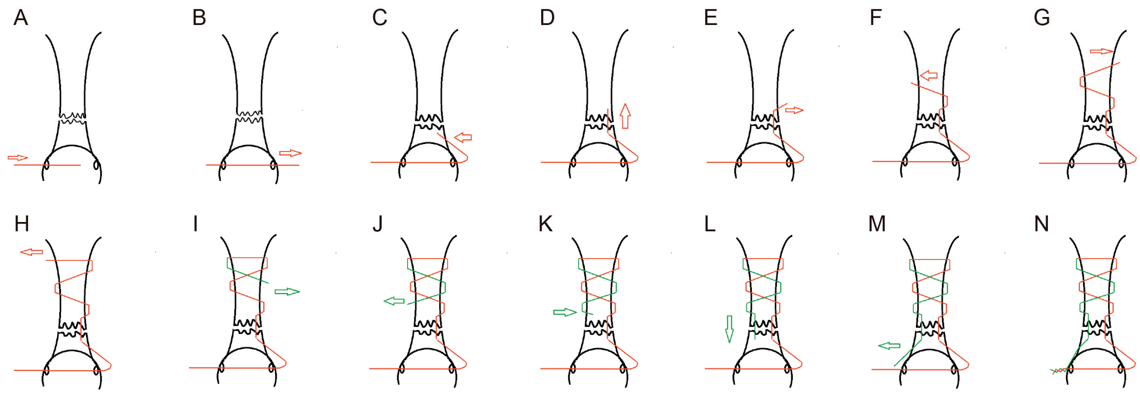

Fig. 2. Illustration of the IFLL suture technique. The suture starts from A to N as indicated by arrows

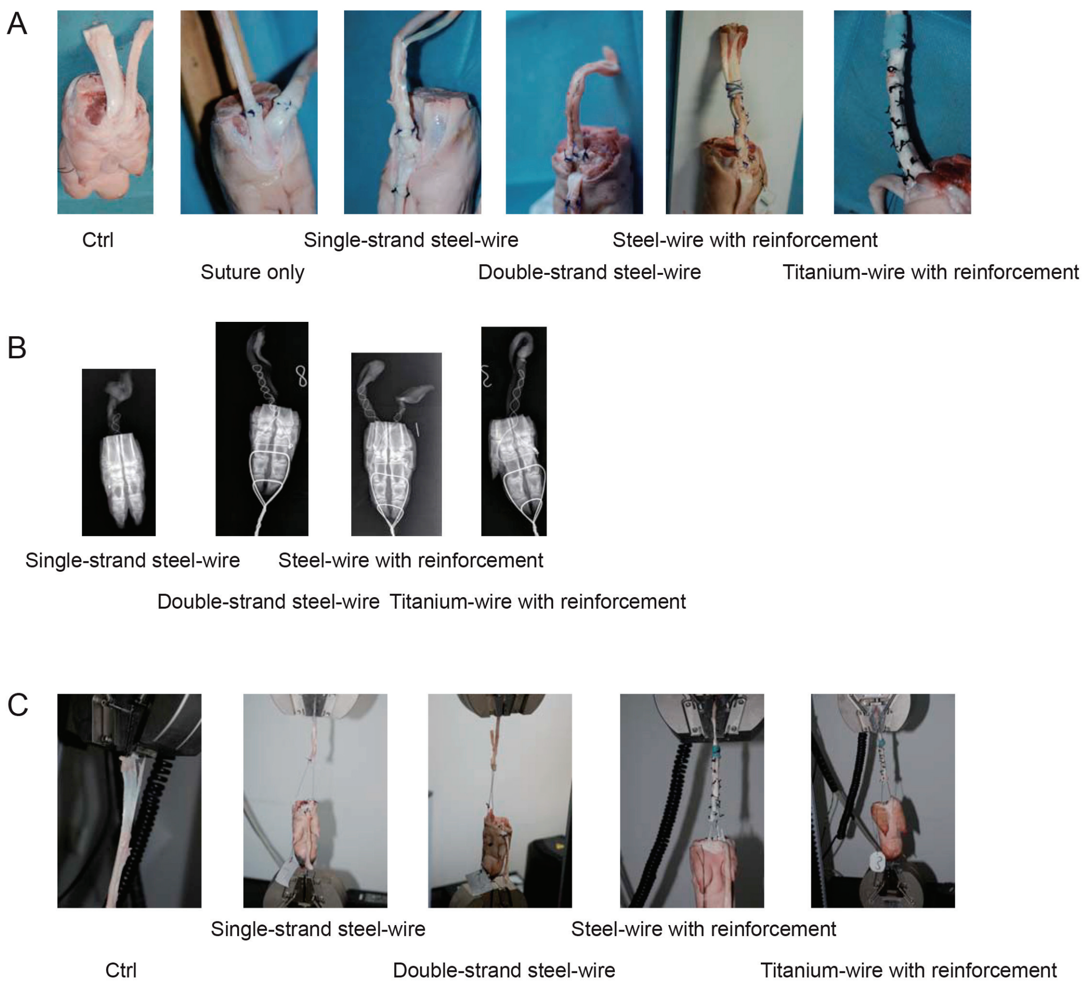

Fig. 3. Images of sutured tendons (A) and radiological pictures of tendons (B) in different groups as indicated. Figure 3C showed images of tendons at failure load in groups as indicated

crossing the tendon diagonally. Then the needle entered the middle of the distal rupturing end of tendon bundle and went through the proximal incision of metatarsal majus after passing subcutaneous tissue and medial inferior part of ipsilateral hind feet. The steel-wire loop was screwed outside the metatarsal majus to tightly connect the two rupturing ends of tendon.

Two-strand steel-wire or titanium cable internal fixation (Figs. 2 and 3A)

The No. 1 steel wire and titanium cable with 1.3 mm in diameter was folded in half to twist twin-rope for suture according to the above-mentioned operation method.

Internal fixation with reinforcement (Figs. 2 and 3A)

The suture operation was performed as mentioned above. For further reinforcement, cotton piece (2.5×0.8 cm^2) was used to wrap the tendon at the proximal vertex of suture fixation.

0.9% saline solution was use to moist experimental subjects to prevent from drying and degeneration.

2.4. Biomechanical test

The American INSTRON (SYSTEM ID NUMBER 5569R 1412) Biomechanical Testing Machine was adopted to conduct biomechanical tensile load testing (Fig. 1B). The procedures were performed according to a previous report [17]. Briefly, start the machine to do pretension process at the speed of 20 mm/min and pull 0.5 mm for 3 times, 3 s in interval. Then tensile testing was conducted by putting a load at stable speed of 20 mm/min, from zero-load to the load of making tendon avulsion. The time-load curve and time-strain curve were generated automatically. Based on these curves, the stiffness and the elastic modulus were calculated. Maximum load values were recorded as failure load.

2.5. Statistical data analysis

GraphPad Prism software was used for statistical analysis. Normality tests were conducted by using the Kolmogorov–Smirnov test. Some of these groups of data passed normality test, while some of those failed. Data were analyzed by the nonparametric Kruskal–Wallis test with Dunns *post-hoc* test and expressed as ($\bar{x} \pm \text{sem}$). $P < 0.05$ was considered to be statistically significant.

3. Results

3.1. Observation of tendon and suture status

Tendons were assigned to several groups, including the control group (tendons without rupture, $n = 24$), suture only (Group A, $n = 16$), single-strand steel-wire (Group B, $n = 6$), double-strand steel-wire (Group C, $n = 6$), single steel-wire with reinforcement (Group D, $n = 24$), titanium-wire with reinforcement (Group E, $n = 6$). Ruptured tendons were sutured using internal fixation method with or without reinforcement, as indicated in each group.

X-ray radiological examination and morphology observation of the stitched tendons were performed to evaluate whether such internal fixation method is strong enough to defend tension. We note that the tension tester did not clamp the metal wires, but clamped the upper side of the tendon instead. As shown in Fig. 3B, the skeletal structure of all subjects were intact, metal wires were penetrated through the bones and connected the ruptured tendons in a way as shown in Fig. 2, namely IFLL. At failure load of each tendon, as shown in Fig. 3C, rupture re-occurred at the suture position due to strong pulling strength. Suture lines were broken while the metal wire loop remained intact, except for the single-strand steel-wire group. Subjects with reinforcement fixation showed no rupture and avulsion in the proximal end and the local metal wire loop was kept intact. These results indicate that surgery of tendon fixation with metal wire was fully done and the tendon fixation with metal wire and reinforcement could provide strong tension for the ruptured tendon.

3.2. Biomechanical testing

Biomechanical tests on tendon failure load, elastic modulus and stiffness were performed to evaluate the exact tensions of sutured tendons in each group (Fig. 4). All groups with metal wire fixation showed a failure load more than 1/4 value of the control tendon, indicating that the IFLL suture can provide enough tension for post-operative rehabilitation.

Surprisingly, fixation with titanium showed the highest improvement of tension, compared to the other groups. Aspects including the failure load, elastic modulus and the stiffness of tendons were improved significantly (far more than 1/4 of the control group) for tendons in the titanium wire group. Ruptured tendons with fixation of titanium wire showed the highest failure load, which was comparable to the undamaged tendon. These results suggest that using the internal fixation suture method with titanium wire could provide far more tension than needed for physical rehabilitation, which is especially helpful for patients with Achilles tendon rupture.

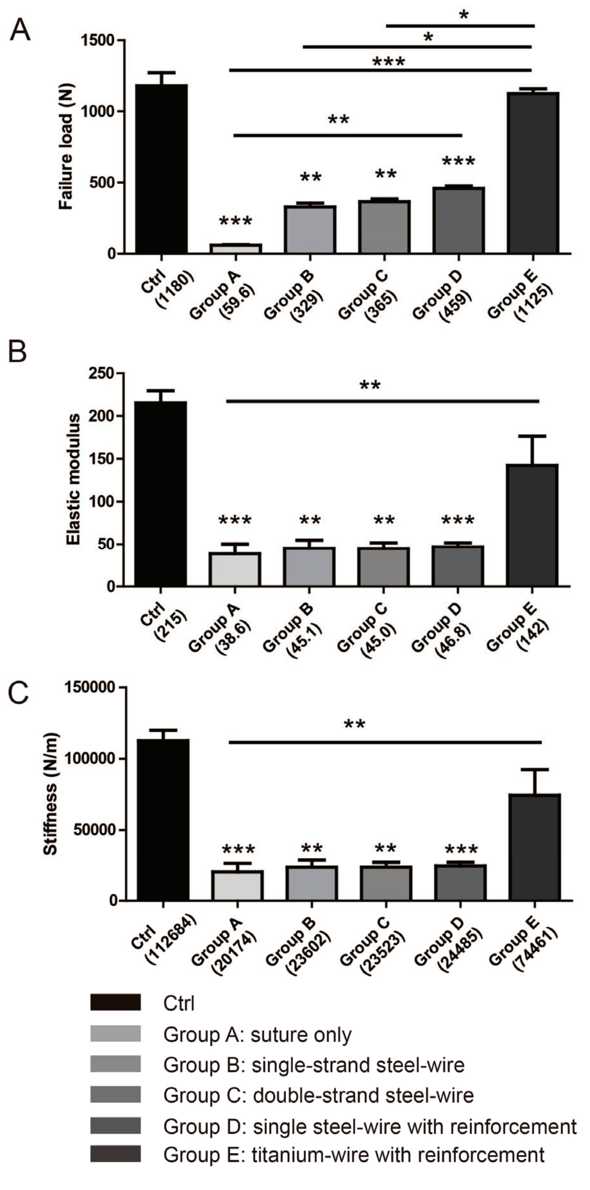

Fig. 4. Failure load (A), elastic modulus (B) and stiffness (C) of tendons in different groups as indicated.
* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

4. Discussion

Achilles tendon is the strongest tendon in human body and bears the maximal load in various kinds of sports. To keep standing balance, Achilles tendon sustains more than half of the body weight [7]. During strenuous exercise, Achilles tendon is capable of providing strong strength equal to 5~10 times of the body weight [15]. With rapid development of the world, Achilles tendon injury increased significantly due to sports competition, increasing occurrence of industrial accident and traffic accident. Like other soft tissues, Achilles tendon forms fibrous scar after suffering acute and chronic injuries, consequently leading to changes of the structure and biomechanical property. Animal experiments have found that the repair of Achilles tendon in rabbit takes 4 months and the repair of patellar tendon in human lasts at least 2 years [4]. If there is not enough time for the repairment, early movement can induce death of the tendon cells due to over stress, which strongly delays the synthesis of collagen, making the remaining tissue more susceptible to injuries.

The therapeutic strategies for acute Achilles tendon rupture include surgical and non-surgical treatment. Compared with non-surgical treatment, surgical treatment can effectively reduce the occurrence rate of repeated rupture, but with higher occurrence of wound infection and nerve injury [12]. Soroceanu et al. [19] analyzed the conservative treatment and the surgical treatment for acute Achilles tendon rupture using *Meta*-analysis and found the occurrence rate of repeated rupture was 10〜12% after conservative treatment and 3% after surgical operation and rehabilitation. Thus, active surgical treatment should be recommended at the early stage of tendon rupture [8], [11]. No matter what kind of therapy used, long-term immobilization will result in abnormal tendon metabolism, collagen degeneration, reduced tendon stiffness and repeated rupture. Groetelaers et al. [9] also found that early rehabilitation is beneficial for tendon recovery. Thus, exploring effective suture method with proper material to enable early rehabilitation is very important for treatment of tendon rupture [2], [13]. A recent report showed that multistrand running locking suture is capable of providing enough biomechanical strength during reducing of trauma [1].

Suture method of IFLL was invented and applied to patients in our hospital with satisfying post-operative performance [5]. However, whether IFLL can provide tendon with enough strength for physical rehabilitation is unknown. The current study used pig' tendons as subjects, as they have similar diameter with human Achilles tendons [10], [16], investigating the biomechanical basis of the internal fixation of steel-wire limited loop. Our results showed that the maximum tensile load of different operation groups reached 1/4 tension of the intact tendon, which is comparable with other suture techniques [14]. Unexpectedly, repaired tendons using titanium wire reached up to 2/3 of the normal tension, which is comparable to the unaffected condition. The use of titanium in repairment of several kinds of fractures has been reported, while the underlying mechanism is unclear. One report showed that titanium is capable of increasing cell apoptosis during microwave treatment probably through remarkable enhancement of tissue temperature [23]. Another report justified the use of porous titanium coated constructs in tendon-to-bone healing [21]. Until now people have no idea how such inert metal benefit tissue repair, further investigation on its theoretical basis is needed.

The present study has several limitations. Although IFLL suture is working well, there is lack of comparison between such technique with other well-applied suture methods, as to decide which is better in the tendon-repair surgery. Another issue is that steel wire or similar materials have been used in Achilles repair in the past accompanied with various morbidity and complication rates due to the necessity of the second operation to remove the suture material. Further experiments comparing such method using absorbable material are needed.

5. Conclusion

Our work provides biomechanical evidence to support that IFLL suture is an efficient therapeutic method for tendon rupture. Such suture method effectively connected the broken tendon ends, thus providing enough tension immediately after operation. Among all the materials tested, IFLL using titanium wire together with reinforcement exhibited the greatest biomechanical recovery, indicating its potential application in the future.

Acknowledgements

This work was supported by Scientific Research Planned Project of Taizhou Science and Technology Bureau in Zhejiang Province (031212).

Conflict of interests

The authors declare no conflict of interest.

References

[1] ANDRZEJEWSKI T., CZARNECKI P., DĄBROWSKI M., SPŁAWSKI R., ROGALA P., ROMANOWSKI L., *Biomechanical properties of alternative suture technique for flexor tendon repair*, Acta Bioeng. Biomech., 2017, 19(2), 167–172.

[2] BADALIHAN A., AIHEMAITI A., SHAWUTALI N., JIELILE J., JIALIHASI A., TANGKEJIE W. et al., *Outcome of a one-stage tensile stress surgical technique and early postoperative rehabilitation in the treatment of neglected achilles tendon rupture*, J. Foot Ankle Surg., 2015, 54(2), 153–159.

[3] BUKVIĆ N., KVESIĆ A., BREKALO Z., BOSAK A., BUKVIĆ F., KARLO R., *The problem of post-traumatic varization of the distal end of the humerus remaining after the recovery of a supracondylar fracture*, J. Pediatr. Orthop. B, 2013, 22, 372–375.

[4] CHEN SHIYI, JAMES H.-C. WANG, *Basic and clinical research progress of the tendon*, Chin. J. Sports Med., 2004, 23(3), 283–287.

[5] CHEN Z., WEI J.S., HOU Z.Y., HU J., CAO Y.G., CHEN Q.X., *Application of internal fixation of steel-wire limited loop in early Achilles tendon rupture*, Asian Pacific Journal of Tropical Medicine, 2013, 6(11), 902–907.

[6] CICCONE W.J. 2nd, BRATTON D.R., WEINSTEIN D.M., ELIAS J.J., *Viscoelasticity and temperature variations decrease tension and stiffness of hamstring tendon grafts following anterior cruciate ligament reconstruction*, J. Bone Joint Surg. Am., 2006, 88, 1071–1078.

[7] ERDEMIR A., HAMEL A.J., FAUTH A.R., PIAZZA S.J., SHARKEY N.A., *Dynamic loading of the plantar aponeurosis in walking*, J. Bone Joint Surg. Am., 2004, 86-A(3), 546–552.

[8] GIGANTE A., MOSCHINI A., VERDENELLI A., DEL TORTO M., ULISSE S., DE PALMA L., *Open versus percutaneous repair in the treatment of acute Achilles tendon rupture: a randomized prospective study*, Knee Surg. Sports Traumatol. Arthrosc., 2008, 16(2), 204–209.

[9] GROETELAERS R.P., JANSSEN L., VAN DER VELDEN J., WIELAND A.W., AMENDT A.G., GEELEN P.H., JANZING H.M., *Functional Treatment or Cast Immobilization After Minimally Invasive Repair of an Acute Achilles Tendon Rupture: Prospective*, Randomized Trial. Foot Ankle Int., 2014, 35(8), 771–778.

[10] HAN X., GUO L2, WANG F., ZHU Q., YANG L., *Contribution of PTHrP to mechanical strain-induced fibrochondrogenic differentiation in entheses of Achilles tendon of miniature pigs*, J. Biomech., 2014, 47(10), 2406–2414.

[11] INGVAR J., TAGIL M., ENEROTH M., *Nonoperative treatment of achilles tendon rupture: 196 consecutive patients with a 7% re-rupture rate*, Acta Orthop., 2005, 76(4), 597–601.

[12] JALLAGEAS R., BORDES J., DAVIET J.C., MABIT C., COSTE C., *Evaluation of surgical treatment for ruptured Achilles tendon in 31 athletes*, Orthop. Traumatol. Surg. Res., 2013, 99(5), 577–584.

[13] JIELILE J., SABIRHAZI G., CHEN J., ALDYARHAN K., ZHEYIKEN J., ZHAO Q. et al., *Novel surgical technique and early kinesiotherapy for acute Achilles tendon rupture*, Foot Ankle Int., 2012, 33(12), 1119–1127.

[14] KANZ B.N., MORRIS R.P., LEWIS T., PANCHBHAVI V.K., *Biomechanical evaluation of a knotless barbed suture repair in a human Achilles tendon rupture model*, Foot Ankle Spec., 2014, 7(3), 176–181.

[15] LICHTWARK G.A., WILSON A.M., *In vivo mechanical properties of the human Achilles tendon during one-legged hopping*, J. Exp. Biol., 2005, 208(24), 4715–4725.

[16] LOHAN A., STOLL C., ALBRECHT M., DENNER A., JOHN T., KRÜGER K. et al., *Human hamstring tenocytes survive when seeded into a decellularized porcine Achilles tendon extracellular matrix*, Connect Tissue Res., 2013, 54(4–5), 305–312.

[17] NAGASAWA K., NOGUCHI M., IKOMA K., KUBO T., *Static and dynamic biomechanical properties of the regenerating rabbit Achilles tendon*, Clin. Biomech. (Bristol, Avon)., 2008, 23(6), 832–838.

[18] NURMI J.T., KANNUS P., SIEVÄNEN H., JÄRVELÄ T., JÄRVINEN M., JÄRVINEN T.L., *Interference screw fixation of soft tissue grafts in anterior cruciate ligament reconstruction*: Part 2, *Effect of preconditioning on graft tension during and after screw insertion*, Am. J. Sports Med., 2004, 32, 418–424.
[19] SOROCEANU A., SIDHWA F., AARABI S., KAUFMAN A., GLAZEBROOK M., *Surgical versus nonsurgical treatment of acute Achilles tendon rupture: a meta-analysis of randomized trials*, J. Bone Joint Surg. Am., 2012, 94(23), 2136–2143.
[20] STRICKLAND J.W., *Flexor tendon injuries: II. Operative technique*, J. Am. Acad. Orthop. Surg., 1995, 3(1), 55–62.
[21] TUCKER J.J., GORDON J.A., ZANES R.C., ZUSKOV A., VINCIGUERRA J.D., BLOEBAUM R.D. et al., *P2 porous titanium implants improve tendon healing in an acute rat supraspinatus repair model*, J. Shoulder Elbow. Surg., 2017, 26, 529–535.
[22] TUDISCO C., BISICCHIA S., *Reconstruction of neglected traumatic Achilles tendon rupture in a young girl*, J. Orthop. Traumatol., 2012, 13, 163–166.
[23] WANG G., XU Y., ZHANG L., YE D., FENG X., FU T. et al., *Enhancement of Apoptosis by Titanium Alloy Internal Fixations during Microwave Treatments for Fractures: An Animal Study*, PLoS One, 2015, 10, e0132046.