



Comparative experimental study of biomechanical features of suture materials in tendon repair

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Abstract

Introduction Many different suture configurations and pathomorphology of tendon repair have been described for tendon repair over the past 20 years. However, the biomechanical properties of suture material at primary flexor tendon repair have not been sufficiently explored. A cyclic loading test is performed to evaluate the performance of the different sutures under repeated loading conditions simulating dynamic conditions in postoperative rehabilitation procedures.

The objective was to compare the strength of suture materials under cyclic loading on a biological model of a tendon.

Material and methods Eighty porcine digital flexor tendons were examined in a pilot study. The sutured tendons were tested with a universal testing machine. Tendon repair was produced using polypropylene in group I, braided polyamide suture in group II, complex polytetrafluoroethylene thread in group III and a thread of superelastic titanium nickelide in group IV. The standard Chang protocol was used for cyclic loading.

Results The percentage of intact sutures was 25 % in group I and in group II, 80 % in group III and 85 % in group IV after completing the entire load cycle. A pairwise comparison showed suture disruption being more common for group I and group II as compared to group III and group IV. Irreversible gap was more common for group I as compared to group IV. Neither knot ruptures nor tissue cutting were seen in the groups.

Discussion The topic of biomechanical properties of suture material remains poorly understood. Although static load testing is commonly used in current experimental studies and cyclic testing is suitable for simulating postoperative conditions. The search continues for the “ideal” suture material for flexor tendon repair to prevent tears and retain tensile properties until the repair reaches strength.

Conclusion The threads of polytetrafluoroethylene and nickelide-titanium showed the best biomechanical properties for tendon repair in the form of linear strength, good elasticity and low plasticity of the suture material. There were no significant differences between polypropylene and braided polyamide threads.

Keywords: tendon, cyclic load, titanium nickelide, tendon suture

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INTRODUCTION

Hand wounds with tendon damage account for 18.8 % of all injuries to the upper limbs [1, 2]. Injuries to flexor tendons are characterized by significant periods of temporary disability and a high level of disability ranging between 21 % and 28 % of all those examined by the Physical Disability Board of Review for the consequences of traumatic injuries [3, 4].

With more than a century of experience in the study and application of flexor tendon suturing techniques, poor outcomes are reported in 7 to 30 % of cases due to insufficient tensile strength of the tendon suture. Mechanical resistance to tendon sliding consists of external and internal sources of resistance [5, 6]. After tendon suture, internal resistance increases by 27.4 % for low-friction repair techniques and 59.9 % for high-friction repair techniques. External resistance can also increase dramatically after injury and surgery due to soft tissue swelling, joint swelling, and pain-induced contraction of antagonist muscles [7, 8, 9]. It is essential to explore ways of increasing the strength of the hand tendon repair.

The strength of the tendon suture depends on such parameters as the type of suture material; its caliber; the number of threads passing through the diameter of the tendon; loop configuration; a distance from the end of the tendon; additional tension at the tendon contact site and the location of the node [10, 11, 12]. Over the past 20 years researchers focused on the types of tendon sutures and the pathomorphology of tendon repair, but the biomechanical properties of the suture material during primary repair of flexor tendons have not been sufficiently explored. It is not the strength of the thread that matters with the strength of the knot being essential with the loss of strength in the knot ranging between 10 and 50 % of the original for most threads [13, 14]. The strength of the knot is associated with the superficial properties of the threads, which determine sliding. The use of synthetic non-absorbable suture materials for tendon sutures is one of the modern global trends in surgery. New types of materials with improved characteristics are being developed and introduced into surgical practice.

The phenomenon of hysteresis delay of biological tissues discovered by V.E. Gunter facilitated a new class of biocompatible materials including superelastic shape memory alloys being used in Russia [15, 16, 17, 18]. A method of manufacturing a superelastic thread from titanium nickelide was patented in 2006 [17, 18]. At a baseline, wire samples and threads are a composite consisting of a core – monolithic titanium nickelide – and a surface layer with a microstructured surface. The diameter of titanium nickelide threads ranges between 60 and 120 microns. The threads have a microstructured surface that increases the area of their contact with the tissues being connected. They are also able to function reliably in the body under alternating effects due to their elasticity and resilience, and can be used for tendon sutures [19, 20]. The strength of this material in tendon repair has not been sufficiently studied and its biomechanical properties can be compared with more common suture materials.

The objective was to compare the strength of suture materials under cyclic loading on a biological model of a tendon.

MATERIAL AND METHODS

Eighty flexor tendons of the second digit of the forelimbs taken from five-month-old piglets weighing 90-110 kg were explored. The mean diameter and length of each porcine tendon were 5 ± 1 mm and 60 ± 10 mm, respectively, which correlated with the parameters of human flexor digitorum profundus tendons. A transverse incision was made through each porcine tendon using a scalpel. The incision area corresponded to the base of the mechanical finger designed as

described below, to simulate a complete tendon injury in a “difficult anatomical area.” The ends of the tendons were repaired by one surgeon using four types of suture material with a 6-strand M-Tang suture [21, 22] (Fig. 1).

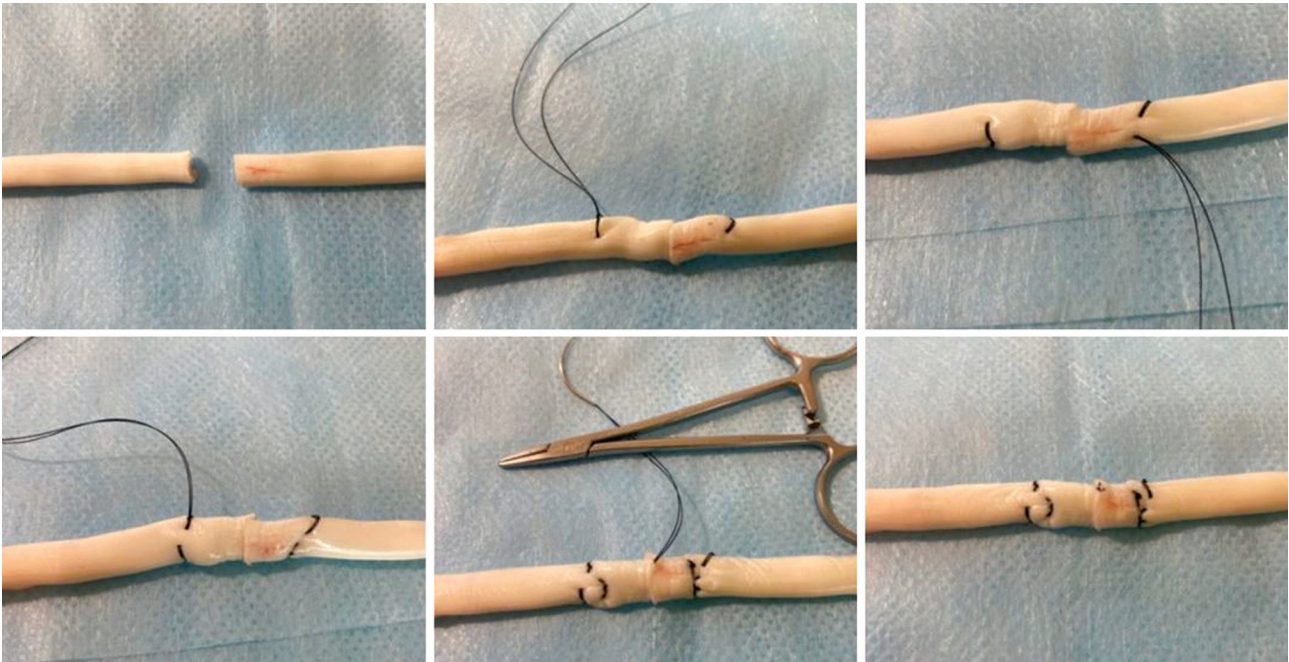


Fig. 1 6-thread M-Tang suturing

The caliber of the suture material was 4/0 (0.15 mm) with 10 mm distance from the ends of the tendons and 2 mm loop length. No additional epitendinous suture was applied for a more objective examination of the strength of the suture material. Institutional ethics committee approval was not required for this type of study. Four types of suture material used to restore the tendon included:

- (1) Polypropylene (monofilament) synthetic thread;
- (2) Non-absorbable polyamide braided thread;
- (3) Complex polytetrafluoroethylene thread;
- (4) Super-elastic titanium nickelide thread.

Depending on the suture material used, all tendons were randomly distributed into 4 groups, 20 samples each. The cross-linked tendons were kept at 5°C and hydrated prior to strength and cyclic testing [23]. At the final stage, all repaired tendons were examined using the original device (Fig. 2).

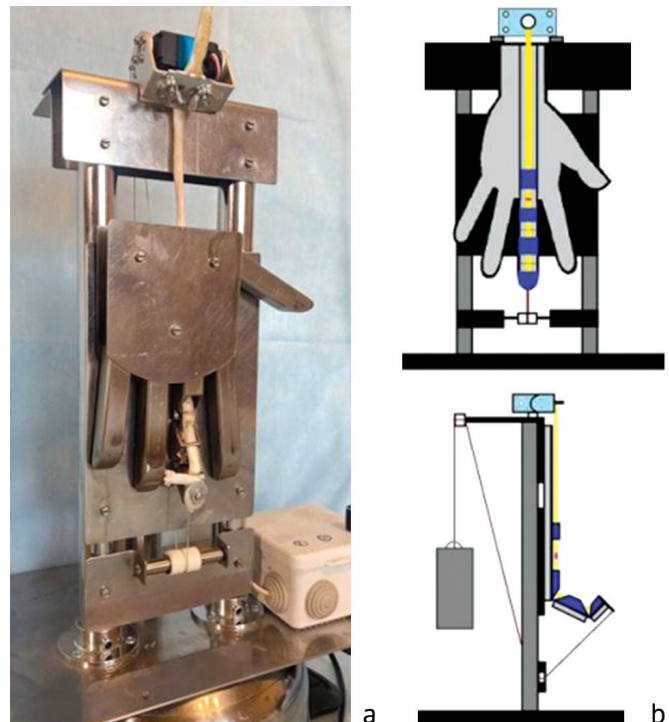


Fig. 2 A device for practicing the skills of applying a tendon suture and testing its strength (a). Diagram of cyclic strength testing (b)

A device (RF patent application No. 2023119917 dated July 28, 2023) was previously developed for applying cyclic testing protocols to examine a biological model of a tendon suture. The distal end of the tendon was secured to the mechanical finger using a clamping screw, and the proximal end of the tendon was secured to the servo drive. A weight of 1 kg was used for static loading to achieve full extension of the finger at the beginning of each cycle and provide a pre-start load.

The standard protocol of Chang et al. was used to determine the fatigue strength of the suture material which was the sum of the number of cycles and the load used in cyclic test protocols for tendon sutures [24, 25, 26]. It was a cyclic tensile strength test using 2 N for preload, then a cyclic load of 15 N to simulate passive mobilization, and 2000 cycles at 0.3 Hz or until the suture breaks. The cyclic tensile strength test was produced as reported in previous publication. Visual confirmation of each parameter was obtained for each cycle using video recording.

Statistical analysis was performed using IBM SPSS 28.0.1. Quantitative data were presented as the arithmetic mean with standard deviation ($M \pm SD$) in the normal distribution and as the median with the interquartile range Me [27, 28] in the non-normal distribution using the Kolmogorov – Smirnov test with Lilliefors correction. Analysis of qualitative variables was produced in groups using the Pearson χ^2 test. A significance level of $p < 0.05$ was accepted for significant differences comparing four groups, taking into account the Bonferroni correction, $p < 0.0085$.

RESULTS

The average size of the gap between the ends of the tendons repaired in the absence of thread rupture was 3.47 ± 2.07 mm in the first group, 1.6 ± 0.7 mm in the second group, 1.32 ± 0.75 mm in the third group, 1.16 ± 0.5 mm in the fourth group with a cyclic loading protocol of 2000 cycles performed. No node ruptures or tissue eruption were detected in any group.

A comparison of different types of suture material showed a reversible gap (up to 1 mm) between the ends of the repaired tendons being common (Table 1) in the group of complex polytetrafluoroethylene thread (group 3) and superelastic titanium nickelide thread (group 4) in comparison with polypropylene (monofilament) synthetic thread (group 1) and non-absorbable polyamide braided thread (group 2). No significant differences were found between groups 1 and 2, and between groups 3 and 4. An irreversible gap was more common for a polypropylene thread as compared to a titanium nickelide thread. Thread rupture was more common for complex polytetrafluoroethylene thread in comparison with groups 3 and 4 (Table 1).

Table 1

Analysis of a gap or thread breakage occurred with different types of suture material

	Group 1 (n = 20)	Group 2 (n = 20)	Group 3 (n = 20)	Group 4 (n = 20)	p (1-2)	p (1-3)	p (1-4)	p (2-3)	p (2-4)	p (3-4)
Reversible gap 1 mm	5 (25 %)	5 (25 %)	16 (80 %)	17 (85 %)	–	0.003	0.001	0.001	< 0.001	–
Irreversible gap \geq 2 mm	12 (60 %)	5 (25 %)	3 (15 %)	2 (10 %)	–	–	0.006	–	–	–
Thread rupture	3 (15 %)	10 (50 %)	1 (5 %)	1 (5 %)	–	–	–	0.006	0.006	–

Dynamic changes in the tendon suture were analyzed depending on the number of load cycles (Fig. 3).

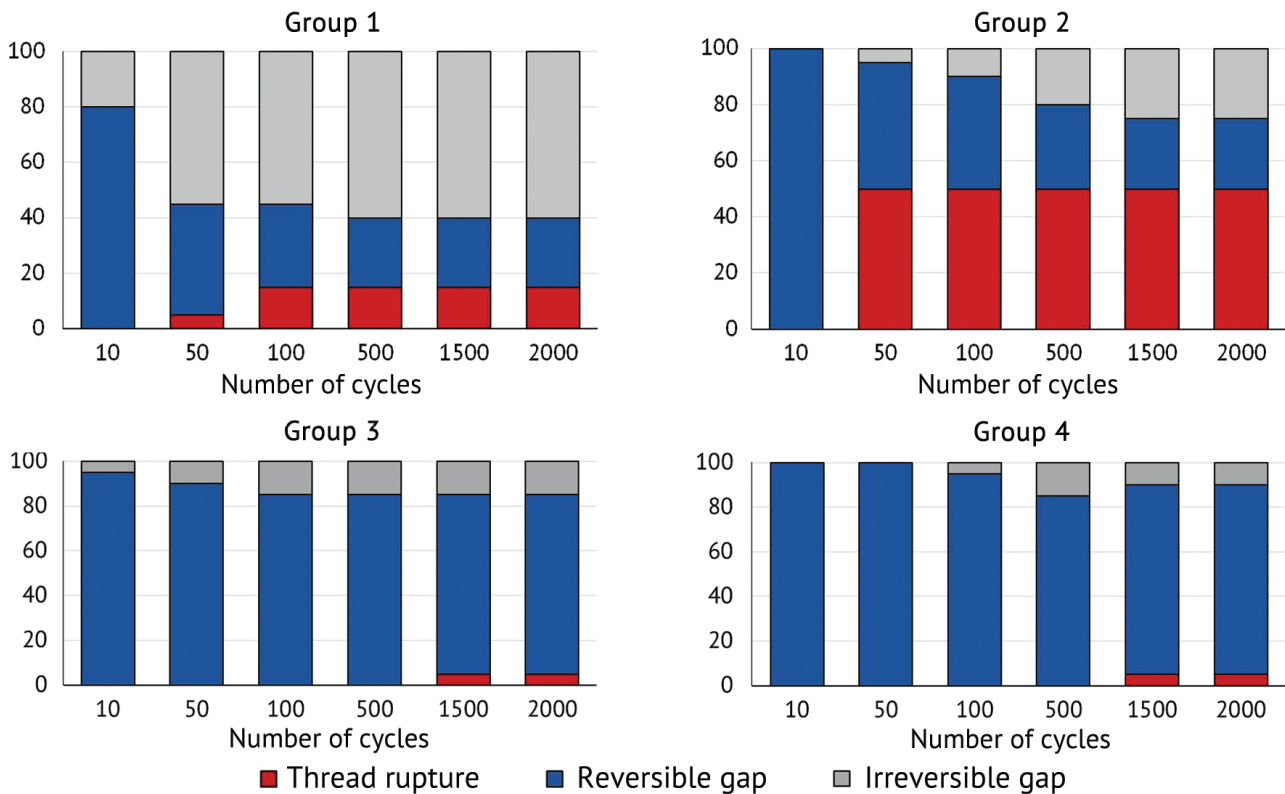


Fig. 3 Correlation between the gap between the ends of tendons (mm) and the number of load cycles in the study groups

An irreversible gap seen in the first group (polypropylene monofilament thread) was recorded in 20 % of cases after the first 10 cycles and in 55 % of cases after 50 cycles. The thread broke in 15 % of cases after 100 cycles of repetitions with an irreversible gap detected in 60 % of cases. The ratio remained until the end of the 2000 cycle. The largest average gap between the ends of the tendons with no thread rupture was recorded after 2000 repeated cycles (3.47 mm) in the first group. The results obtained confirm the excessive elasticity and plasticity of polypropylene, which can lead to weakening and stretching of tendon sutures after 50 repeated loading cycles.

The thread broke in half of the cases (50 %) of the second group (polyamide braided thread) with 50 repeated cycles. An irreversible gap of more than 2 mm detected after 50 cycles in 45 % of cases, decreased to 30 % after 1000 cycles. The high probability of thread breakage with 50 repeated cycles was associated with the low elasticity and low linear strength of the braided polyamide thread compared to other materials. An irreversible gap was recorded in 10 % of cases of the third group (polytetrafluoroethylene thread) with 50 repeated cycles. This number increased to 15 % and remained unchanged after 100 repetition cycles throughout the test. A single case of thread breakage was recorded after 100 repeated cycles with the only case of thread rupture registered after 1500 cycles. A single case of irreversible gap was detected after 100 repeated cycles, and a single case of thread rupture occurred after 1500 cycles in the fourth group (superelastic nickel-titanium thread).

DISCUSSION

Over the past 20 years, there has been a marked increase in the number of clinical and experimental publications on primary flexor tendon repair. Researchers sought to compare different tendon sutures and explore the pathomorphology of tendon repair, while biomechanical properties

of suture material remained poorly studied, although early postoperative rehabilitation and the final functional result would be dependent on the strength of the suture material.

Four suture materials were examined in our experimental study using an original device for cyclic testing of a biological model of a tendon suture. Static load-to-failure testing was produced in the experimental studies of suture material strength using Instron 3343 Single Column System (Instron Corp, Canton, Massachusetts) [29, 30, 31, 32, 33]. Cyclic testing is indicated for simulating postoperative conditions compared to static testing, which uses a constant speed of movement with increasing force. Cyclic testing has also been shown to induce tear formation in repaired flexor tendons at lower loads compared to static testing. This suggests that cyclic testing is a more rigorous and realistic measure of the effectiveness of flexor tendon repair than linear stretch testing.

Twenty-five percent of the tendon sutures remained intact for the polypropylene and braided polyamide sutures after completing the entire cyclic loading protocol of 2000 repetitions. When using, an irreversible gap was recorded in half of the cases with a polypropylene (monofilament) synthetic thread after 50 cycles of load repetitions, and suture rupture was more common after 2,000 cycles in comparison with complex polytetrafluoroethylene thread and nickel-titanium thread. This indicates that polypropylene thread has excessive elasticity and plasticity, unlike other types of suture material, which leads to weakening and stretching of the tendon sutures with early mobilization rehabilitation protocol.

There were no significant differences between polypropylene and braided polyamide threads. With the latter, a thread break was recorded in half the cases after 50 repeated cycles. A rupture in the group was more common after 2000 cycles as compared to the use of complex polytetrafluoroethylene thread and nickel-titanium thread. This indicated low elasticity and linear strength with the braided polyamide suture as compared to other groups, which explained the likelihood of suture rupture during the first two weeks after surgery with the connected tendon ends being the weakest during this period. Polytetrafluoroethylene and nickel-titanium threads demonstrated the best biomechanical properties in the form of linear strength, good elasticity and low flexibility.

There were no significant differences between the threads after 2000 cycles, however, an irreversible gap was seen later being less common with use of a titanium nickelide thread. The average gap size in the absence of a thread breakage after 2000 repetition cycles was also minimum for the titanium nickelide thread.

CONCLUSION

The results of an experimental study of the fatigue strength of the tendon suture were demonstrated in four groups of biological models.

The demonstrated results of comparing the strength of different types of suture material on a biological model of a tendon under cyclic loading will allow in clinical practice to select the optimal suture material for suturing the flexor tendons and will ensure an improvement in the functional result, since the strength of the tendon suture guarantees the success of early active postoperative rehabilitation.

Conflict of interest The authors declare that there are no obvious or potential conflicts of interest related to the publication of this article.

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Paskov R.V. – methodology, validation, formal analysis.

Sergeev K.S. – conceptualization, reviewing and editing, supervision, project management

All authors confirm that their authorship meets the international ICMJE criteria (all authors made a significant contribution to the development of the concept, conduct of the study and preparation of the article, read and approved the final version before publication).