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Original Research

Biomechanical Analysis of a New Odd-Numbered Strand Suture Technique for Early Active Mobilization After Primary Flexor Tendon Repair

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A R T I C L E I N F O

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Purpose: The placement of multistrand sutures during flexor tendon repair is complex and challenging. We developed a new, simpler, nine-strand suture, which we term the Tajima nines. The Tajima nines repair method is a new odd-numbered strand tendon technique.

Methods: Fourteen porcine flexor tendons were transected and repaired using the Tajima nines repair method, without placement of peripheral sutures. This technique is a modification of the Lim and Tsai repair method; it uses a 4-0 monofilament nylon, 3-strand line, and two needles. The repaired tendons were tested for linear, noncyclic, load-to-failure tensile strength. The initial gap, 2-mm gap-formation force, and ultimate strength were measured.

Results: The initial gap-formation force was 27.9 ± 7.5 newtons (N), the 2-mm gap-formation force was 39.2 ± 4.7 N, and the ultimate strength was 76.7 ± 17.2 N. Eight, three, and three of the 14 tendons repaired using the Tajima nines method demonstrated failure because of thread breakage, knot failure, and suture pull-out, respectively.

Conclusions: This biomechanical study demonstrated that Tajima nines repair was associated with particularly high initial tension at the repair site; there were minor variations in the initial load and 2-mm gap-formation load. Our results suggest that Tajima nines repair with peripheral suturing allows the repaired flexor tendon to tolerate the stresses encountered during early active mobilization.

Clinical relevance: This simple nine-strand technique will be particularly useful for inexperienced surgeons who perform early active mobilization after primary flexor tendon repair because the technique is a modification of the Lim and Tsai repair method using a triple strand instead of a double strand.

Current flexor tendon repair techniques involve the use of multiple sutures, with at least two strands passing through the repair site. Flexor tendon repair techniques that use multistrand sutures tolerate high tensile forces generated by early active mobilization.[1–3] Considering the soft tissue responses and reduced tensile strength after repair, multistrand sutures are required to have a baseline ultimate strength of 40–50 newtons (N) and the capacity to resist a gap load of 20–30 N during early active mobilization.[4] The load associated with a 2-mm gap is commonly used as the threshold in comparative biomechanical studies because gaps >2 mm are associated with significantly worse adhesion-related patient outcomes.[5,6] Multiple tendon repair techniques with different repair configurations have been proposed to achieve strong repairs.[1,2,4,7] Existing techniques involve an even number of strands (eg, 2–10). Thus far, no odd-numbered strand suture technique has been proposed.[2,3,7]

Here, we present a new nine-strand suture technique for early active mobilization after flexor tendon repair. This study evaluated tensile properties after use of the new suture technique.

Methods

This study is based on the design of a previously published biomechanical assessment of in vitro porcine flexor tendon repair techniques.[3,8–10] The use of animal tissues complied with the guidelines of the authors' institute, the National Institutes of

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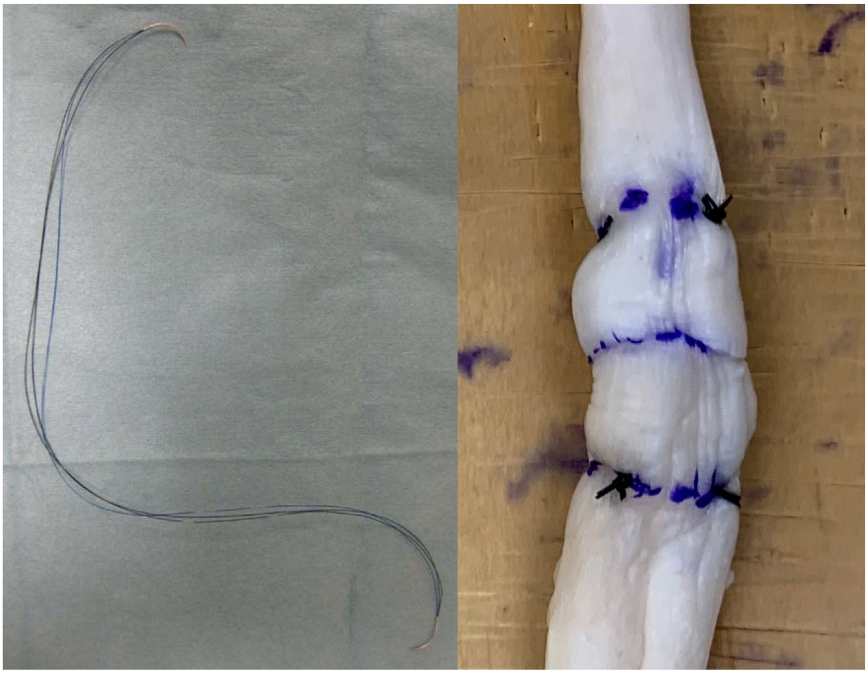

Figure 1. Triple Tajima needle and Tajima nines method.

Health, and the Japanese law on the use of laboratory animals.[11,12] All experimental procedures were performed in accordance with ethical standards after approval had been granted from our hospital ethics committee.

We created a new suture material termed the "triple Tajima needle" to achieve strong flexor tendon repair. This material, consisting of three monofilament nylon strands and two needles, was used for the new suture technique, which we termed the "Tajima nines method" (Fig. 1). We used linear loading tests to evaluate the mechanical properties of tendon repairs using the Tajima nines method. Fourteen porcine flexor digitorum profundus tendons (mean length, 132.8 ± 3.5 mm) were harvested from the second and third toes of the hind feet of adult pigs, then stored at −20 °C; they were thawed to room temperature for 4 hours prior to testing. Excess proximal tendons were removed to achieve a final tendon length of 100 mm. The tendons were transected in the middle zone, which corresponds to the human flexor tendon zone 2. At this level, the mean porcine flexor digitorum profundus tendon width was 8.3 ± 0.6 mm.

Repair method

The tendons were repaired by the lead author (K.M.), who has considerable experience in flexor tendon surgery (level 4 expertise).[13] The suture configuration of the Tajima nines repair is similar to that of the Lim and Tsai 6-strand repair method,[14,15] which uses one triple Tajima needle with two extratendinous knots (Fig. 2). We used a 4-0 monofilament nylon triple strand with two needles (Bear Medic Corp). The core suture purchase length was 10 mm, the lock width was 4 mm, and all lock depths within the tendon were approximately 2 mm. The core suture was tightened by shortening the tendon segment within the core suture strands by 10%.[16] All sutures were knotted with a surgical knot using a double throw, followed by two single (square) throws. No peripheral sutures were placed to exclude the effects of variations in core sutures.

Biomechanical testing

Repaired tendons were moistened with wet gauze and then subjected to linear load-to-failure testing using a tensile test machine (AG-I 10kN; Shimadzu Corp; Fig. 3). The force transducer of the machine was connected to the upper clamp, and the force was recorded using specialized software (Trapezium; Shimadzu Corp). The tendon ends were tightly gripped in the upper and lower clamps; the initial distance between clamps was 5 cm. A preload of 0.5 N was applied before loading evaluation. The overhead crossbar connected to the upper clamp was advanced at a constant speed of 25 mm/min. The preload and tendon pull rate were adjusted to simulate tendon loading during active finger flexion.[17] The distance between stumps was monitored using a video camera vertically mounted at the level of the tendon repair site, along with monitoring of the pulling force. Any force that produced gaps evident on the monitor was recorded on the display board; each force was regarded as an initial gap-formation force. The 2-mm gap-formation force was defined as the force required to separate more than 50% of the transverse cut ends of the tendon by 2 mm.[8] The tendons were pulled until complete suture pull-out or rupture occurred. The ultimate repair strength was the peak force recorded during the test.

Results

Under linear loading conditions, the mean initial gap-formation force was 27.9 N (range: 11.8–41.4 N), the mean 2-mm gap-formation force was 39.2 N (range: 29.1–46.8 N), and the mean ultimate strength was 76.7 N (range: 52.8–105.7 N; Table 1). Despite the absence of peripheral sutures, 86% of tendon repairs met the essential criteria for early active mobilization. Eight, 3, and three of the 14 tendons repaired using the Tajima nines method failed because of thread breakage, knot failure, and suture pull-out, respectively (Fig. 4).

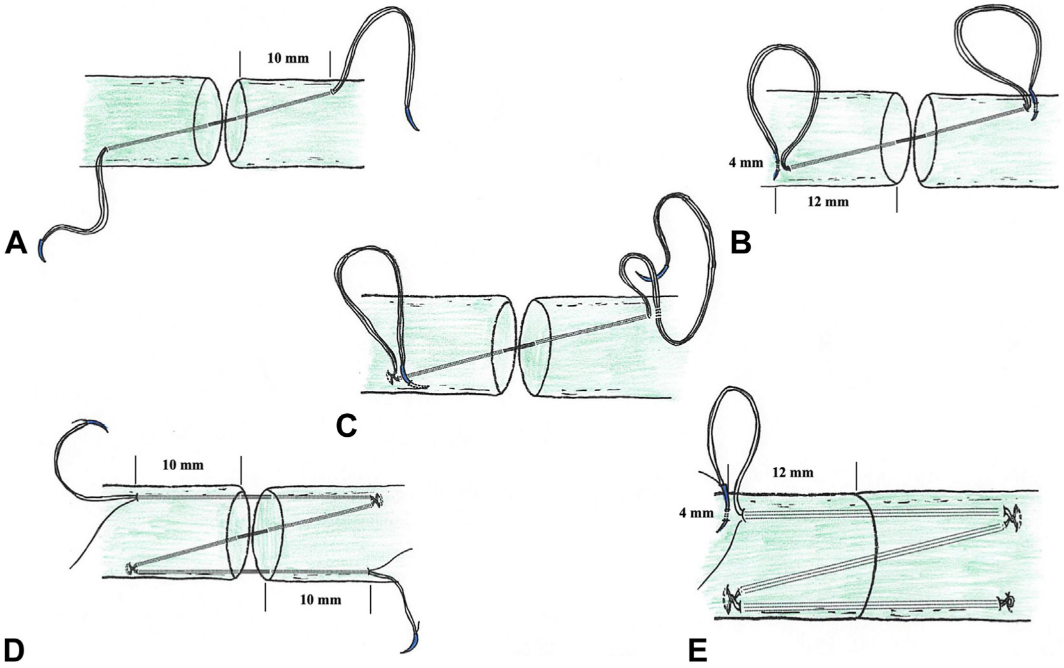

Figure 2. Tajima nines method. **A** At first, each needle is inserted at the center of the ends of both cut surfaces, with an oblique orientation to exit 10 mm from the tendon end. **B** A superficial 4-mm transverse tendon bite is created by both needles, 12 mm from the tendon end. **C** Locking sutures are made by inserting the needles through the loop sutures at both sides. Next, the needles are inserted close to the locking sutures. **D** Each needle is longitudinally passed through the cut surface to the other side of the cut, exiting 10 mm from the tendon end and cutting one of three strands. **E** A superficial 4-mm transverse tendon bite is created by both needles, 12 mm from the tendon end, and the extra-tendinous knot is made using three throws under tension that reduced the encompassed tendon segment length by 10%.

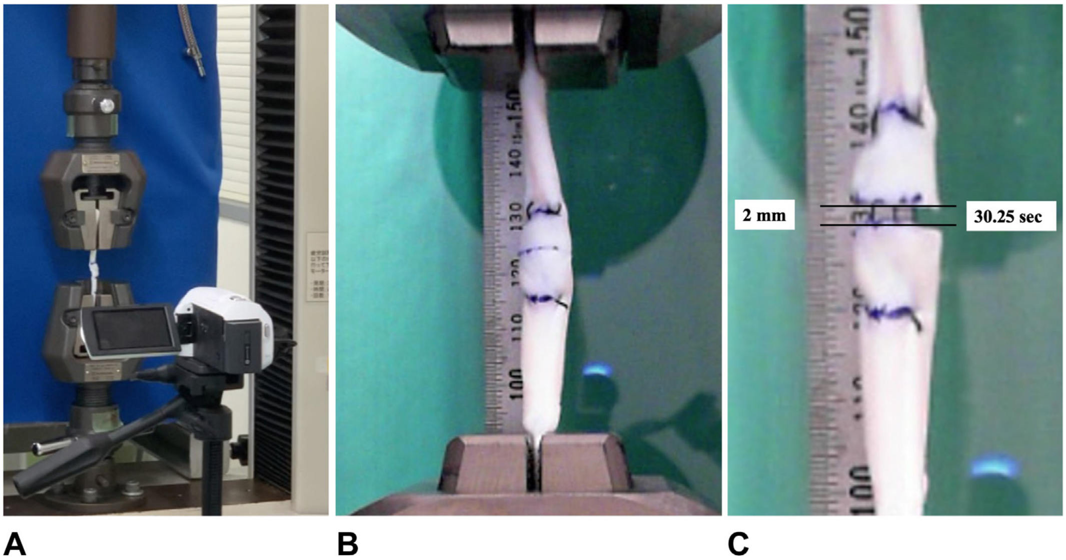

Figure 3. Experimental setup. Stump separation and repair failure were monitored using a high-resolution video camera **A** that recorded vertical tendon views at repair sites. Gap sizes were measured using a scale **B** placed adjacent to tendons on still images **C** from the videos.

Discussion

Among various factors affecting the strength of a surgical repair, the tensile strength is proportional to the number of suture strands crossing the repair site.[3,18,19] The number of strands can be increased by using a double-stranded needle because each suture pass adds two strands to the core. The triple Tajima needle was constructed using three strands and two needles to easily increase the number of core suture strands with each pass. Thus, the Tajima nines method is a new suture technique characterized by the use of an odd number of strands. Despite the absence of peripheral sutures, the mean initial gap-formation force, mean 2-mm gap-formation force, and mean ultimate strength after Tajima nines repair were 27.9 N (range: 11.8–41.4 N), 39.2 N (range: 29.1–46.8 N), and 76.7 N (range: 52.8–105.7 N), respectively. Thus, 86% of the tendon repairs fulfilled the essential criteria for early active mobilization. Our study showed that the Tajima nines method provides particularly high initial tension at the repair site, which is crucial for the prevention of gap formation.[4,20]

Table 1
Summary of the Biomechanical Test Data for the Tajima Nines Repair

Specimen	Tensile Strength (N)			Essential Criteria for EAM[*]	Mode of Failure
	Initial Gap	2-mm Gap	Maximal Load		
1	41.4	45.6	76.5	Fulfilled	Thread breakage
2	34.2	41.2	54.3	Fulfilled	Thread breakage
3	32.8	38.3	105.7	Fulfilled	Pull-out
4	20.5	33.7	75.0	Fulfilled	Thread breakage
5	32.2	42.8	94.2	Fulfilled	Pull-out
6	30.0	38.1	92.5	Fulfilled	Knot failure
7	31.2	41.7	57.2	Fulfilled	Knot failure
8	18.5	36.7	57.0	Failed	Thread breakage
9	25.7	34.6	95.1	Fulfilled	Knot failure
10	33.3	46.8	72.2	Fulfilled	Thread breakage
11	26.6	39.9	86.3	Fulfilled	Pull-out
12	11.8	29.1	86.5	Failed	Thread breakage
13	24.3	38.8	68.8	Fulfilled	Thread breakage
14	27.6	41.1	52.8	Fulfilled	Thread breakage

EAM, early active mobilization; N, newton.

[*] Ultimate strength of 40–50 N and the capacity to resist a gap load of 20–30 N.

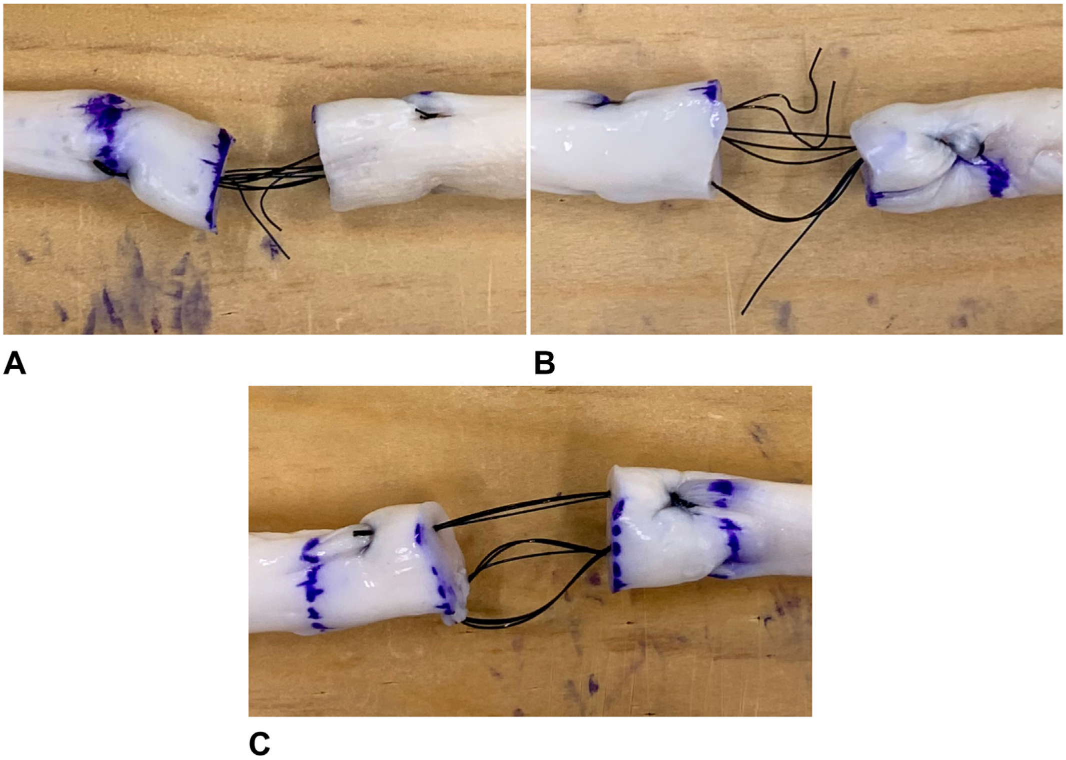

Figure 4. Mode of failure. **A** Thread breakage, **B** knot failure, and **C** suture pull-out.

In the biomechanical studies, the tensile properties were strongly influenced by the repair technique. Core suture strength was extensively investigated using both a single-cycle load-to-failure test and a cyclic test setup. Based on these studies, a 6-strand repair afforded an ultimate strength of about 50–60 N, and an 8-strand repair, an ultimate strength of about 60–70 N when using a 4-0 suture material similar to that employed in this study (Table 2).[3,8,15,16,21–23] However, given the lack of consistency in the methods of investigation, these studies are not easily comparable with our study. We believe that the Tajima nines method will allow early active motion after primary flexor tendon repair when supplemental peripheral stitches are used to achieve greater tensile strength because 14% of tendon repairs lacking peripheral sutures did not meet the essential criteria for early active mobilization.

The ideal technique for primary flexor tendon repair should be simple and reliable. The disadvantages of existing multistrand repair methods include greater tissue handling with a higher number of suture passes and greater technical difficulty.[2,7] Among various proposed suture techniques, the Lim and Tsai repair method is relatively simple compared with other 6-strand techniques.[3] The Lim and Tsai repair and its modifications are commonly performed; modifications to a standard core suture configuration do not compromise the biomechanical competence of the repair techniques.[10] Additionally, the modified Lim and Tsai repair method can easily be performed by junior surgical trainees

Table 2
Summary of the Results of Biomechanical Studies on Multistrand Repair Methods Using a Single-Cycle Load-to-Failure Test

Authors (y)	Tendons	Core Techniques (Material)	Peripheral Techniques (Material)	Mean 2-mm Gap Force (N)	Mean Ultimate Strength (N)
Gill et al[15]	Human	Lim and Tsai, 6-strand (4-0 NAM)[*]	Simple running (6-0 NAM)[†]	27.6 (8.4)	49.0 (13.4)
Xie et al[22]	Human	Triple Tsuge, 6-strand (4-0 NAM)[*]	Simple running (6-0 NAM)[‡]	44.5 (4.3)	60.2 (5.4)
Wang et al[23]	Porcine	M-Tang, 6-strand (4-0 NAM)[*]	Simple running (6-0 NAM)[‡]	46.2 (5.2)	61.9 (6.0)
Chang et al[8]	Porcine	Lim and Tsai, 6-strand Original Modified (4-0 NAM)[*]	None	11.0 (2.0) 15.0 (1.0)	48.0 (3.0) 55.0 (5.0)
Nelson et al[21]	Human	Winters-Gelberman, 8-strand (4-0 NAM)[*]	Simple running (6-0 NAM)[†]	40.1 (9.0)	71.0 (12.9)
Lee et al[3]	Porcine	Modified Lim and Tsai 8-strand 10-strand (4-0 nylon)	Simple running (6-0 nylon)	32.9 (3.9) 41.3 (8.1)	62.3 (9.1) 86.8 (7.6)
This study (2024)	Porcine	Tajima nines, 9-strand (4-0 nylon)	None	39.2 (4.7)	76.7 (17.2)

N, newton; NAM, nonabsorbable monofilament.
The *N* values in parentheses are the standard deviations.
[*] Supramid (S. Jackson Inc, Alexandria, VA).
[†] Prolene (Ethicon Inc, Somerville, NJ).
[‡] Ethilon (Ethicon Inc, Somerville, NJ).

with level 1 surgical expertise.[24] Therefore, we believe that the Tajima nines method may be easily and reliably performed by less experienced surgeons because it is a modification of the Lim and Tsai repair method using a triple strand instead of a double strand.

The Tajima nines method has some limitations, such as the requirement for a triple Tajima needle and the formation of two extratendinous knots, which increase gliding resistance between the repair and the tendon sheath.[25] Extratendinous knots provide greater strength than intratendinous knots because knots within the tendon repair interface contribute to a partial gap at the tendon repair site, even before loading at the repaired tendon.[8,26] Most multistrand repairs involve the placement of at least two knots over the tendon surface, and the use of extratendinous knots is not associated with adverse clinical consequences.[1] Furthermore, the modified Lim and Tsai technique with an extratendinous knot has a shorter operation time than the modified Lim and Tsai technique with an intratendinous knot.[26] We believe that placement of a knot during the Tajima nines method does not affect clinical outcomes after early active mobilization, and it is easier for inexperienced surgeons to perform. The cross-sectional areas of 3-0 and 4-0 sutures are approximately 0.051 and 0.028 mm^2, respectively. Thus, a 4-0 triple Tajima needle has a larger suture diameter than a 3-0 monofilament nylon and a 4-0 monofilament nylon double strand. The extratendinous knot of Tajima nines does not have a larger cross-sectional area, compared with a 3-0 monofilament nylon, because three 4-0 monofilament nylon strands are divided into two and one strand at the time of knot tying. Therefore, the triple Tajima needle can increase the number and caliber of suture strands without increasing the knot cross-sectional area.

Several important limitations of this study should be considered when interpreting our results. First, we used porcine tendons, rather than human cadaveric tendons; the human flexor tendon is smaller than the porcine flexor tendon. Second, we conducted a static test with a linear distraction force. This test did not consider cycling conditions during repetitive passive or light active motion activities.[27] Experiments involving cadaveric fingers, along with testing of the cyclic conditions and gliding resistance of repaired tendons, are needed to overcome these limitations. Third, this study was conducted at time zero without considering the healing process. Fourth, no biomechanical test was conducted to compare the tensile strength of this technique with the tensile strengths of other multistrand repair techniques; further studies are needed to determine whether our technique is superior to others. Additionally, techniques that involve at least eight strands, including the Tajima nines method, are excessively bulky for extremely small tendons, such as extensor tendons; thus, the use of our technique is limited to flexor tendons. Tendon nutrition and vascularity may also be affected by multiple suture passes.

Conflicts of Interest

No benefits in any form have been received or will be received related directly to this article.

Acknowledgments

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