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ORIGINAL ARTICLE

Tensile Strength of Flexor Tendon Repair Using Barbed Suture Material in a Dynamic Ex Vivo Model

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Abstract The purpose of this study was to compare two sutures; a knotted polydioxane with a knotless barbed in a 4-strand Kirchmayr-Kessler suture technique. Human flexor digitorum tendons were separated into four groups. Group 1 – polydioxane; Group 2 - barbed suture; Group 3 and 4 – same as group 1 and 2 with an additional peripheral running suture. In each group the repaired tendons were subjected to linear and cyclical loads. No difference in maximum tensile strength after linear and cyclical force could be detected between the knotted polydioxane suture and the knotless barbed suture. On linear force tests an additional circumferential repair increased the maximum tensile strength of both sutures. Cyclical force loading did not lead to a reduction of maximum strength. Following linear and cyclical loading the 4-strand barbed suture achieved maximum tensile strengths comparable to the 4-strand repair using the polydioxane suture. Barbed suture repair may offer the advantage of knotless suture techniques.

Keywords Barbed suture · Load to failure · Tenorrhaphy · Dynamic testing · Tensile strength · Ex vivo

Introduction

One of the challenges of tendon surgery lies in facilitating early after-care in order to prevent adhesion, as this adhesion adversely affects the functional outcome [1, 2]. For functional after-care to be safe tendon repair strength has to be between 9 N for the passive mobilisation, and 35 N for active mobilisation for the finger [3]. Tendon repair strength depends on the biomechanics of tendon sutures particularly the material and technique utilised [4, 5]. The suture materials which are available today possess tensile strengths capable of withstanding forces far above what occurs during active treatment. For this reason, suture ruptures are rarely the cause of suture insufficiency [6, 7]. Through an increase in the number of suture strands and additional circumferential sutures, the tensile strength of the tendon repair is further increased [8–12]. Considerable influence on tensile strength of the tendon suture was noted during the interaction between tendon and suture material and especially at the locking configuration [13, 14]. Knots are potential weak points in tendon suturing [15, 16].

To avoid the potential weakness from knots, barbed sutures can be utilised. In the 1950s, barbed sutures were described by Bunnell for tendon repairs [17]. However, it wasn't until 1967 that a biomechanical comparative study was first conducted by McKenzie. He compared tendon sutures with multiple barbed sutures with stainless steel, silk and nylon sutures [18]. In 2009, Parikh at al. [19] and Trocchia et al. [20] published study results in which they used a non-absorbable polypropylene bidirectional barbed suture (Quill™ 2/0; Angiotech, Vancouver, Canada). Parikh compared a knotless three- and six-strand cruciate barbed polypropylene suture repair technique with a knotted four-strand polypropylene, braided polyester and composite polyethylene suture technique. Trocchia et al. undertook a comparison between a modified Kessler knotless polypropylene barbed-Bunnell suture technique and a modified Kessler knotted braided polyester suture technique. The disadvantage of these studies lies in the lack of cyclical testing that model in vivo situations more realistically than

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linear tests alone. We wished to determine the maximum tensile strength of barbed and knotted sutures by linear and cyclical loading. Another difference in our study was the use of absorbable material in the control group (polydioxane) and the study group (glyocolic-carbonate), and the use of an uni-directional barbed suture material. The barbed suture (V-Loc™ 3–0; Covidien Deutschland GmbH, Neustadt, Germany) was manufactured using a copolymer of glycolic acid and trimethylene carbonate, and consists of an absorbable thread with uni-directional shallow barbs with circumferential distribution (Fig. 1). We compared a modified knotted 4-strand Kirchmayr-Kessler mono-filament polydioxane suture technique with a modified knotless 4-strand Kirchmayr-Kessler barbed gylocolic-carbonate suture technique, both with and without a braided circumferential running polyglactine suture.

Methods

Tendon Repair

60 human cadaver flexor digitorum superficialis tendons from Zone II proximal of chiasm to Zone IV and 60 flexor digitorum profundus tendons from Zone II to Zone IV were harvested. Subsequently the 120 human flexor digitorum tendons were trimmed to 10 cm in length and separated into four groups randomly. All repairs were performed immediately after laceration by a single surgeon (M.H.). The flexor tendon core suture was carried out by way of a modified 4-strand Kirchmayr-Kessler technique. In the case of the modified Kirchmayr-Kessler technique, the core stitches were placed in the middle plane of the tendon and the transverse strand passed superficially to the longitudinal strand 7 mm from the transection. (Fig. 2). All tendons were repaired end-to-end, resulting in loops for tensile testing (Fig. 3). The suture material/technique test groups consisted of: Group 1 (n=30) – absorbable monofilament polydioxane suture (PDS 3–0; Johnson & Johnson Medical GmbH, Norderstedt, Germany); Group 2 (n=30) - absorbable unidirectional barbed glycolic-carbonate suture material (V-Loc 3–0; Covidien Deutschland GmbH, Neustadt, Germany); Group 3 (n=30) – same as group 1, yet with an additional peripheral running suture with a braided polyglactine thread (Vicryl 5–0, Johnson & Johnson Medical GmbH, Norderstedt, Germany); Group 4 (n=30), same as group 2, with an additional peripheral running suture with a braided polyglactine thread.

Fig. 1 Close-up view of the unidirectional barbed glycolic-carbonate suture (V-Loc™ 3–0; Covidien Deutschland GmbH, Neustadt, Germany)

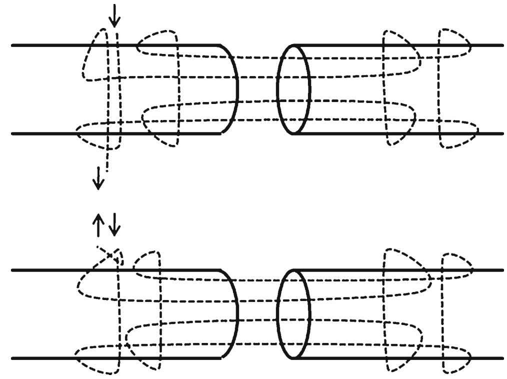

Fig. 2 Suture technique: modified knotless (above) and knotted (below) 4-strand Kirchmayr-Kessler technique

Biomechanical Testing

Immediately after repair, biomechanical tests were carried out in a universal axial and torsion testing machine (Zwick/Roell, Ulm, Germany). To determine the maximum strength, each group of 15 tendons (n=15) was subjected to linear loading. To this end the loops were stretched vertically until they reached a pre-load of 1 N (kg·m/s²), and then retracted at a rate of 20 mm/minute until mechanical failure of the repair occurred. The cyclical stress test was carried out with the remaining 15 tendons in every group in a graduated manner. Therefore the tendon sutures were put through a total of 2,500 cycles, in stages of 500 cycles carried out with 10, 15, 20, 25, and 30 N. Thereafter, linear retraction continued until a mechanical failure

Fig. 3 Tensile testing configuration

occurred (Fig. 4). A suture pullout with a visible gap of > 3 mm equated to a suture breakage or knot rupture. A load displacement graph was recorded for each sample, and the mode of failure was noted.

Statistical Analysis

A data analysis was performed using SPSS 15.0 (SPSS, Inc., Chicago, Ill.). All results are expressed as mean and standard deviation (SD). For an individual statistical group comparison, the student's *t*-test was used due to normal distribution. Differences at the $p \leq 0.05$ level were considered significant.

Results

Mode of Failure

Maximum strength was determined by a gap of > 3 mm appearing in all tendon groups. This gap remained post cessation of loading. In the groups *with* an additional running suture, the suture breakage of the braided polyglactine epitendinous suture appeared during maximum strength exposure.

Load to Failure

Load to failure data are listed in Fig. 5. Regardless of whether a peripheral circumferential suture was used, no difference could be detected between a polydioxane suture and a barbed glycolic-carbonate suture at maximum tensile strength after linear and cyclical force ($p > 0.05$). On linear force tests an additional circumferential repair increased the maximum tensile strength of a knotted 4-strand Kirchmayr-Kessler mono-filament polydioxane suture by 38 % ($p < 0.001$) and of a knotless barbed gylocolic-carbonate suture by 63 % ($p < 0.001$). On cyclical tests, additional circumferential repair increased the maximum tensile strength of a knotted polydioxane suture by 50 % ($p < 0.001$) and of a knotless barbed gylocolic-carbonate suture by 91 % ($p < 0.001$). Cyclical force did not lead to a significant reduction of maximum strength ($p > 0.05$).

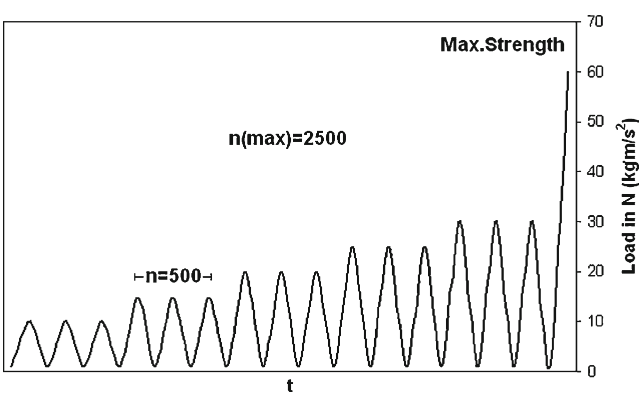

Fig. 4 Schematic representation of the cyclical loading test being carried out. After a total of 2500 cycles with each 500 cycles being conducted at 10, 15, 20, 25 and 30 N, a linear load occurs until the emergence of a suture pullout with a >3 mm gap through suture breakage or a knot failure

Discussion

Immobilised tendon sutures lose 50 % of their initial tensile strength within the first week [21, 22], an early passive and active motion rehabilitation programme can improve tendon nutrition, healing, and remodelling [23–26]. Therefore, it is absolutely essential that the tendon repair is sufficiently strong to withstand forces generated during early active mobilisation.

Barbed suture materials increase the interaction between the tendon tissue and suture material. Through an increase in this interaction, the number of threads can be reduced and a knot can be dispensed of. This was proven by Parikh et al. [19]. Using a non-absorbable uni-directional barbed suture material they achieved a knotless 3-strand cruciate repair technique and a tensile strength comparable to that of a knotted 4-strand monofilament or braided cruciate suture. When using a modified knotless Kessler-Bunnell barbed polypropylene suture technique, Trocchia et al. [20] found that its maximum load to failure compared to a modified knotted Kessler braided polyester suture could be significantly increased. In addition to that we were able to show that a knotless 2-strand Kirchmayr-Kessler barbed suture proved to be insufficient and significantly weaker than a knotted 2-strand polydioxane suture, but the comparison of maximum tensile strength of a knotless with that of a knotted 4-strand Kirchmayr-Kessler technique resulted in no significant difference [27]. It must be noted, however, that all these studies measured only the maximum tensile strength after linear loading and therefore these readings may not be applied absolutely to the conditions in vivo. In addition, the studies of Parikh et al. and Trocchia et al. worked with two variables (suture material and suture technique), whereby the value of the statistical worth must be examined critically.

McClellan et al. compared porcine flexor digitorum profundus tendons that were transected and repaired with a 2-strand Kessler-, 4-strand-Savage- or 4-strand-knotless technique. By testing the 2 mm-gap formation force and the ultimate strength they demonstrated that knotless flexor tendon repair with barbed suture has equivalent strength and reduced repair-site cross-sectional area compared with traditional techniques [28]. So it can be stated that through the enabling of a knotless suture, a knot can be eliminated as

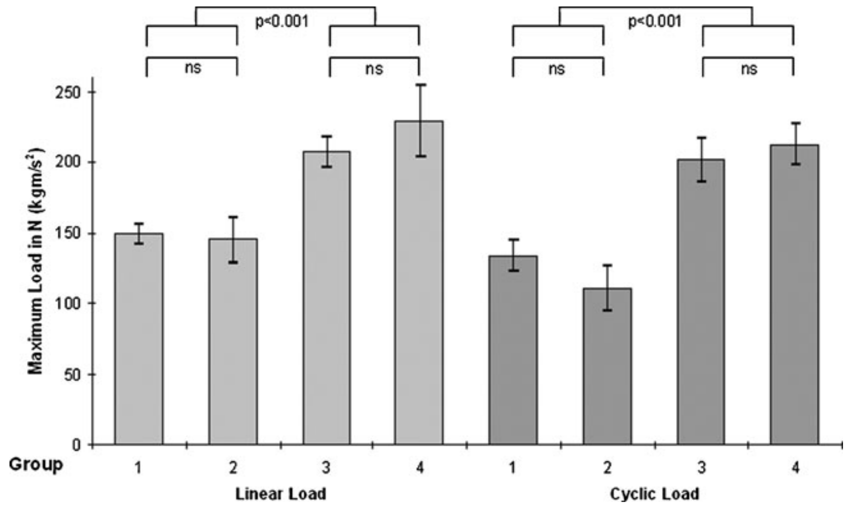

Fig. 5 Maximum tensile strength in Newton (kg·m/s^2) after linear (light grey) and cyclical (dark grey) loading. All results are expressed as mean ± SD. Group 1 – absorbable monofilament polydioxane suture (PDS 3/0); Group 2 - absorbable uni-directional barbed glycolic-carbonate suture (V-Loc 3/0); Group 3/4 – same as group 1/2, yet with an additional peripheral running braided polyglactine suture (Vicryl 5/0). The statistical method used was the Student´s t- test. $p \leq 0.05$ was considered significant, ns = not significant

one of the weak points of the mechanical loading capacity of a suture-material, but further in vivo tests are necessary to examine whether the omission of a knot reduces friction inside the tendon sheath that could be the cause of adhesions.

To determine the strength of tendon sutures ex vivo, it is our view that the simulation of physiological conditions is crucial. For this reason, our biomechanical tests implemented a study model which encompassed the calculation of maximum tensile strength after linear and cyclical loading. The cyclical load correlates better with physiology as opposed to linear testing, since the early function and active after-care relies upon the principal of phasic loading and discharge [29, 30]. In our study we knowingly abstained from determining specific gap formation forces. The gapping point from which a functional deficit occurs varies a lot between 2 mm and 10 mm [31–33]. Tran et al. described three varieties of tenorrhaphy gapping under cyclic load [12]. The oscillatory type had no clinical relevance. In the case of the residual type, the gap remained after the load was released, and had significant clinical relevance – just as in the case of the catastrophic type where the applied loads could not be transmitted across the tenorrhaphy. An oscillatory gap appeared during our dynamic tests when we applied ≤ 30 N force. We equated the maximum load to failure after linear loading and the occurrence of a gap > 3 mm to a suture breakage or knot failure.

Our test set-up, considering the tendons were repaired end-to-end, creating a loop apposes different flexor tendon zones with different structures and biomechanical properties and leads to a increased load to failure [34]. That makes the interpretation and a direct comparison of loads between different studies more complex. Another weakness of our study is that an ex vivo model was utilized and the measurement of tensile strength was the only parameter for quality of flexor tendon repair. Additional in vivo studies are needed in order to compare the biological behaviour of the studied suture materials. Thus the seeming advantage of a "knotless" repair of the barbed suture might be lost in an in vivo setting if the suture is absorbed prematurely or creates denser scarring.

As a conclusion of these ex vivo findings, we maintain that it is possible to carry out active after-care of tendon injuries by way of an increase in the tendon tissue-suture material interaction through utilisation of a barbed suture.

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Patient confidentiality and informed consent None

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