Direct Radiological Visualization of Loading on Four Flexor Tendon Repair Suture Configurations

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Purpose To study the deformation of 4 suture configurations used in flexor tendon repair using fluoroscopy.

Methods All flexor tendon repair techniques have a longitudinal component, a link component, and/or a transverse component. We had previously described 4 types of link components, namely an arc (grasping loop), a simple loop (locking loop), a complex loop, and a knot. The effect of loading on suture configurations using each of these link components was tested in flexor tendon from the first ray of porcine feet. Forty flexor tendons were divided into 4 groups of 10 each, and one-half of a tendon repair was simulated on each group using 0.5 mm stainless steel wire. The tendons were mounted on a materials testing machine, and tensile force was applied until failure. The deformation of the suture within the tendon substance was observed using an image intensifier, and the maximal load to failure was measured.

Results The loading of the suture led to unraveling of the suture in an arc, constriction and unraveling in a simple loop, and initial constriction with no further change of the construct in the complex loop with no change in the knot design. The mean pullout strength of the complex loop was statistically greater than all the other 3 designs.

Conclusions Each of the link component designs demonstrated unique deformation characteristics. The complex loop design had the strongest grasping ability.

Clinical relevance This study identified the differences in the deformation characteristics of the 4 types of link components used in flexor tendon repair. This knowledge may allow for the development of better flexor tendon repair techniques and the adoption of a more precise classification of flexor tendon repair techniques. (J Hand Surg Am. 2016;41(1):40–46. Copyright © 2016 by the American Society for Surgery of the Hand. All rights reserved.)

Key words Flexor tendon, radiological imaging, tendon repair.

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Sebastian et al.1 identified 3 components of any tendon core suture technique, namely a longitudinal, a transverse, and a link component. The link component represents the junction between a longitudinal and a transverse component, the junction between 2 longitudinal components, or the termination of a longitudinal component. All tendon core suture techniques have longitudinal and link components and may have the transverse component. The longitudinal and transverse components are usually placed within the tendon substance, and the link component typically lies outside the tendon (Fig. 1).
Variations in the design of the suture configuration result from the orientation of the transverse component in relation to the longitudinal component and/or from differences in construction of the link component. The transverse component may be placed distal or proximal to the far end of the longitudinal component (Fig. 2A). If the transverse component is placed proximal to the far end of the longitudinal component (ie, closer to the cut end of the tendon), 2 additional variations are possible. The transverse component may be passed below or above the longitudinal component (Fig. 2B). If the transverse component is passed below the longitudinal component, it forms an arc (Fig. 3). An arc (also known as a bight in knot terminology) results when the 2 suture components forming it do not cross each other when loaded. This has also been described as a grasping loop.\textsuperscript{2-4} An arc link component does not encircle any tendon fibrils when loaded. If the transverse component is passed above the longitudinal component, it forms a loop. A loop link component results when the suture components cross each other on loading and encircle the tendon fibrils within the loop. This has been previously described as a locking loop.\textsuperscript{5,6} A loop is simple when there is a single loop and complex when there is more than one loop (Fig. 3). A knot link component results when a loop is secured with a knot (Fig. 3).\textsuperscript{1}

Differences in the construction of the link component (arc, simple loop, complex loop, or knot) result in a sliding or an anchored repair on each half of a divided tendon. A sliding repair allows the suture to slide within the tendon substance when tension is applied to one of the longitudinal components, whereas an anchored repair does not allow the suture to move independent of the tendon. An arc and a simple loop link component result in sliding repair, whereas a complex loop and a knot link component result in an anchored repair.\textsuperscript{1} In practice, this means that when an arc or a simple loop is used in a multistrand repair, the repair can be tensioned after the placement of multiple arcs/simple loops, whereas when a complex loop or a knot is used, the tension cannot be changed after the first complex loops/knots are set.

Our hypothesis was that these 4 types of link components (arc, simple loop, complex loop, and knot) would behave differently under tension. Our aim was to observe and record this behavior in real time using stainless steel sutures and fluoroscopic imaging. We also wanted to analyze the maximal load responsible for the failure of these 4 link components designs.

**MATERIAL AND METHODS**

The first ray flexor tendons of 40 fresh frozen porcine limbs were harvested, and they were divided into 4 groups. Each group was assigned one of the 4 link component suture designs (Fig. 3). Only half of a tendon repair was simulated, and repair was done using 30 cm of 0.5 mm stainless steel wire (Lai Xin Feng & Sons Hardware Pte Ltd, Singapore). The caliber of the suture was chosen according to pilot experiments such that failure would occur by suture pullout rather than
suture breakage. Suture needles were fashioned by removing the hub from 18-gauge hypodermic needles, passing the wire through the hub end, and crimping the hub end to hold the wire. The purchase point of the repair was measured at 1 cm from the tendon end. Staples were anchored onto the free end of the wire to act as radiopaque markers at 0 cm and 1 cm from the end of the tendon. The free end of the tendon and the free ends of the wire were secured with industrial clamps and mounted onto a materials testing machine (Instron 5543; Instron, Norwood, MA). A radiopaque ruler parallel to the tendon gave the measurement of distance (Supertech Acrylic radiopaque ruler, Elkhart, IN). The materials testing machine loaded the tendon suture complex at 50 mm/min until failure. All suture designs failed by suture pullout.

The changes in suture configuration and the tendon were recorded in real time using an image intensifier (Hologic Fluroscan Insight, Bedford, MA). For each group, videos were recorded in an anteroposterior (AP) orientation for 8 repairs and lateral orientation for 2 repairs. The videos were played back at normal speed for analysis. The AP videos were analyzed to examine the change in the shape of the link and transverse components and the change in the transverse dimension of the tendon. The lateral videos recorded the change in the angle formed by the axis of the link component to the axis of the longitudinal component and the changes along longitudinal axis of the tendon.

The force required to pull out the suture was calculated with Merlin v5.31 software (Instron). Data were expressed as the means ± standard deviation. In all figures, vertical error bars denote standard deviation. The significance of changes was evaluated using analysis of variance followed by the Tukey test. A P value of less than .05 was considered to indicate a significant difference.

RESULTS

Arc design

In the AP view (Video 1, available on the Journal’s Web site at www.jhandsurg.org), there was unraveling of the arc link component on both sides with eventual complete loss of both arcs and transformation into a “U”-shaped configuration (Fig. 4). The position of the transverse component remained relatively constant. The loss of the arc was associated with the lengthening of the longitudinal component that initially manifested as a slack. With progressive loading, the slack was taken up by the tendon construct moving to the right and the wire construct moving to the left. Eventually, the entire slack was taken up, and the transverse component moved through tendon substance before finally pulling out. There was no change in the transverse dimensions of the tendon in the AP view (Fig. 4). In the lateral view (Video 2, available on the Journal’s Web site at www.jhandsurg.org), the transverse component stayed relatively constant. There was also a change in the link component-longitudinal component angle. It was approximately 60° to begin with and ended at 180° (Fig. 5). This was associated
with a buckling of the tendon (Fig. 5). The mean pullout load for the arc design was 95 ± 13 N.

**Simple loop design**

In the AP view (Video 3, available on the Journal’s Web site at www.jhandsurg.org), there was a progressive constriction of the loop link component (Fig. 4). Then the behavior became similar to the arc design with complete loss of loops, transformation into a “U”-shaped configuration, slack in the longitudinal component, and eventual pullout. There was also a kink in the link component as it changed from a simple loop to a “U”-shaped configuration. This kink was not noted in the arc design. In the AP view, a narrowing of the tendon substance at the level of the link component and a bulge in the tendon immediately proximal to the link component was associated with the constriction of the loop (Fig. 4). This bulge subsided with transformation of the loop into the “U”-shaped configuration. The behavior of the simple loop on the lateral view (Video 4, available on the Journal’s Web site at www.jhandsurg.org) was similar to the arc, with stable transverse component and change in the link component-longitudinal component angle (Fig. 5). Likewise, a buckling of the tendon was similar to the arc design (Fig. 5). The mean pullout load for the simple loop design was 113 ± 231 N.

**Complex loop design**

In the AP view (Video 5, available on the Journal’s Web site at www.jhandsurg.org), the slack in the longitudinal component was taken up initially. As soon as the slack was taken up, the knot started moving through the tendon substance. Because there was no transverse component, the knots were not linked to each other and did not move at the same pace. The shape of the link component remained stable, and there was no change in the transverse dimensions of the tendon as the knot moved through the tendon substance. The findings were similar in the lateral view (Video 8, available on the Journal’s Web site at www.jhandsurg.org). There was no change in the link component-longitudinal component angle or any buckling of the tendon. The mean pullout load was 106 ± 24 N.

The complex loop design required the greatest force to pull out compared with the other 3 designs (172 ± 33 N; Fig. 6). This was statistically significant ($P < .001$). There is no statistically significant difference between the load to failure between the arc, simple loop, and knot designs. The load deformation curve for the different suture configurations is depicted in Figure 7.

**DISCUSSION**

In this study, we were able to observe in real time using fluoroscopic imaging the differences in behavior between 4 flexor tendon suture configurations. The link and transverse components changed into a “U”-shaped configuration in both the arc and the simple loop designs (Fig. 4). This change was associated with a progressive constriction and formation of a kink in the simple loop design that was not seen in the arc design.
Some initial constriction of the complex loop design was noted, but the overall shape of the construct was maintained in the complex loop and knot designs. This behavior of the arc, complex loop, and knot designs confirms the hypothesis of previous studies. In the arc design (grasping loop), the suture strands do not cross each other and, therefore, do not hold or grasp any tendon fibers. This explains the unraveling of the arc on loading. The complex loop and knot design encircle tendon fibers, and unraveling cannot occur without tearing through the tendon fibers. It is, however, difficult to explain the behavior of the simple loop. Our understanding of the simple loop (locking loop) is that the suture strands cross each and, therefore, encircle the tendon fibers held within the loop. This loop should not unravel without tearing through the fibers. There is an initial constriction suggesting hold of the tendon fibers, but suddenly the loop transforms into a “U”-shaped configuration. Hotokezaka hypothesized that the twisting of the tendon fiber on loading could result in unraveling of the locking loop (simple loop), and this allowed the tendon fibril to escape from the grasp of the simple loop (Fig. 8). Further dynamic studies are required to test this hypothesis.

In the arc and simple loop designs (Fig. 5), the link component lies proximal to the far end of the longitudinal component and makes an angle of approximately 60°. As the tendon was loaded, there was a change in this relationship with the link and longitudinal components ending up lying on the same axis. This change in the angle was associated with a buckling of the tendon. We believe that this happened because the link component lay outside the tendon, whereas the transverse and longitudinal components were within the tendon. The transformation of the arc and simple loop design into a “U”-shaped configuration requires that the axes of the link and longitudinal components become parallel, and this results in a buckling of the tendon. This buckling was not noted in the complex loop and knot designs because the longitudinal and link components were parallel to begin with.

A change in the transverse dimensions of the tendon was noted in the simple loop (Fig. 4) and complex loop designs. A bulge occurred proximal to the link component and a narrowing of the tendon at the level of the link component. We believe that the narrowing was caused by the progressively increasing constriction of the link component on loading, resulting in a narrowing of the tendon at the level of the link component and a bulge proximal to the area of constriction. These changes were most obvious in the simple loop design compared with the complex loop and not visualized in the arc and knot designs. It was more prominent in the simple loop as maximal constriction was noted in this design. The bulge was lost in the simple loop once the loop transformed into a “U”-shaped configuration and lost hold of the tendon fibrils within it. There was no narrowing of or bulge in the tendon in the arc and knot designs, as there was no constriction of the link component. There was some bulge in the tendon in the complex loop design associated with the initial constriction.

Our analysis of maximal load to failure (Figs. 6, 7) suggests that the complex loop design had the strongest grasp of the tendon fibers. There were no statistically significant differences in the maximal load before failure between the arc, simple loop, and knot link component configurations. The poor grasp of the arc and simple loop link components can be explained by the failure of their link components and their transformation into the “U”-shaped configuration. However, in the complex loop and knot designs, the overall construct stayed stable and failure occurred by fiber disruption. Therefore, it is difficult to understand the low load to failure of the knot design. One major difference between the complex loop and the knot designs is the absence of the transverse component. The load was distributed between the 2 longitudinal components via the connecting transverse component in the complex loop design, whereas the lack of the transverse component seems to have resulted in earlier failure of the knot design.

Peltz et al reported a similar study with static radiological images using sheep hindlimb tendon and 3.0 multifilament stainless steel sutures. They used a Kessler type suture although it is not clear if an arc or a simple loop link component was created. They took 2 radiographs, one immediately after repair and one
after loading the repair for 30 seconds. Our findings mirror theirs. They also reported the transformation of the link component into a “U”-shaped configuration, relatively stable position of the transverse component, narrowing of the tendon at the level of the link component, and buckling of the tendon. Our work builds on the research carried out by Peltz et al. The use of fluoroscopy allowed us to visualize the deformation characteristics in real time, and the measurement of the load to failure gave us an idea of the hold of the different techniques. A static study without the measurement of the load to failure would have missed the difference between the arc and simple loop and between the complex loop and the knot designs.

Our study has some limitations. The stiffness and pliability of stainless steel wire are different from those of conventional suture materials. However, we wanted to have a real-time visualization of the deformation of the suture material within the tendon under tension. This could only be achieved with a radiopaque suture material. Some reports have suggested suture impregnation with iodine contrast. However, iodine contrast impregnated sutures have an inferior image quality. Another alternative would be to use nitinol sutures or surgical steel wires. Our pilot experiments with these materials all resulted in suture breakage before suture pullout. This resulted in failure to visualize the deformation of the link component. Stainless steel wire of diameter 0.5 mm proved to be the wire with the smallest diameter that could serve the purpose of suture pullout before breakage. This resulted in failure to visualize the deformation of the link component. Stainless steel wire of diameter 0.5 mm proved to be the wire with the smallest diameter that could serve the purpose of suture pullout before breakage. Another limitation was the usage of porcine tendons with higher tensile strengths instead of human tendons. Also, the use of an 18-gauge needle could have led to a greater opening in tendon substance compared with the needle used in clinical practice. This may have resulted in the suture pulling out earlier. The values for the maximal tensile force before pullout obtained in our study are similar to the values obtained by other studies that have used porcine tendon with conventional sutures. Therefore, the impact of the use of the 18-gauge needle may not be noteworthy.

Overall, the results of this study may not hold good for human tendons in the clinical setting. However, the objective of this study was not to compare wire sutures with conventional suture material but to document the differences in the deformation of stainless steel sutures in commonly used flexor tendon repair configurations. Although the deformation patterns of stainless steel sutures and conventional sutures may not be identical, they allow us to draw some general inferences. Further
experiments with human cadaveric tendons using radiopaque conventional sutures might be helpful.

REFERENCES