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Flexor Digitorum Superficialis Repair Outside the A2 Pulley After Zone II Laceration: Gliding and Bowstringing

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Abstract

Purpose—To evaluate the changes in maximum flexion angle, gliding coefficient, and bowstringing following a combined repair of both flexor tendons with the flexor digitorum superficialis (FDS) re-routed outside of the A2 pulley in cadaveric hands.

Methods—Four different repairs were performed on cadaveric hands, with each repair tested on 9 unique digits. In total, 12 cadaveric hands and 36 digits were used. The first and fifth digits were removed from each hand and excluded from testing. Group 1 was sham surgery. Group 2 combined flexor digitorum profundus (FDP) and FDS laceration and repair with both slips of the FDS repaired inside the A2 pulley. Group 3 was FDP repair with one slip of the FDS repaired inside A2 and the other slip left unrepaired. Group 4 was FDP repair with both slips of the FDS re-routed and repaired outside the A2 pulley. Maximum flexion angle, gliding coefficient, and bowstringing were measured in simulated active digital motion for each group.

Results—Re-routing and repairing the FDS outside the A2 pulley (group 4) significantly lowered gliding coefficient compared to repairs with both slips inside A2, with values similar to sham surgery. No significant differences in maximum flexion angle were observed between the 4 groups. Increased bowstringing was observed with both slips of the FDS repaired and re-routed outside of the A2 pulley.

Conclusions—In this cadaveric model, repair of both slips of the FDS outside the A2 pulley improved the gliding coefficient relative to repair within the A2 pulley, suggesting a decreased resistance to finger flexion. Repair of the FDS outside the A2 pulley led to a slight increase in bowstringing of the FDS tendon.

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Keywords

flexor tendon laceration; flexor tendon repair; flexor digitorum superficialis; zone 2

INTRODUCTION

The management of flexor digitorum superficialis (FDS) injury in zone II remains controversial. In the setting of combined FDS and flexor digitorum profundus (FDP) injury, there is consensus that the FDP should be repaired with a multi-strand core suture technique. No clear consensus exists regarding the management of the FDS. The literature supports management of the FDS by repair of both slips of the FDS (1), repair of one slip of the FDS with excision of the other slip (2-4), or complete excision of the FDS (5,6). Excision of the FDS avoids the bulk conferred by a repair within the confines of the tight A2 pulley. However, repair of the FDS must take into consideration the balance between bulk and strength, given the 4% re-rupture incidence seen after repairs of the FDP and FDS in zone II (7).

We currently employ an alternative technique in select patients to manage the FDS tendon when retraction has occurred into the palm or proximally. In such cases we reroute and repair both slips of the FDS outside of the A2 pulley, leaving the repaired FDP inside the A2 pulley. To facilitate rerouting of the FDS, a small sheath defect must be created within the pulley system, disrupting both the C1 and A3 pulleys. Recent reports describe the effects of pulley modification, both intentional and traumatic, on flexor tendon function in zone II (8-10). Further, Lowrie et al. describe the best current knowledge regarding the role of individual pulleys (11). Taken together, the literature suggests that some degree of pulley modification may be tolerated, and that among the annular pulleys, A3 has a limited functional role. One proposed role for A3, without established clinical importance, is to elevate the volar plate during finger flexion, creating space for rotation of the middle phalanx (12).

The rationale for this surgical technique is the improved gliding associated with a less bulky tendon repair under the A2 pulley, along with the belief that bowstringing is a greater problem for FDP than the FDS at the A2 pulley. Given the re-rupture incidence after zone II flexor tendon repairs of the FDS and FDP, the question of discarding half of the FDS tendon versus a repair of both slips of the FDS tendon outside of the pulley seems open.

We tested our current surgical technique in a cadaveric model, which allowed assessment of gliding coefficient (13) and bowstringing. We formed a two-part hypothesis: first, the gliding coefficient should decrease significantly with the FDS re-routed outside the A2 pulley compared to the traditional repair inside the pulley. Second, sufficient anatomic constraints are conferred by the presence of the A1 pulley and the anatomic insertion of the FDS tendon at the base of the middle phalanx such that only a modest amount of bowstringing should result from rerouting the FDS outside of the A2 pulley.

MATERIALS AND METHODS

Specimen Preparation

Cadaveric forearm specimens were obtained through the University's Anatomical Gift Program in compliance with institutional policies. The distal upper extremity was harvested at the mid-forearm from 6 lightly embalmed cadavers. The wrist was immobilized in neutral by external fixation applied dorsally from the radius to the third metacarpal. The metacarpophalangeal (MCP) joints were immobilized in 30 degrees of flexion with Kirschner wires. An screw was passed through the 2nd, 3rd, 4th, and 5th metacarpal heads in an ulnar to radial direction. The volar forearm was dissected to identify the musculotendinous junction of the FDP and FDS tendons associated with each digit. All muscle was stripped from the tendons and crossing tendons were identified and released. With the fingers in full flexion, the proximal ends of the FDP and FDS tendons associated with each digit were sutured together and attached to a small S-hook for testing purposes. The thumb and fifth digit were then disarticulated from the hand. The volar surface of the digits was dissected free of soft tissue to expose the flexor tendon sheath.

Tendon Laceration, Repair and FDS Rerouting

The C1 and A3 pulleys were identified and resected (Figs. 1A and 1B), as it has been previously shown that incision of the A3 pulley minimally effects gliding and bowstringing (14). For each experimental group, the laceration and repair of the FDS and FDP tendons were performed 5mm distal to the A2 pulley with the fingers in full extension (Figure 1B). The FDS was repaired with a two-strand modified Kessler technique with 4-0 FiberWire (Arthrex, Naples, FL) (15), and the FDP was repaired with a 4-stranded repair in which a basic two-strand core suture was supplemented by a horizontal-mattress suture with 4-0 FiberWire with a running locking epitendonous stitch with 6-0 Prolene (Ethicon, Edinburgh, UK) (16). To reroute the FDS, the 2 strands proximal to the laceration were passed between the A1 and A2 pulleys and sutured to their distal ends, such that the FDS reentered the pulley system at C2 (Figure 1C).

Biomechanical Testing

The immobilized cadaver specimen was mounted by attaching the external fixator to a ring stand such that the fingers had range of motion. The proximal tendon was loaded using the S-hook with the direction of force consistent with the direction of the anatomical pull. Loads were applied in 50-gram increments up to a final load of 700 grams (Figure 2). The neutral, unloaded tendon was used as the starting point; and following each incremental load, a digital image was captured from the lateral view to record the flexion angle. Eight specimens were tested for each group. Specimens were continuously irrigated with phosphate buffered saline during testing to maintain tissue hydration.

Experimental Groups

Biomechanical testing was performed for 4 groups. Each group consisted of 9 fingers across 3 different hands, giving a total of 12 cadaveric hands. Specimens were not reused after initial testing. All groups except the control had lacerations to the FDP and both slips of the

FDS. The groups were as follows: group 1 - control (sham): dissected finger with uninjured flexor tendons. Group 2 - 2 slips in: laceration and repair of both the FDP and FDS, with both slips of the FDS inside the A2 pulley. Group 3 - 1 slip in: laceration and repair of the FDP and one slip of the FDS, with the other slip unrepaired. Group 4 - 2 slips out: laceration and repair of the FDP, with both slips of the FDS repaired outside of the A2 pulley.

Maximum Flexion Angle and Gliding Coefficient

The joint flexion angles across the proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints were measured by 3 independent observers using ImageJ software (<http://rsb.info.nih.gov/ij/>), and plotted versus the applied load. Normalized flexion angles are reported as the change in flexion relative to the angle of the unloaded tendon. The maximum flexion angle was determined by calculating the difference in flexion angle between the tendon loaded with 700g and the angle in the neutral, unloaded position. The gliding coefficient was determined by fitting the flexion data to a single-phase exponential equation where the flexion angle = $[\beta \times 1 - \exp(-m/\alpha)]$; where m is the applied load (Prism GraphPad 4.0a; GraphPad Software, Inc., San Diego, CA). The curve fit was constrained to the maximum flexion angle (β) for normal tendons, determined previously to be 75° (13). Non-linear regression was used to determine the gliding coefficient (α), which has been previously shown to correlate inversely with the range of joint flexion (13). The gliding coefficient is a useful quantitative measure of the resistance to flexion and correlates significantly with the work of joint flexion (17).

Bowstringing

Bowstringing of the FDS was determined in group 2 and group 4 by measuring the moment arm at the distal border of the A2 pulley (Figure 2). Since bowstringing was unchanged across the first 3 experimental groups – the tendons travel an identical course with the same pulley constraints – measurements from group 2 are reported in lieu of repeated measurements from groups 1, 2 and 3. This allows for a direct comparison of bowstringing between the FDS repaired within and outside of the A2 pulley. The moment arm is defined as the shortest distance between the FDS tendon and the center of rotation about the PIP joint (18), which was marked on the proximal phalanx with a midcoronal drill hole for reference during testing. Using ImageJ software (<http://rsb.info.nih.gov/ij/>), measurements were made from a line perpendicular to the volar surface of the proximal phalanx at the distal border of the native A2 pulley to where this line encounters the FDS tendon.

Statistical Analysis

Data from the gliding coefficient was analyzed using a one-way analysis of variance followed by the Bonferroni multiple comparisons with a significance level of $\alpha=0.05$. Two-way analysis of variance was used to analyze bowstringing data, followed by the Bonferroni multiple comparisons with a significance level of $\alpha=0.05$.

RESULTS

Maximum Flexion Angle

There was no statistically significant difference in the maximal flexion angle between any of the experimental groups. (Figure 3a)

Gliding Coefficient

A lower gliding coefficient (13) represents less resistance to joint flexion, while a higher gliding coefficient corresponds to an increased resistance to flexion. Gliding coefficients are shown in Figure 3B. The gliding coefficient was significantly elevated in group 2 compared to group 1. There was a statistically significant decrease in gliding coefficient in group 4 compared to group 2, suggesting less resistance to finger flexion in group 4. No significant differences in gliding coefficient were observed when comparing group 3 to group 4 or group 1.

Bowstringing

Maximum bowstringing (SEM) was observed with 450g loading and was 0.3mm (± 0.5 mm) for group 2, 5mm (± 2 mm) for group 4. Two-way analysis of variance revealed a statistically significant increase in bowstringing in group 4 compared to group 2 ($p < 0.01$), however that increase averaged less than 5mm.

DISCUSSION

Our results showed that laceration and repair of the FDP and both slips of the FDS resulted in an increased gliding coefficient when the FDS was repaired inside the A2 pulley, corresponding to an increase work in finger flexion. However, when the FDS was repaired outside the A2 pulley, the gliding coefficient significantly improved and was similar to that of the uninjured tendon (Figure 3B).

Previous studies have examined modifications of the FDS tendon in attempts to improve gliding function, showing that resection of one or both slips of the FDS tendon reduced gliding resistance (2-4,19). A common conclusion is that crowding the A2 pulley with the repaired FDP along with both slips of the FDS, repaired or uninjured, creates a restricted space for movement and greatly increases gliding resistance.

Results from a cadaver study by Zhao et al., in which the FDP was repaired and one slip of the FDS was removed, demonstrated a 35-47% decrease in gliding resistance (variations based on suture technique) compared to FDP repairs with both slips of the FDS left within the A2 pulley (5). Similarly, Tang et al. reported that removing one slip of the FDS after repair of FDP decreased the work of flexion (WOF) to 80% of that measured in repairs that left both slips of the FDS within the A2 pulley (19). These findings are consistent with those reported by others (3,4).

While previous work has demonstrated that overcrowding the A2 pulley impaired gliding, it remains to be settled what should be done with the FDS tendon if it is not repaired within the A2 pulley. None of the above studies examined the effects of repairing the FDS tendon

outside the A2 pulley. One would surmise that repair of the FDS outside of A2 provides similar improvement in gliding resistance by leaving the FDP tendon less restricted. Any improvements in gliding afforded by removing one slip of the FDS from the A2 pulley would be compounded by removing both slips from the A2 pulley. Further, repair of both slips of FDS should negate concerns of weakened flexion that may occur if the FDS is not repaired.

The FDS tendon repair outside the A2 pulley should increase bowstringing because the A2 pulley normally constrains the FDS tendon in close approximation to the proximal and middle phalanges. Bowstringing affects rotational forces around the proximal interphalangeal (PIP) joint, including work of flexion and amount of tendon excursion, thus bowstringing has important biomechanical implications. What is less clear is the effect of bowstringing conferred by repairing the FDS outside of the A2 pulley, while allowing the FDP repair to reside alone in the A2 pulley.

In this study, maximum bowstringing of the FDS tendon was 4.5mm (Figure 4). Bowstringing is typically investigated in the setting of closed pulley ruptures in rock climbers (20-22) or as the result of iatrogenic pulley release for management of trigger finger (23). In either of these settings, the point at which bowstringing becomes symptomatic and limits function has not been established. However, theoretically both of these scenarios would create far greater bowstringing than the model we propose, since the FDP deviates away from the proximal phalanx. Using ultrasound measurements, Klauser et al. showed that climbers with closed A2 pulley ruptures had an average bowstringing of 3mm (± 0.1), which increased to 5mm (± 2 mm) under conditions of forced flexion (20). This is consistent with our measurements of the FDS bowstringing outside of the A2 pulley, however the significance of 4.5mm of the FDS bowstringing has not been directly investigated. Further, Klauser's study involved intact tendons where the bulk of a repair need not be considered. It might be expected that in the setting of a zone II flexor tendon injury, perhaps some bowstringing may be tolerated for the added strength conferred by complete FDS and FDP repairs. Further, the functional consequences of subtle bowstringing may be offset by the benefits imparted by improved gliding function. Future studies may examine the functional consequences of different degrees of FDS bowstringing.

Rerouting the FDS may offer benefits in the setting of adhesion formation, as the FDP and FDS are less likely to form intratendinous adhesions. However, rerouting the FDS tendon may promote scarring outside of the A2 pulley, since in the clinical setting the tendon will move through soft tissue (24). Our measurements of gliding coefficient did not take into account this additional source of resistance that may be encountered. Further, this was an *in vitro* study that was not designed to assess the effects of healing on the gliding coefficient, either positive or negative.

There are limitations to our study. Although we employed this technique in certain human cases, we present no clinical data on their outcomes. The clinical feasibility of FDS rerouting outside of the A2 pulley therefore has not been fully investigated. However there are scenarios where FDP repair may be bulky and clearly compromise gliding. In such cases repair of the FDS outside the A2 pulley may be warranted. Second, we have not directly

investigated whether or not it is necessary to repair both slips of the FDS. No studies have directly measured the clinical effects of removing one slip of the FDS tendon from the repair. This sacrifice is made primarily for improvements in gliding. A direct assessment of the added strength conferred by a complete FDS repair versus half an FDS repair was beyond the scope of this manuscript but would be relevant in the decision to place one slip of the FDS inside the A2 pulley or repair both slips outside. A third limitation of this study was that the gliding resistance of the FDS tendon through the soft tissue between the A2 pulley and the skin was not directly assessed (32), as soft tissue was removed for the purposes of our model. Rerouting the FDS may offer benefits in the setting of adhesion formation, because it prevents scarring between the FDS and the FDP. However, as this is an *in vitro* study, we cannot currently comment on adhesion formation using this repair.

An additional consideration is the healing potential of combined lacerations to the FDP and FDS tendons, since the vincular supply to the FDP within the A2 pulley may be disrupted. Current clinical outcomes do not clearly favor a single configuration of the FDS repair. In the setting where all vincula have been disrupted with retraction of the tendons into the palm or proximal, the case for additional bulky repair of the FDS in the A2 pulley cannot be made based on the preservation of blood supply alone.

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Clinical Relevance

We describe a technique to manage combined laceration of the FDP and FDS tendons that improves gliding function and merits consideration.

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Figure 1.

Flexor tendon laceration, repair and the FDS rerouting outside of A2. **A** Palmar and lateral views of the uninjured flexor tendons and pulley system (PA = palmar aponeurosis; A = annular pulley; C = cruciate pulley). The pulleys to be excised are labeled in red (C1 & A3). **B** Flexor tendons and pulleys following C1 and A3 excision. The site for combined FDP and FDS laceration is labeled 5mm distal to the A2 pulley by the vertical, red line. **C** Combined FDP and FDS repair, with both slips of the FDS re-routed outside of the A2 pulley (X = sutures). **D** Lateral view of finger flexion with the FDS repaired outside of the A2 pulley; bowstringing of the FDS can be appreciated from this view. The sutures (black X) migrate proximally during flexion. **E** Cadaveric repair from group 4, with both slips of the FDS repaired outside of the A2 pulley.

Figure 2. Cadaveric testing with the specimen secured in an external fixator. The weight exerts a force on the proximal ends of the flexor tendons in line with the direction of the anatomical pull.

Figure 3.

A Normalized flexion angles during incremental loading from zero to 700g. The overlaid curve is a single-phase exponential equation used to determine the gliding coefficient for each group. **B** Gliding coefficients for the 4 experimental groups. A lower gliding coefficient represents less resistance to flexion and is associated with better gliding function. (2SI = 2 Slips In; 1SI = 1 Slip In; 2SO = 2 Slips Out).

Figure 4.

Bowstringing measurements at each incremental load comparing both slips of the FDS repaired inside the A2 pulley to both slips of the FDS repaired outside of the A2 pulley. (2SI = 2 Slips In; 2SO = 2 Slips Out).