The Effect of Pulley Reconstruction on Maximum Flexion, Bowstringing, and Gliding Coefficient in the Setting of Zone II Repair of FDS and FDP: a Cadaveric Investigation

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Published online: 18 October 2013
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Abstract

Purpose The purpose of this experiment was to determine the effect of A2 pulley reconstruction on gliding coefficient (GC), bowstringing, and proximal interphalangeal (PIP) joint maximum flexion angle after zone II repair of flexor digitorum superficialis (FDS) and flexor digitorum profundus (FDP) lacerations.

Methods Fresh frozen cadaver forearms were mounted, and the wrist and MCP joints fixed. FDS and FDP tendons were dissected free, and sequential loads were applied while digital images were captured. The dissected digit with intact native A2 pulley, FDS, and FDP tendons was used as the control (group 1). Zone II lacerations followed by four-stranded repair of FDP plus epitendinous suture and repair of FDS were then performed, and the data recorded (group 2). A2 pulley excision and reconstruction with a loop of palmaris longus autograft was then completed and the specimens sequentially loaded and photographed (group 3). Using the digital images, GC, bowstringing, and maximum flexion angle were calculated.

Results No difference in maximum flexion angle was observed across the three testing conditions. Zone II laceration and subsequent FDS and FDP tendon repair significantly increased the GC for group 2 specimens; however, pulley reconstruction alleviated some of this increase for group 3. Bowstringing was significantly greater after pulley reconstruction, with a mean increase of 1.9 mm at maximum flexion for group 3 specimens relative to group 1 controls.

Discussion Strong flexor tendon repairs are needed to prevent gap formation and subsequent triggering; however, the

increased bulk from these large repairs can itself produce deleterious triggering, as well as tendon abrasion. Pulley reconstruction, in the setting FDP and FDS repair (group 3), significantly reduced the GC relative to tendon repair alone (group 2). While bowstringing was significantly greater after pulley reconstruction (group 3), it averaged only 1.9 mm over group 1 specimens and did not compromise maximum flexion angle compared to the uninjured controls (group 1) or the isolated tendon repair digits (group 2).

Keywords A2 pulley · Flexor tendon · Flexor tendon repair · Pulley reconstruction · Zone II

Introduction

Primary flexor tendon repair of lacerations in zone II are fraught with problems, and outcomes have been rated as fair or poor in 7–20 % of cases [22, 26]. Complications include adhesion formation, joint contracture, tendon rupture, triggering, pulley failure, bowstringing, quadriga, swan neck deformity, and lumbrical plus deformity [9, 12, 33]. Early mobilization is important to prevent adhesion formation and joint contracture [15]. Early motion must be supported by a strong repair which resists gap formation or tendon rupture [8]. Widely accepted principles of repair include the use of a core suture of 3-0 or 4-0 nonabsorbable polyfilament material with an increased number of sutures equally tensioned across the repair [12]. The addition of an epitendinous suture is believed to enhance flexor digitorum profundus (FDP) repair strength and reduce gapping [14]; however, increases in core suture size and number will lead to a more bulky repair and a likely increase in triggering [12].

Intraoperatively, after flexor tendon repair, the surgeon may find they are concerned that significant triggering or abrasion

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is occurring where the bulkier segment of the repaired tendon encounters the A2 pulley. Several alterations to the pulley have been described and studied for this reason, including partial pulley excision, pulley plasty, and extensor retinaculum rim reconstruction of the pulley [5, 21, 29]. Pulley reconstruction is typically performed in the setting of an unsalvageable traumatic laceration to the native pulley, pulley rupture, iatrogenic pulley injury, or for staged tendon reconstruction [1, 2, 6, 16]. Pulley reconstruction is performed by weaving a graft through the remaining pulley rim or by creating a new pulley loop around bone [6, 16]. Looped pulley reconstructions have been shown to provide superior strength over rim reconstructions in the laboratory [35].

One of the concerns of pulley alteration—including reconstruction—is bowstringing. Bowstringing of the flexor tendon is associated with loss of flexion, flexion contracture, and alterations in the kinematics of the tendon [2, 31]. This investigation is a cadaveric principle study with a hypothesis that looped pulley reconstruction with palmaris longus autograft leads to a decrease in gliding coefficient (GC) with no significant increase in bowstringing or alteration in maximum flexion angle in the setting of a clinically relevant repair of the flexor digitorum superficialis (FDS) and four-strand repair of the FDP with an epitendinous suture.

This is the first study to use GC in human cadaveric specimens. GC offers information about the joint range of motion and the resistance to flexion with increased loading. Measurement of GC is based on joint flexion data over a range of applied loads with respect to the maximum flexion angle of the proximal interphalangeal (PIP) joint of the native unrepared control. Unlike gliding resistance, GC more fittingly describes the dynamic relationship between applied load and flexion angle. Unlike work of flexion, which also considers resistance to flexion over a range of excursions, GC is unaffected by errors in determining the neutral starting position [10].

Materials and Methods

Specimen Preparation

Cadaver forearm specimens were obtained through an anatomical gift program in compliance with institutional policies and under the supervision of support personnel. The distal upper extremity was harvested at the midforearm from three fresh frozen cadavers. The volar forearm was dissected, and the proximal radioulnar joint was secured to prevent forearm rotation. The thumb and small finger were removed. The forearms were dissected at the level of the musculotendinous junction to identify the FDP and FDS tendons associated with each digit. With the finger in full flexion, the FDS and FDP tendons were sutured side to side. The tendons associated with

each digit were then secured together and attached to a small S-shaped hook for testing purposes. The wrist was immobilized in the neutral position by external fixation (Synthes, Paoli, PA) from the dorsal radius to the dorsal third metacarpal. The MCP joints were immobilized in 30° of flexion with K-wires (Synthes, Paoli, PA). An intermetacarpal screw was passed through the second, third, fourth, and fifth metacarpal heads in an ulnar to radial direction. The volar surface of the digits was dissected free of soft tissue to identify the flexor tendon sheath. The C1 and A3 pulleys were resected. Dissected specimens with intact native A2 pulley mechanisms and undamaged FDP and FDS tendons were used as group 1 controls.

Group 2 specimens underwent laceration and repair of the FDP and FDS tendons with preservation of the A2 pulley. Tendon laceration was performed 5 mm distal to the A2 pulley with the finger in full extension to ensure that the repaired region would enter the A2 pulley on finger flexion. The FDS was repaired with a two-strand modified Kessler suture with 4-0 Fiberwire (Arthrex, Naples, FL), and the FDP was repaired with a four-strand modified Kessler suture with an additional horizontal mattress suture with 4-0 Fiberwire and a running locking epitendinous stitch with 6-0 Prolene [25].

Group 3 digits underwent FDS and FDP laceration and repair as described above, followed by excision of the native A2 pulley and reconstruction with palmaris longus graft. A slip of autologous palmaris longus was wrapped circumferentially around the repaired FDS and FDP tendons, as well as the proximal phalanx, and secured with 4-0 Fiberwire suture at the level of the native A2 pulley.

The external fixator and specimen were attached to a ring stand such that the fingers were allowed full, uninhibited range of motion. The pulley system consisted of two pulleys (P1 and P2) suspended from a modified ring stand. P1 was in line with the flexor tendon being tested. P2 was placed along the same axis as P1 but further from the specimen to allow for loading of weights. Fifty-gram increases in load were applied to the origin of the flexor tendons of a single digit to bring the finger through a full arc of flexion. Digital images were captured at each weight increment increase up to 700 g. Each specimen was then retested with additional digital imaging. Eight digits were tested for each group as required by a power analysis. Specimens were irrigated with phosphate buffer solution continuously during testing.

Biomechanical testing was performed for three groups of digits: (group 1—dissected control) dissected finger without laceration of FDP or FDS within the native pulley, (group 2—native pulley) four-strand FDP repair with epitendinous suture and both slips of repaired FDS within the native pulley, and (group 3—pulley reconstruction) four-strand FDP repair with epitendinous suture and both slips of repaired FDS within the reconstructed pulley.

Data Analysis

Images were viewed, and the PIP flexion angles were measured by two independent observers utilizing Image J software (<http://rsbweb.nih.gov/ij/>). The measurements and corresponding weights were then imported into Prism 4 (GraphPad Software, Inc.). Maximum flexion angles among the groups were compared using two-way analysis of variance (ANOVA). The flexion angles were then normalized to group 1 (dissected control) at maximum flexion. Lines representing best fit curves of the normalized angles were based on modeling the data using the single-phase exponential association equation $\text{PIP flexion angle} = \beta \times [1 - \exp(-m/\alpha)]$, where m is the applied mass, β is the maximum flexion angle, and α is the gliding coefficient, as previously described [10].

Bowstringing of the FDS at the distal border of the native A2 pulley was determined using Image J software. Measurement was taken as the length of the line drawn perpendicularly 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 under maximum flexion (Fig. 1). The point on the proximal phalanx was marked with a midcoronal drill hole for reference during testing. Using two-way ANOVA technique, the bowstringing measurements were compared between groups 2 and 3 and reported as the difference relative to group 1.

Results

Maximum Flexion Angle

The maximum flexion angles at 700 g were $73.8 \pm 13.2^\circ$, $73.4 \pm 18.8^\circ$, and $74.0 \pm 14.8^\circ$ for groups 1, 2, and 3, respectively (Fig. 2).

Fig. 1 A photograph of a group 3 specimen under maximum flexion. Bowstringing was measured by selecting a point on the proximal phalanx just distal to the A2 pulley (yellow diamond) and drawing a line such that it lies perpendicular to the proximal phalanx and obliquely intersects the FDS tendon (solid line). The horizontal plane of the volar surface of the proximal phalanx is represented with the dashed line

Fig. 2 Graph representing the maximum flexion results of the three groups. Red, blue, and green bars represent groups 1, 2, and 3, respectively

One-way ANOVA found no significant difference among the three groups with regard to maximum flexion data ($p=0.9972$).

Gliding Coefficient

GC values of 178.9 ± 65.8 , 348.9 ± 191.1 , and 221.2 ± 91.9 were found for groups 1, 2, and 3, respectively (Fig. 3). Using paired Student's t tests, GC was determined to be significantly increased in group 2 relative to group 1 ($p<0.001$) and decreased in group 3 relative to group 2 ($p=0.003$).

Bowstringing

Bowstringing was significantly greater in group 3 compared with group 2 (Fig. 4). Using two-way ANOVA testing, it was found that pulley reconstruction accounted for 19.3 % of the total variance found ($p<0.0001$). For group 2 specimens which did not undergo A2 pulley reconstruction, there was no statistically significant relationship between load and bowstringing ($p=0.0949$). For group 3 specimens, pulley reconstruction did not have the same effect at all values of load ($p=0.2838$), with maximum bowstringing identified at maximum load (700 g). Maximum bowstringing for group 3 digits was found to be increased by 1.97 mm, compared to the dissected, but otherwise intact, group 1 controls.

Discussion

Surgical repair of flexor tendons in zone II is a clinically challenging problem that requires balance between competing

Fig. 3 Graphic comparison of the results of gliding coefficient (GC) with respect to the three groups. Red, blue, and green bars represent groups 1, 2, and 3, respectively

factors. Favorable clinical outcomes are dependent on early motion and strong repairs that can support this motion without gapping [8, 15]. Contrarily, bulky repairs lead to an increased risk of triggering, as well as increased frictional resistance and abrasion of the tendon surface [12, 36]. These competing factors, and the high rate of complications of these repairs, can leave a surgeon concerned intraoperatively. To address this problem, several alterations to the pulley mechanism have been described and biomechanically tested. Observing the need to balance gliding kinematics with integrity of the tendon repair and subsequent functionality, we hypothesized that a looped pulley reconstruction would optimize the GC of a standard four-stranded FDP tendon repair with epitendinous suture and FDS repair while minimizing bowstringing.

The results of this study confirmed that a standard flexor tendon repair increases GC and is consistent with other studies that show laceration and repair of the flexor tendons within the

sheath increases gliding resistance, a directionally related measure [5, 7, 29, 30]. Expectedly, pulley reconstruction produced a decrease in the GC after tendon repair, which we attribute to a decrease in normal forces at the tendon–pulley interface and less acute arc of tension across the pulley.

A concern of decompressing the pulley unit would be that an increase in bowstringing would occur with acute pulley reconstruction. Accordingly, complete excision of the A2 pulley would obviously eliminate friction at the tendon–pulley interface, but would produce clinically unacceptable bowstringing [3, 17, 21, 29, 31]. This can lead to a reduction in the efficiency of finger flexion and to finger flexion contractures [2, 27, 31]. While bowstringing was increased in the pulley reconstruction group (3) when compared to the native tendon–pulley group (1), it was noted to be an average of just 1.97 mm greater. We suspect this minimal increase in bowstringing is of only marginal clinical relevance, especially because no difference in maximum flexion angle was observed after pulley reconstruction. A looped palmaris longus A2 pulley reconstruction appears to allow enough relaxation of the tendon–pulley interface to improve GC without considerably altering the functional performance of the tendon.

Conceptually, GC has many advantages compared with traditionally used measures such as work of flexion (WOF) or gliding resistance (GR). Like GC, WOF considers the dynamic relationship between applied force and degree of flexion—though traditional WOF models may fail to separate friction at the tendon–pulley unit from extrinsic factors, such as joint stiffness [28]. Further, WOF is critically dependent on precise determination of the neutral position, which can be challenging in biomechanical studies. GC subtracts away extrinsic factors by comparing the tendon flexion curves for each experimental group against the uninjured controls. While accurate recording of maximum flexion angle is important to the GC determination, the neutral position is not.

Unlike WOF, GR almost synthetically isolates friction at the tendon–pulley interface, but is measured at only one joint configuration. Because of this, it poorly represents the dynamic and nonlinear relationship between applied force and degree of flexion which defines the functional capacity of the digit in situ. Their detractors notwithstanding, it is obvious that WOF, GR, and GC are all directionally related. Indeed, Tanaka and colleagues observed a strong correlation between internal work of flexion (IWO) and GR within 1 week of FDP repair in a canine model [28].

While we discuss our preference for a loop pulley reconstruction, other manipulations of the pulley unit have been studied extensively. Paillard and colleagues noted a significant decrease in GR after pulley plasty, as described by Kapandji, when compared to controls with repair of the FDP and both strands of the FDS [11, 21].

Partial pulley resection has been postulated as another method of decompression. Tang and colleagues found significant

Fig. 4 Graphical comparison of the two-way ANOVA between group 2 (blue) and group 3 (green) with respect to bowstringing and applied load

improvement in tendon excursions and resistance to motion after partial A2 pulley incision [32]; however, Mitsionis and colleagues noted that excision of up to 25 % of both the A2 and A4 pulleys did not have a significant effect on the efficiency of motion and did not decrease sheath resistance [17]. Tang and colleagues demonstrated an improvement in WOF after pulley incision and graft enlargement and showed excursion efficiency was not different from intact pulley specimens in an in vivo animal model [32].

Bunata and colleagues established that pulley and sheath enlargement with extensor retinaculum in an in vitro cadaveric model significantly improved GR. The authors concluded their findings supported further investigation into primary pulley enlargement, but specifically noted that a limitation of their work was the lack of evaluation of bowstringing [5].

Based on the promising results of their laboratory study, Bunata published a case series of nine digits in which primary pulley enlargement with extensor retinaculum was performed. They described their findings as encouraging, though concerns over flexion contracture were present in their results. This led them to hypothesize that it was caused by either their use of the classic Kleinert rehabilitation program or bowstringing from excessive initial graft enlargement, graft relaxation, or failure [4].

Widstrom and colleagues demonstrated that a single-loop pulley reconstruction with tendon graft, as used in our study, was stronger than reconstruction to the remaining rim of the pulley or reconstruction with a single loop of extensor retinaculum [34]. As an in vitro study, this investigation is unable to assess the positive or negative effects of interventions on the healing of the flexor tendon. Additionally, long-term performance of the pulley reconstruction in this setting is unknown.

In the present study, a single loop of palmaris longus graft was utilized to develop the A2 pulley reconstruction, which withstood a 6.9-N load on the flexor tendons. This reconstruction is not as wide as a native A2 pulley, likely altering the moment arm and excursion of the tendon for a given joint rotation as observed by Lin and colleagues [34]. It is possible that one loop may generate less resistance than 1.5-, 2-, or 3-loop techniques, which have been also described [13, 20, 34]. Further, grafts were tensioned by the surgeon independently, as would be done intraoperatively. This might be expected to reduce standardization of the procedure, but Seiler and colleagues found no difference in frictional resistance when grafts were deliberately tensioned heterogeneously [23].

The palmaris longus was chosen for the loop reconstruction because it is commonly used clinically, is available, and produces a robust repair [6]. Further decreases in the gliding coefficient may have been obtainable with a different graft substrate; however, the palmaris longus has been shown to have higher frictional resistance than the extensor retinaculum or volar plate [18]. Extrasynovial graft sources were also

found to have decreased excursion resistance in an in vivo canine model by Nishida and colleagues [19].

We agree with Paillard and colleagues that resistance after repair is relevant to clinical outcome [21]. This has been indicated through preliminary data by Silva and colleagues [24]. Our data suggest that single-loop palmaris longus pulley reconstruction reduces GC after repair. Additionally, these data indicate that pulley reconstruction with a loop of tendon autograft leads to a statistically significant, albeit minimal (1.9 mm), increase in bowstringing. Most importantly, the bowstringing did not impact maximum flexion of the digit. This may defray some of our concern in undertaking primary pulley reconstruction for patients at more borderline risk for tendon triggering and abrasion. However promising this data, it should be noted that the effects of the pulley reconstruction on tendon healing and the formation of adhesions remain unknown. Future in vivo studies in humans would be reasonable to address these effects before widespread clinical recommendation can be made.

Acknowledgments This research was supported by NIH grant funding (1 K08 AR060164-01A) to support the involvement of the senior author.

Statement of Human and Animal Rights This article does not contain any studies with human or animal subjects. For the purposes of this study, cadaveric specimens were obtained with consent from the Center for Anatomical Gifts at the University of Rochester Medical Center.

Conflict of Interest SS, CE, ZY, JR, HA, and JE declare that they have no conflicts of interest.

Statement of Informed Consent Individual consent for use of the cadaveric tissue is kept on file at the Center for Anatomical Gifts. All specimens were returned to the center at the conclusion of the study in accordance with the charter of the program for appropriate disposition as per the wishes of the donor.

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