INTRODUCTION: Clinicians have long noted the substantial variation in the cross-sectional size of flexor tendons both within and between hands. Tendon size is of importance because small lacerated tendons may be technically more difficult to repair than large tendons, and sutures placed in small tendons may be less resistant to pullout because of decreased frictional interaction between suture and tendon. However, no data exist to indicate that surgical repair of lacerated flexor tendons be altered according to tendon size or that small tendons have inferior repair strength compared to large tendons. One difficulty in addressing these issues is that accurate techniques for measuring tendon cross-sectional area have required use of customized devices such as the laser micrometer [1]. Our objective was to measure the size of human flexor tendons \textit{ex vivo} using peripheral computed tomography (pQCT), a technique not previously applied to tendon, and to correlate tendon size with tensile mechanical properties following suture repair. We hypothesized that: 1) pQCT can detect significant variations in tendon cross-sectional area between digits, and 2) Cross-sectional area correlates with the failure force of a simple transverse suture and with the failure force of tendons repaired with use of a four-strand core suture.

METHODS: \textit{Area Measurements:} Seventy tendons from 14 fresh-frozen cadaver hands were dissected and scanned by pQCT ( XCT Research M, Norland Stratec). Tendons were positioned horizontally and pulled taut with a 1 N force. Scans of the tendon cross-section were performed: 1) at the site corresponding to the distal edge of the A2 pulley, 2) 10 mm distal and 3) 10 mm proximal to this site. Tendon areas were determined using a density threshold of $-61$ mg/cm$^3$. We previously determined that this threshold resulted in accurate (0.03%) and precise (0.04%) measurements of area of a Solid Water$^\text{TM}$ phantom having approximately the same CT attenuation as tendon. Width and height of the tendons were measured with calipers to determine rectangular ($\text{Area} = \text{width} \times \text{height}$) and elliptical ($\text{Area} = \pi \times \text{width} \times \text{height}/4$) area approximations. \textit{Pullout Tests:} Twenty tendons were cut at the A2 pulley site and a transverse double-stranded 4-0 Supramid suture was passed through the medial-lateral plane of the tendon 10 mm from the transection site. Tendons were subjected to a tensile pullout test (Instron 8500R) to determine yield and ultimate force. \textit{Four-strand Repairs:} Twenty-four tendons were cut and repaired using a modified Kessler suture with double-stranded 4-0 Supramid suture. Tendons were tested to failure in tension. Ultimate force, rigidity and repair-site strain at failure were determined from plots of force versus strain.

RESULTS: Cross-sectional area varied significantly with digit ($p < 0.001$), with a 32% difference between the average values for the smallest (fifth) and the largest (third) fingers (Table 1). Tendon area determined by pQCT was significantly correlated with area estimated from caliper measurements ($p < 0.001$; $r^2 = 0.59$). The rectangular approximation of tendon area was not significantly different from the area determined by pQCT ($p = 0.083$; mean difference 5%), whereas the elliptical approximation significantly underestimated tendon area ($p < 0.001$; mean difference 25%). Yield and ultimate force determined by pullout tests of a simple transverse suture were moderately well correlated with tendon width determined by pQCT (Fig. 1); correlations with tendon area approached significance ($p = 0.093$ for ultimate force; $p = 0.060$ for yield force). In contrast, tensile properties of tendons repaired with a four-strand core suture did not depend significantly on tendon width or area, despite a difference of more than two-fold in the area of the specimens (8-20 mm$^2$) ($p > 0.05$; Fig. 2).

<table>
<thead>
<tr>
<th>Digit</th>
<th>First (Thumb) (mm$^2$)</th>
<th>Second (Index) (mm$^2$)</th>
<th>Third (Middle) (mm$^2$)</th>
<th>Fourth (Ring) (mm$^2$)</th>
<th>Fifth (Small) (mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-Sectional Area</td>
<td>13.2 (2.9)</td>
<td>14.8 (2.8)</td>
<td>15.8 (2.3)</td>
<td>14.3 (2.3)</td>
<td>12.0 (2.0)</td>
</tr>
</tbody>
</table>

Figure 1. Failure force measured during a pullout test of a simple transverse suture was significantly correlated with tendon width at the suture site.

Figure 2. Ultimate force of tendons repaired using a four-strand core suture was not correlated with average tendon cross-sectional area at the repair site determined by pQCT ($p = 0.91$).

DISCUSSION: Our investigation of interactions between the size and the tensile mechanical properties of repaired flexor tendons, while limited to time-zero properties and to a single suture technique, supports the following conclusions: 1) pQCT is a precise and practical technique for non-destructive measurement of tendon cross-sectional area. 2) The large variation in size between the smallest and largest digits (Table 1) correlates with variations in failure force of intact tendons reported previously [2] and suggests that no single repair technique is optimal for all tendons. 3) The resistance to pullout of a simple transverse suture increased in proportion to tendon width (Fig. 1), indicating that increased tendon size can potentially increase tendon-suture friction. 4) Despite the size effect for the simple pullout configuration there was no significant influence of tendon size on the tensile properties of tendons repaired with use of a four-strand core suture (Fig. 2), indicating that the strength of the commonly used Kessler suture technique does not increase in proportion to tendon size and thus does not take advantage of potential benefits of increased tendon-suture friction.


ACKNOWLEDGEMENTS: N.I.H. AR33097