INTRODUCTION:
The skeletal system exhibits functional adaptation to optimise structure-function relationships at both tissue and structural levels. For bone the mechanotransduction mechanisms have been elucidated using isolated bone preparations in vivo(4). Tendons have been shown to respond to changes in mechanical environment, although the specific mechanical cues have not been determined. The studies to date have utilized limb immobilization or surgical interventions. This study presents a novel approach to developing an isolated tendon system in vivo to test the hypotheses that 1) stress-shielding of tendon in the presence of normal joint motion causes significant deterioration in biomechanical properties, and 2) imposing functional loading after mechanical isolation restores normal mechanical properties.

MATERIALS AND METHODS:

Animals

Twelve skeletally mature Welsh Mules were used. All animal procedures were carried out under licences granted by the UK Home Office in accordance with the Animals (Scientific Procedures) Act of 1986 and had local ethical committee approval.

Experimental design

In Group 1, six sheep had the right patellar tendon stress-shielded for six weeks before sacrifice. In Group 2, six sheep had the right patellar tendon stress-shielded for six weeks, then the stress-shielding device was removed, allowing return of physiological loading for a further six weeks. Biomechanical analysis was performed on the tendons after sacrifice. The untreated left patellar tendons were analysed as controls.

Stress-shielding the patellar tendon

A custom-built external fixator was used to stress-shield the patellar tendon. This consisted of a tibial component, a patellar component and a wire linkage. The device was attached to the tibial diaphysis with two 6mm percutaneous half pins and the patella component attached with a 3mm diameter full pin. The distance between the two components was adjusted by means of a turn buckle to achieve a slackening of the patella tendon throughout the range of motion of the joint.

Tensile testing

Patellar tendon cross-sectional area was measured using a moulding technique(1) and length was measured. The testing was performed using custom clamps to hold the bone-tendon-bone specimen in a computer controlled servo-hydraulic material test machine. The specimen was preconditioned for 20 cycles and tested to failure at 30mm/sec.

Stiffness was the gradient of the linear part of the load vs deformation curve. Likewise, elastic modulus was the gradient of the stress vs strain curve. Ultimate load, ultimate stress, and ultimate strain were derived from peak values before failure. Strain energy was the area under the stress vs strain curve. Mode of failure of each tendon was also recorded.

Statistical analysis

The Shapiro-Wilks test was used to check for normality of data distribution. Data from the untreated tendons of both groups was tested for statistical significance using the unpaired t-test. A one-way analysis of variance was used to examine data between the two experimental groups and controls. Where statistical differences were found, these were further explored using the Tukey-Kramer method for multiple comparisons. The significance level was set at p < 0.05.

RESULTS:

Two animals were lost to study from complications. This left 5 animals in each group that were included for the results. The Shapiro-Wilks testing did not reveal any evidence of non-normality of data distribution. There were no significant differences between the control tendons in both groups. Therefore, these results were pooled and used as the control data. 7 of the 10 control tendons failed in the midsubstance, 2 at the patellar insertion and 1 at the tibial insertion. All the stress-shielded tendons in group 1 failed in the midsubstance. Out of the 5 restressed tendons, 4 failed in the midsubstance and 1 at the patellar insertion. None failed by bone avulsion. Table 1 shows the mean values for all parameters measured expressed as a percentage of the control mean.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Stress-shielded (n = 5)</th>
<th>Restressed (n = 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>91.5</td>
<td>93.0</td>
</tr>
<tr>
<td>CSA</td>
<td>96.3 *</td>
<td>114</td>
</tr>
<tr>
<td>Stiffness</td>
<td>79.2</td>
<td>96.7</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>76.2</td>
<td>79.8</td>
</tr>
<tr>
<td>Ultimate load</td>
<td>68.5</td>
<td>92.7</td>
</tr>
<tr>
<td>Ultimate stress</td>
<td>69.3</td>
<td>91.8</td>
</tr>
<tr>
<td>Ultimate strain</td>
<td>98.1</td>
<td>111</td>
</tr>
<tr>
<td>Strain energy</td>
<td>60.7</td>
<td>96.5</td>
</tr>
</tbody>
</table>

DISCUSSION:
Both the structural and mechanical properties of the patellar tendon were significantly decreased by stress-shielding. Yamamoto(5) reported much greater decreases in the stress-shielded rabbit knee, with a minimum modulus of approximately 20% of controls after 6 weeks of stress-shielding. Keira(3) reported no significant change in modulus after 6 weeks of stress-shielding the canine ACL, but a modulus of 61% control value after 12 weeks. The sheep patellar tendon might respond differently to that of the rabbit due to its larger mass, or stage of skeletal development; the differences compared to the canine ACL may be due to morphological and biochemical variation.

Six weeks of stress-shielding did not significantly change the tendon length or the cross-sectional area. Restressing tendons for 6 weeks demonstrated a recovery of mechanical properties such that they were no longer significantly different to controls. Restressing tendons after 2 or 3 weeks of stress-shielding has been reported to decrease CSA and increase tendon length. In contrast, we found that the cross-sectional area was significantly increased in restressed tendons compared to the stress-shielded tendons. Hayashi(2) suggests that stress-shielded tendons might compensate for decreased tensile strength by increasing their CSA. The increased CSA combined with a recovery of properties seen in our restressed tendons may reflect this compensatory process.

Both the hypotheses have been upheld, but the exact timing and magnitude of the changes observed, together with the effect on tendon CSA, differ from previous reports. This novel model will be used to apply defined mechanical signals to the functionally isolated tendon to elucidate mechanotransduction and mechanobiological mechanisms in a physiologically relevant environment.

REFERENCES:

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