INTRODUCTION:
Tendons and ligaments experience sustained and repeated loads in vivo but those loads are higher for tendons than ligaments: 30-40% of ultimate tensile strength (UTS) for tendons and 5-10% UTS for ligaments [1]. Previous studies which compared creep and fatigue in ligaments [2] or tendons [3,4,5] have been performed using fatigue protocols that are not suitable to subsequently compare ligaments to tendons. Tendon protocols typically had higher minimum stresses [4,5], around 10MPa; whereas, ligament protocols had minimum stresses around 1MPa. Thus, at the same maximum stress and higher minimum stress, the tendons would experience greater mean stresses and smaller amplitudes between maximum and minimum stresses. Tendons may have appeared to have smaller relative differences between creep and fatigue time-to-rupture compared to ligaments [2] because the tendon fatigue protocols [6] produced smaller amplitude strains from the greater mean stress and less cycle-dependent damage from the smaller amplitude. In order to compare the creep and fatigue behaviour of ligaments and tendons, our approach in this study was to develop a tendon fatigue protocol with minimum stress around 1MPa. Using a rabbit patellar tendon (PT) model, the UTS of the PT had to be determined at an extension rate comparable to that which would be experienced during the fatigue tests at 1Hz. Yamamoto and colleagues [6,7] found that the UTS of rabbit PT was dependent on extension rate comparing 0.33mm/s to 53mm/s. However, based on the reported extension at failure [6], we anticipate that the maximum extension rate in the loading portion of a 1Hz fatigue cycle to be less than 5mm/s. Our purpose in this study was, first, to determine the UTS of rabbit PT at an extension rate of less than 5mm/s and, second, to compare creep and fatigue of rabbit PT at 50% of that UTS. Our hypothesis was that an extension rate below 5mm/s would not result in an UTS different than at 0.33mm/s, and that fatigue loading would result in a shorter time-to-rupture than creep.

METHODS:
Failure Testing: For this study approved by the institutional animal care committee, 9 PTs were harvested from skeletally-mature female New Zealand White rabbits. Two groups were formed, wherein n=3 were elongated to failure at 0.33mm/s and n=6 at 3.3mm/s. With the patella and tibia mounted in an MTS system, the patellar tendon was trimmed in order to test its central third [6,7]. Following measurement of cross-sectional area and length, the PT was preconditioned by loading at 1Hz for 30 cycles from 1N to a force corresponding to 5% UTS [6,7]. The PT was then immediately elongated to failure at either 0.33mm/s or 3.3mm/s.

Creep and Fatigue Testing: An additional group of 6 PTs were similarly harvested from skeletally-mature female New Zealand White rabbits. Within this new group, n=3 tendons were fatigue tested and n=3 were creep tested. There were 2 pairs, where one limb from each pair was creep tested, and the contralateral limb was fatigue tested. After preparation and preconditioning as described above, the PT was either fatigue or creep tested. For fatigue tests, the PT experienced cycles at 1Hz from 1N to a force corresponding to 50% of the UTS measured in the failure testing at 3.3mm/s described above. The creep tests were held at the constant force corresponding to 50% UTS, except for occasional unloading/loading cycles to measure modulus. Time-to-rupture was defined as the last time the PT attained 99% of the test force. Strain was calculated as the deformation divided by the undeformed PT length. Steady-state strain rate (SSSR) was taken as the slope of the linear regression on a strain-time curve from 20% to 70% of the time-to-rupture.

Statistical Analysis: UTS measured at 3.3mm/s was compared to UTS measured at 0.33mm/s in other studies (n=14 in [6] and n=5 in [7]) and the current study (n=3) using Student’s t-test. Creep and fatigue parameters were compared using Mann-Whitney U tests. Significance for all tests was set at p≤0.05.

RESULTS:
The UTS obtained for the PTs tested at 3.3mm/s (58.5±10.2MPa, n=6) was not statistically different than the UTS obtained for the PTs tested at 0.33mm/s from the current study (59.0±5.2MPa, n=3) or previous studies (data reported as mean±se: 57.1±2.5MPa, n=14 [6] and 56.9±4.2MPa, n=5 [7]). The initial extension rates for creep (2.47±0.36mm/s) and fatigue (2.51±0.17mm/s) tests at 50% UTS were indeed below 5mm/s. All other initial properties assessed (deformation, strain and modulus) were not statistically different between creep and fatigue. The fatigue time-to-rupture was shorter than that of creep (Table 1, p=0.05). While the strain at 20% of the time-to-rupture was not different comparing creep and fatigue, the SSSR, calculated between 20% and 70% of the time-to-rupture, was greater during fatigue than creep (Table 1, p=0.05).

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Time-to-Rupture (hrs)</th>
<th>Strain at 20% of UTS (mm/mm)</th>
<th>SSSR (μ/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatigue</td>
<td>(n=3)</td>
<td>(0.16-1.72)</td>
<td>0.0542</td>
</tr>
<tr>
<td>Creep</td>
<td>(n=3)</td>
<td>(2.8-21.00)</td>
<td>0.0615</td>
</tr>
</tbody>
</table>

Data are median (range). * Fatigue different than creep (p=0.05).

DISCUSSION:
The UTS measured at 3.3mm/s was similar to that previously reported for rabbit PT at 0.33mm/s by Yamamoto and colleagues [6,7]. At 50% UTS, the cyclically-loaded (fatigue) tendons experienced more damage than the statically-loaded (creep) tendons, as demonstrated by the 17-fold decrease in fatigue time-to-rupture compared to that of creep. Rabbit PT tested in fatigue had shorter time-to-rupture and faster SSSR than in creep which was similar to the fatigue versus creep differences observed for rabbit medial collateral ligament (MCL) [2]. At 50% UTS, the fold-change difference between creep and fatigue time-to-rupture predicted for rabbit MCL [2] was similar to that measured for rabbit PT in this study. However, the relative difference in creep versus fatigue time-to-rupture for rabbit PT was greater than previous studies on wallaby tail tendon [3,4] and human Achilles tendon [5]. These differences could be due to differences between the tendons but may be due to differences in the fatigue protocols, i.e. minimum stress of 10MPa versus 1MPa. Because a fatigue test of a tensile load-bearing tissue (i.e. ligament or tendon) does not have a mean stress equal to zero, the fatigue test produces time-dependent damage from the non-zero mean stress and cycle-dependent damage from the stress oscillating about that non-zero mean stress. The preliminary findings of this study emphasize the importance of developing mechanical testing protocols with comparable test stresses for comparison of ligament and tendon creep and fatigue responses.

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