Introduction
Evidence for the load bearing role of the lumbar spine facet joints has been documented through clinical findings of facet osteoarthritis in combination with deformation of the highly innervated joint capsule\(^4\). Abnormal loads can cause tissue damage or inflammation, which may lead to low back pain. Surgical techniques to relieve excessive joint loading have been developed, but their effectiveness has not been studied extensively because of the limitations of existing methods for assessing facet loads. Current approaches to measure facet loads in the lumbar spine are complex in setup and processing. Extra-articular strain gauge measurements are highly sensitive to the placement and number of strain gauges\(^5\), while Fuji pre-scale film is limited to measuring only the peak force at any given location for one cycle of loading\(^6\).

Thin, flexible, resistive sensors (Tekscan Inc., Boston, USA) have been assessed and validated for measuring contact pressure in the patellofemoral joint\(^3\). However, it is not clear how accurately and repeatably these sensors will determine loads in the facet joints. In this study, our objective was to validate the use of Tekscan sensors to measure facet loads by focusing on three questions. 1) What is the repeatability of directly measuring facet joint loads with a Tekscan sensor? 2) What is the accuracy of directly measuring facet joint loads with a Tekscan sensor? 3) What effect does calibration protocol have on measured loads in the facet joints?

Methods
We measured loads in the natural facet joint with Tekscan 6900 QUAD sensors. The 6900 has four independent 14 mm x 14 mm sensing elements. Each element was conditioned and calibrated by loading it between machined aluminum plates coated with 3.2 mm thick rubber in a materials testing machine (Instron DynaMight 8841, Canton, USA). The sensors were calibrated linearly at 80 N and using a two-point power law method at 20 N and 80 N.

Repeatability of load measurements was determined with flexibility tests in axial rotation and flexion-extension (Figure 1a). We prepared four cadaveric lumbar spine specimens (L2-L5) with an average age of 76 years (2 male, 1 female, 1 unknown). After potting the L2 and L5 vertebra in dental stone, each specimen was subjected to injury at the L3-L4 level (nucleotomy, facet joint capsule cut, and posterior ligament sectioning). The specimens were mounted in a spine testing machine and subjected to pure moments of ±7.5 Nm for five trials in each loading direction. We assessed repeatability of resultant force by calculating the standard deviation as a percentage of the mean. To assess the effect of calibration protocol on results, we compared average peak resultant force calculated using a linear calibration and a two-point calibration.

Accuracy of load measurements was assessed by applying known compressive loads to the natural facet joint. Four facet joints (L3-L4) from two cadaveric lumbar spine specimens (L2-L5, 70yr old male, 73 yr old female) were tested. The L2 and L5 vertebrae were potted in dental stone and the segment was then transacted (disc removed) at the L3-L4 level, resulting in two independent sections. To eliminate adjacent level motion at L2-L3 and L4-L5, screws were driven through the vertebral bodies. Each of the two sections was mounted in a materials testing machine (Instron 8874, Canton, USA) so that the surfaces of one facet joint were perpendicular to the loading direction (Figure 1b). Each of the four facets was subjected to four randomized sinusoidal trials at 0.1 Hz to 25 N, 50 N, and 100 N. Force measurement error (E\(_{\text{mean}}\)) was calculated as the percent difference between the Tekscan sensor and the Instron load cell measurements.

Figure 1: (a) Repeatability measurements. (b) Accuracy measurements

Results
Accuracy tests showed that the sensors were more accurate with higher loads but overestimated force at all three load levels. The linear calibration method was found to be more accurate than the two-point method (Figure 2a). Repeatability was not affected substantially by the type of calibration used. In axial rotation, repeatability was 4%±3% (average of standard deviation as a percentage of the mean for all trials) and 6%±4% for the linear and two-point calibration methods, respectively. In extension, repeatability was 7%±5% and 8%±4% for the two methods. Calibration method did affect the measured force in axial rotation. Peak resultant force in axial rotation was, on average, 30% smaller when calculated using the linear calibration method than when calculated using the two-point method (Figure 2b).

Figure 2: (a) Force accuracy at three different load levels. (b) 30% difference in axial rotation force calculated with two different calibration methods.

Discussion
We assessed the repeatability and accuracy of facet load measurements made with a new sensor and the influence of calibration protocol on measured results. While repeatability was quite consistent for different loads and loading types, the accuracy decreased for smaller loads. Limited accuracy of the sensor in our tests may be explained, in part, by the fact that the applied loads used only the bottom 15% of the sensor’s measurement range. Reduced accuracy at smaller loads is consistent with results reported for strain gauges and Pre-Scale Fuji Film in canine lumbar spines\(^7\). Strain gauge accuracies were found to be 3-15% while accuracy of Fuji film was 10-47%\(^7\).

We found that measurements made using a linear calibration were more repeatable and more accurate than those made with a two-point calibration for the range of loads studied. The flexibility test measurements suggest that there would be no loss in repeatability if the sensor were calibrated once for a standard series of spine flexibility tests. Our repeatability values during flexibility tests are consistent with previous findings for the I-Scan sensor in the patellofemoral joint\(^7\).

The Tekscan 6900 sensor is repeatable and as accurate as Fuji film with the benefit of allowing continuous measurements. It also avoids the intensive setup and processing required for extra-articular strain gauges. However, reduced accuracy for small loads limits the utility of the sensor for loads such as those measured during extension in this study. In addition, measurement accuracy appears to be highly dependent on calibration protocol. This sensor offers many advantages over existing methods for measuring force at the facet joints but the accuracy and repeatability depend critically on sensor preparation, calibration method, and load levels assessed.

References