INTRODUCTION
Failure of posterior rods in long thoracolumbar deformity correction cases often requires revision surgery to treat pseudoarthrosis and prevent loss of correction. Entire rod replacement involves re-opening the incision which can increase morbidity. Minimally invasive surgical approaches such as percutaneous insertion of connectors and additional rods are clinically advantageous. This study compares the bending rigidity of various revision rod fixation techniques for long thoracolumbar deformity cases, specifically considering double rod vs. in-line connector options and the effect of revision rod orientation.

METHODS
Specimen Preparation and Treatment Groups
Seven fresh-frozen human spines (M/F=6/1; 69±8y.o.) were procured and T11 and the pelvis were potted in a polymer casting agent (Smooth Cast 300, Smooth-On). Each specimen underwent sagittal alignment and posterior bilateral screw-rod fixation (Depuy Spine) from T12 to S1, excluding L3 (6.0x40mm pedicle screws, connected by 5.5 mm rods, SS) with ili fixation (8.0x80mm, SS). An L3 pedicle subtraction osteotomy (PSO) was performed (approx 30º).

Each specimen was tested in the following sequential configurations: 1) Posterior instrumentation and L3 pedicle subtraction osteotomy (PSO), 2) rotation of rods bilaterally (simulation of broken rods) and addition of bilateral in-line rod connectors; the L2 pedicle screws were removed to allow access [in-line connectors], 3) 2 crosslinks connecting the rods above and below the in-line connectors [in-line + xlink], 4) addition of sat rod oriented parallel (directly lateral) to the original broken rods [satellite parallel], 5) sat rod rotated 45º anterior from the parallel orientation [satellite ANT 45], 6) 45º posterior from the parallel orientation [satellite POST 45], 7) 45º posterior with crosslinks connecting the original rod above and below the in-line connectors [satellite + xlink on original rod], and 8) 45º posterior with crosslinks connecting sat rod above and below the in-line connectors [satellite + xlink on sat rod]. Testing order was randomized across all specimens to minimize bias due to tissue fatigue.

Multi-Directional Bending Rigidty
Non-destructive flexion/extension (FE), lateral bending (LB), and axial rotation (AR) tests were conducted using a validated, non-constraining, pure moment loading apparatus (Figure 1, left). Specimens were tested up to 7.5 Nm with 1.5 Nm increments and held at each moment for 45 seconds. Intervertebral motion was measured in real-time using a 3D motion tracking system (Optotrak 3020, Northern Digital).

RESULTS
Results are presented in terms of stiffness normalized to the PSO test group (intact rod prior to rod breakage), and expressed as percentages. All values presented are the means ± 1 standard deviation.

TABLE 1:
Percentages of intact rod stiffness from the PSO group for each of the revision strategies across the entire site (T12-S1). Values presented are the means ±1 standard deviation. (*) denotes statistically significant difference compared to the PSO group. (#) denotes statistically significant difference compared to the in-line connectors group. The level of significance was set at p<0.05.

The normalized AR stiffness (Figure 2) of the in-line connectors alone was significantly less than the PSO group across T12-S1 and L2-L4 [64.9±16.8% and 41.8±18.4%, respectively, p<0.05]. The satellite rod revisions [groups 4-6] also showed significantly lower stiffness than the PSO group across T12-S1 [p<0.05, Table 1]. The stiffness across L2-L4 for the crosslink revisions [groups 3, 7, 8] was significantly lower than the PSO test group (56.3±24.0%, 67.0±29.4%, and 66.1±30.6%, respectively, p<0.05) and were not significantly different between one another across T12-S1 and L2-L4. However, these same revisions were statistically equivalent in stiffness compared to the PSO test group across T12-S1 (p>0.05, Table 1) and were significantly stiffer than in-line connectors alone [group 2] across T12-S1 (20.8±8.8%, 29.9±16.3%, and 29.7±11.7% respectively, p<0.05). Only the crosslink revisions were significantly stiffer than the in-line connectors alone across L2-L4 (25.1±15.8%, 24.3±15.2% respectively, p<0.05).

DISCUSSION
Results suggest that the revision strategies examined in this study restore stiffness following rod failure without the need to reopen the wound to replace the rod. The in-line connectors alone and 3 satellite rod orientations restored stiffness in all bending modes except AR, but the in-line connectors alone with the addition of crosslinks restored the stiffness independent of any satellite rods. While this may suggest the possible option of not using satellite rods, the satellite rods may have a large benefit in fatigue, which is a limitation of the study. The lack of positioning of the satellite rods is not an important factor to consider in strengthening the revision, and therefore, placement of the rods should be under the surgeon’s discretion based on anatomical considerations.

![Figure 1: (left) View of the entire test set-up. (right) Close up of double rod construct in the “parallel” orientation. Left arrow = satellite rod, right arrow = in-line connector.](image-url)