INTRODUCTION:
Up to 80% of the general population experience at least one significant bout of low back or neck pain in their lifetime. The leading known cause of this pain is degenerative disc disease (DDD); yet the mechanism through which back/neck pain and disc degeneration develop is not fully understood. Epidemiologic data indicate that altered mechanical loading is a stimulus for disc degeneration. However, our knowledge of how environmental and/or occupational factors affect in vivo mechanical loading is limited. Factors such as posture, lifting technique and rate, experience, and fatigue (among others) are thought to affect mechanical loading in the spine. Yet force-sensing implants for direct in vivo measurement of loads in the interbody space have remained elusive. As such, there are few studies and limited data correlating spinal load magnitude to these occupational/environmental factors during dynamic activities. Therefore, the purpose of this study was to use a novel force-sensing implant to measure in vivo loads in the disc space of the goat cervical spine in real time while varying activity, posture, and rate of neck motion.

METHODS:
We developed a force-sensing implant to directly measure uniaxial compressive loads in the goat cervical disc space in vivo. The implant was comprised of two components between which was housed a wired miniature load cell. Following IACUC approval, an anterior cervical discectomy was performed at the C4-C5 level of a skeletally mature Alpine-Nubian goat. The implant was placed in the interbody space with the wire exiting percutaneously at the dorsal surface of the neck. Post-operatively, interbody loads were measured at a rate of 50 samples/sec as the animal performed full flexion-extension motion and walked a set course. Video was recorded of the animal’s activity during data collection. The measured loads were animated and synchronized with the video. For each flexion-extension trial, the magnitude and range of forces imposed on the spine were determined. Forces were correlated to head position, neck position, rate of motion, and technique (the overall path the neck took from its starting point in extension to its ending point in flexion). Loads were also analyzed for each walking trial in terms of observed gait, acceleration/deceleration, head position, and leg position. The Kruskal-Wallis and Mann-Whitney tests were used with Sidak corrections to detect statistically significant differences in the loads for each of the factors analyzed.

RESULTS:
For each of the 125 flexion-extension maneuvers, the load data were highly repeatable. The highest magnitude of force measured during dynamic activity was 272 N. Holding the head upright in neutral position imposed an average of 90 N on the interbody implant. As the goat raised its head and neck to full extension, interbody forces increased significantly. In all cases, the maximum loads occurred just prior to maximum flexion (as the head dropped) when the neck extensor muscles were firing to decelerate the head. The load dynamics followed this specific pattern for each flexion-extension trial. However, the magnitude of load was modulated by factors including 1) Neck position, 2) Head position, 4) Rate of motion, and 3) Compensation techniques. Peak forces were always at the point of maximum deceleration. Highest magnitudes resulted from trials where motion ended in full flexion of the head and neck (Figure 1, Technique K). When the neck was fully flexed but the head was in neutral position (relative to the upper cervical spine), peak forces were lower (Technique C1). When the neck was fully flexed but the head was extended (relative to the upper cervical spine), peak forces were further reduced (Technique C2). When the neck was slightly flexed and the head was extended (relative to the upper cervical spine), peak forces were even further reduced (Technique B).

During walking and running, load data were also highly repeatable and coincided with gait cycle. As expected, higher forces were observed during running than walking (Figure 2). Force magnitude was also highly dependent on whether the animal was accelerating, moving at a steady state, or decelerating, as well as head and neck position.

DISCUSSION:
Results from this study demonstrate repeatable load dynamics which correlated with activity. The interbody space was subjected to a wide range of forces during normal activities. During voluntary flexion and extension, changes in force were substantial. Peak forces within each motion cycle (extension to flexion) appeared to correspond to muscle activity. Although we did not specifically measure muscle recruitment in this study, the instant of highest force measurements consistently correlated to maximum deceleration of the head and neck and likely corresponded with maximum contraction of the primary neck extensors. The highest peak magnitudes were recorded when the neck extensors were decelerating the head and neck while simultaneously the neck flexors were pulling the head into full flexion. Slight alterations in technique and final head/neck position resulted in significantly different resulting loads. Similar patterns were observed during gait where head and neck position were highly dynamic.

SIGNIFICANCE:
Results from this study suggest that muscle forces are the major contributor to axial compressive loads in the cervical spine during motion. Load magnitude appears to be primarily modulated by muscle recruitment patterns of the extensor and flexor muscles. Subtle differences in muscle recruitment have substantial effects on interbody force magnitude, even during every day voluntary activities.

Figure 1 – The technique used to complete the flexion-extension motion, as well as the specific neck position used, had significant effects on the change in load achieved. (**) represents statistical significance with p<0.01

Figure 2 – The head position, gait, and acceleration stage used during the walking motion all had a significant effect on load magnitude. (***) represents statistical significance with p<0.01