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The failure response of the human cervical facet capsular ligament during facet joint retraction

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ABSTRACT

Studies implicate the cervical facet joint and its capsule as a primary anatomical site of injury during whiplash exposures to the neck. Although the facet joint is known to undergo stretch as the superior vertebra is retracted relative to the inferior vertebra during the whiplash kinematic, the response of the facet capsular ligament and its microstructure during failure in joint retraction is unknown. Polarized light imaging and vector correlation analysis were used to measure the collagen fiber alignment in the human capsular ligament, together with traditional mechanical metrics, during joint retraction sufficient to induce ligament failure. Anomalous fiber realignment occurs at 2.95 ± 1.66 mm of displacement, which is not different from the displacement when the ligament first yields (2.77 ± 1.55 mm), but is significantly lower ($p = 0.016$) than the displacement at tissue failure (5.40 ± 1.65 mm). The maximum principal strain at the first detection of anomalous fiber realignment (0.66 ± 0.39) also is significantly lower ($p = 0.046$) than the strain at failure (1.39 ± 0.64), but is not different from the strains at yield or partial failure. The onset of collagen fiber realignment determined in this study corresponds to the ligament's yielding and supports assertions that the facet capsule can undergo tissue injury during joint retraction. Further, such microstructural responses may indicate tissue damage in the absence of rupture.

1. Introduction

Neck pain is one of the most frequently occurring musculoskeletal disorders, and whiplash is a common cause of chronic neck pain (Freeman et al., 1999; Quinlan et al., 2004). Biomechanical investigations of the neck during whiplash simulations indicate that the cervical spine exhibits an abnormal S-shaped curve in which the primary motions of the vertebrae in the lower cervical spine is posterior retraction relative to their inferior adjacent vertebrae (Cusick et al., 2001; McConnell et al., 1995; Panjabi et al., 1998; Stemper et al., 2004). Although joint motions during the whiplash kinematic have been reported to include both tension and retraction across the facet joint, the retraction component is the dominant mode of loading for this joint (Stemper et al., 2004). During vertebral retraction the facet joint undergoes shear as the inferior facet translates posteriorly relative to the superior facet and the facet capsular ligament undergoes excessive stretching and is at risk for injury (Ito et al., 2004; Panjabi et al., 1998; Pearson et al., 2004). Indeed, capsule stretch has been reported to occur for joint retractions up to 4.25 mm but in the absence of any tissue rupture (Cusick et al., 2001; Deng et al., 2000; Luan et al., 2000; Panjabi et al., 1998; Pearson et al., 2004; Siegmund et al., 2001; Stemper et al., 2004; Stemper et al., 2005; Sundararajan et al., 2004; Yoganandan et al., 1998; Yoganandan et al., 2002). Those studies conjecture that excessive motion of the facet joint may disrupt the integrity of the capsular ligament and may be the mechanism of pain generation. To date, only one study has defined the failure response of the facet capsular ligament during joint retraction and while two of the specimens in that study were found to sustain strains that were greater than those at partial failure of the ligament (Siegmund et al., 2001), the microstructural responses of the capsular ligament during joint retraction to failure are not defined.

Mechanical trauma to ligament tissue can cause microstructural damage that may not be visually detected (Lu et al., 2005; Petterson et al., 1997; Quinn and Winkelstein, 2008; Voyvodic et al., 1997). Because of this, common macroscale indicators of tissue damage, such as a visible tissue rupture or partial failure during mechanical loading, may not fully characterize the threshold for injury to ligament tissue. As such, polarized light has been used to assess microstructural tissue changes as a means of estimating the onset of tissue injury. Polarized light has been used to quantify the collagen orientation and alignment in a variety of different tissues including the human and canine Achilles tendon, rat tail, human and rat cervical facet ligament, and the supraspinatus muscle (Dickey et al., 1998; Quinn and Winkelstein, 2008; Quinn et al., 2010; Thomopoulos et al., 2003; Whittaker and Canham 1991). This technique takes advantage of collagen's natural birefringence to estimate the fiber alignment of such tissues (Tower and Tranquillo, 2001). In fact, anomalous fiber realignment has been detected in the facet capsular ligament

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under tensile loading before tissue failure or any visible tissue damage (Quinn and Winkelstein, 2008). In a subfailure study of facet joint retraction, no ligament yield, partial failure, or anomalous fiber realignment were detected (Quinn and Winkelstein, 2011). However, both unrecovered strain and laxity were induced in the ligament (Quinn and Winkelstein, 2011). Although those findings of reduced ligament function suggest that joint retraction may induce damage to the collagen fiber network, there is still no clear definition of the thresholds for yield, partial failure, and fiber realignment in the facet capsule during joint retraction.

The relationship between facet joint retraction and the onset of subfailure and failure damage in the capsular ligament is unknown. Therefore, the objective of this study was to quantify the changes in fiber kinematics of the facet capsule during facet joint retraction to gross failure of the capsular ligament. The occurrence of mechanical yield, partial failure, and gross failure were measured, as well as fiber realignment using polarized light during retraction. Ligament strains at the initial detection of fiber realignment, yield, partial failure, and gross failure were also measured and optical and mechanical metrics were compared to investigate whether these microstructural changes and mechanical events occur under different conditions.

2. Methods

The facet joint capsular ligaments ($n=8$) were harvested from C6-C7, C5-C6, and C3-C4 of three unembalmed human cadavers (56.8 ± 8.4 years). Each motion segment was finely dissected and the surface musculature was removed. In order to establish the natural orientation of the capsule in the testing apparatus, four fiduciary pins (0.5 mm diameter shaft; 3.175 mm diameter spherical head) were inserted into the superior and inferior bones surrounding the facet joint (Fig. 1). The facet joint was imaged and the coordinates of the fiduciary pins were digitized. The joint was then excised by cutting the pedicles and laminae. All remaining musculature and tendon insertions were removed from the capsule surface by fine dissection, keeping the entire capsular ligament intact. In order to track the kinematics of the collagen fibers in the capsular ligament, light must be transmitted through it; this requires the ligamentum flavum to be transected and articular bone be removed from the medial edge of the facet (Quinn and Winkelstein, 2011). Kirschner wires were placed in the superior and inferior bones of the joint to provide solid gripping of the specimen. Polymethyl methacrylate (Dentsply International; York, PA) was molded around the articular processes to reinforce the bone and casting material during testing. The joint was then cast in aluminum cups with FlowStone (WhipMix Corporation; Louisville, KY), and the cups were subsequently fixed to an Intron 5865 testing machine (Instron Corporation; Norwood, MA) using a customized jig to simulate retraction (Quinn and Winkelstein, 2011) (Fig. 1). Using the digitized positions of the fiduciary pins in the intact motion segment, the *in situ* orientation of the joint was then recreated in the Instron for the start of each test.

All specimens were preconditioned from 0 to 1 mm at 0.5 mm/s for 30 cycles of triangular cyclic retraction. This displacement produces less than 5% of the average load to failure for this joint in retraction and has been shown to not produce any yield, failure, or damage to the ligament (Siegmund et al., 2001; Quinn and Winkelstein, 2011). Following preconditioning, the specimen was allowed to rest for 10 min before the inferior facet of the superior vertebra was retracted relative to the superior facet of the inferior vertebra at 0.5 mm/s until ligament failure occurred. Yield, partial failure, and gross failure were measured using the load and displacement data that were collected by the Instron Bluehill software at 1 kHz. Yield was defined as a decrease in at least 10% of the measured stiffness of the tissue (Quinn and Winkelstein, 2008; Yoganandan et al., 1989). Partial failure was defined to occur at any instance where the force decreased with increasing displacement, and gross failure was taken as the maximum force recorded during loading.

Polarized light imaging was used to determine the direction of fiber alignment in the capsular ligament. Using an optical system modified to operate with an Instron machine that has been previously reported (Quinn and Winkelstein, 2008), polarized light images of the ligament were collected during loading using a high-speed Phantom v5.1 CCD camera (Vision Research Inc.; Wayne, NJ) with a frame rate of 500 fps and a 206×400 pixel window. The CCD camera was triggered to begin recording at the start of the retraction. Fiber alignment maps were generated using Matlab7 (Mathworks, Inc.; Natick, MA) with the harmonic analysis method (Tower et al., 2002). A vector correlation technique was used to analyze serial fiber alignment maps to detect fiber realignment in the facet capsule (Quinn and Winkelstein, 2009). For this study, vector correlation measurements were obtained using both the fiber alignment strength and direction at each pixel to create an alignment vector (Quinn and Winkelstein, 2009). The correlation coefficient was computed for a given image map at each pixel using the alignment vectors of the pixels in a 5×5 window surrounding it in the image maps derived from those preceding and following it. The vector correlation values were calculated continuously during loading for all areas of the capsular ligament that had sufficient light transmission and an adequate signal-to-noise ratio (SNR). Adequate SNR and correlation thresholds were computed using the alignment maps in the period before the sample was loaded and were set for each specimen.

Vector correlation values range between 0 and 1, with a value of 1 defining consistent fiber alignment between alignment maps and a value of 0 indicating random alignment between alignment maps. In a single pixel with adequate SNR, a change in the correlation value greater than the threshold value determined during the period in which the ligament was stationary was categorized as anomalous fiber realignment. For each specimen, all instances and locations of anomalous fiber realignment were recorded and compared to the mechanical metrics of yield, partial failure, and gross failure. A similar vector correlation tracking technique was also used with virtual markers to measure the Lagrangian strains in the ligament throughout the loading period until ligament failure (Quinn

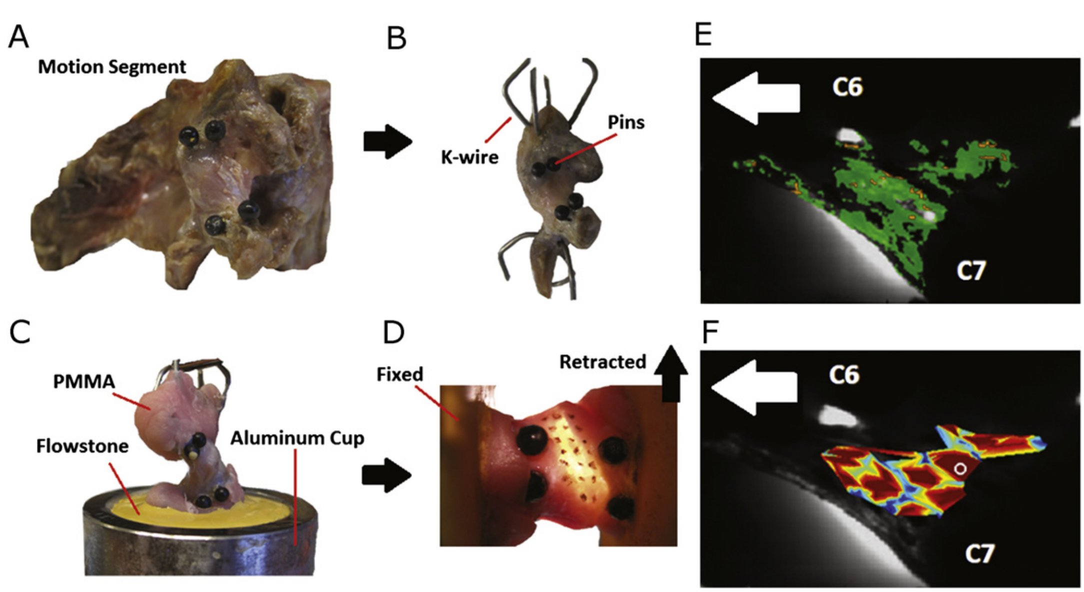

Fig. 1. **(A)** Motion segment showing fiduciary pins placed in the facet joint to mark the *in situ* configuration. **(B)** Corresponding excised facet joint with pins and Kirschner wires. **(C)** Specimen with the C6 vertebra cast in the aluminum cup. **(D)** Specimen mounted in the mechanical testing device backlit for imaging; C6 is retracted as indicated. **(E)** Image of specimen at gross failure where green pixels indicate acceptable SNR and yellow pixels indicate where anomalous fiber realignment is detected. **(F)** The corresponding first principal strain field at gross failure with the location of the maximum value circled. Arrows in **(E)** and **(F)** indicate the direction of applied retraction.

and Winkelstein, 2010). As such, the first principal strain (E_1) and the maximum shear strain (E_{12}) were measured at each of anomalous fiber realignment, yield, partial failure, and gross failure. Separate repeated-measures ANOVAs with post-hoc Bonferroni tests compared each of the forces, displacements, maximum principal strains, and maximum shear strains at yield, partial failure, gross failure, and the initial detection of anomalous fiber realignment.

3. Results

All specimens exhibited yield and anomalous fiber realignment (Fig. 2; Table 1). Gross failure of the facet capsule occurred at an average load of 61.81 ± 26.40 N and displacement of 5.40 ± 1.65 mm (Fig. 2; Table 1). Partial failure was observed in six of the specimens and occurred before gross failure at an average force of 45.81 ± 22.99 N and displacement of 3.48 ± 0.96 mm. Ligament yield occurred at an average force of 30.65 ± 25.54 N and displacement of 2.77 ± 1.55 mm and was at a significantly smaller displacement ($p=0.006$) than at tissue failure. However, there were no other differences in the displacements at any of the mechanical events. In addition, the loads at which the ligament sustained yield, partial failure, and gross failure were not different.

Anomalous fiber realignment was detected in seven of the specimens during retraction (Table 1). Image data were not acquired from one specimen (specimen #C446_C56L) because the polarizer was not started; as such, no strain or fiber alignment data were obtained. The first detection of anomalous fiber realignment occurred at an average load of 32.86 ± 29.70 N and a displacement of 2.95 ± 1.66 mm (Table 1) and was not different from the displacement at yield or partial failure. Yet, the displacement corresponding to the first detection of anomalous fiber realignment was significantly lower ($p=0.016$) than the displacement at gross failure (Table 1).

The strains at the first occurrence of anomalous fiber realignment, yield, and partial failure of the ligament were all lower than those strains sustained at gross failure of the ligament. The average maximum principal strain and maximum shear strain at gross failure were 1.39 ± 0.64 and 0.78 ± 0.22, respectively (Fig. 3). Corresponding strains at the first partial failure were 0.61 ± 0.13 and 0.48 ± 0.08, respectively, and were both significantly lower (E_1 $p=0.018$; E_{12} $p=0.015$) than at gross failure (Fig. 3). The strains at yield were also significantly lower (E_1 $p=0.016$; E_{12} $p=0.009$) than at gross failure and were not different from those at partial failure. The strains at the first detection of fiber realignment were 0.66 ± 0.39 (E_1) and 0.44 ± 0.17 (E_{12}) and were significantly lower (E_1 $p=0.046$; E_{12} $p=0.026$) than the strains at gross failure (Fig. 3). There were no differences between the strains at the first detection of fiber realignment, yield, and partial failure. However, the first detection of fiber realignment occurred before both yield and partial failure in three of the specimens (Table 1). Yield and partial failure were both detected prior to fiber realignment detection in one specimen (Table 1).

4. Discussion

This study demonstrates that the facet capsular ligament undergoes anomalous fiber realignment before gross failure of the ligament occurs during vertebral retraction (Table 1). This finding is consistent with a previous report that anomalous fiber realignment can occur before gross failure of this tissue during *tensile* loading (Quinn and Winkelstein, 2009). In that study, the dorsal and ventral aspects of the facet capsular ligament were removed and only the lateral aspect of the facet capsule underwent tensile loading directed along the superior–inferior axis of the spine (Quinn and Winkelstein, 2009). In the current study, the entire capsule was left intact, leaving more of the ligament's collagen fibers available in the lateral aspect of the ligament to carry load. The initial detection of anomalous fiber realignment in facet capsules prepared this way occurred at both a greater force and displacement in joint retraction than for the same ligament under tension (Quinn and Winkelstein, 2009). The failure load and displacement of the cervical facet

Table 1
Displacement at the first occurrence of each mechanical event.

Specimen	Donor gender	Anomalous realignment	Yield	Partial	Gross failure
C500_C67L	male	1.07	1.53	2.45	3.05
[b]C500_C67R	male	6.07	5.58		6.05
C947_C67L	male	3.67	1.10	3.19	3.67
C947_C67R	male	1.78	2.09	3.00	8.09
C446_C56R	female	1.77	2.03	4.05	6.09
[b]C446_C34L	female	3.25	3.24		4.16
C446_C34R	female	3.04	2.06	3.07	6.19
C446_C56L	female	[a]	4.49	5.14	5.93
Mean		**2.95**[c]	**2.77**[c]	**3.48**	**5.40**
S.D.		**1.66**	**1.55**	**0.96**	**1.65**

[a] No image data acquired.
[b] No partial failure detected prior to gross failure.
[c] Significant difference compared to displacement at gross failure.

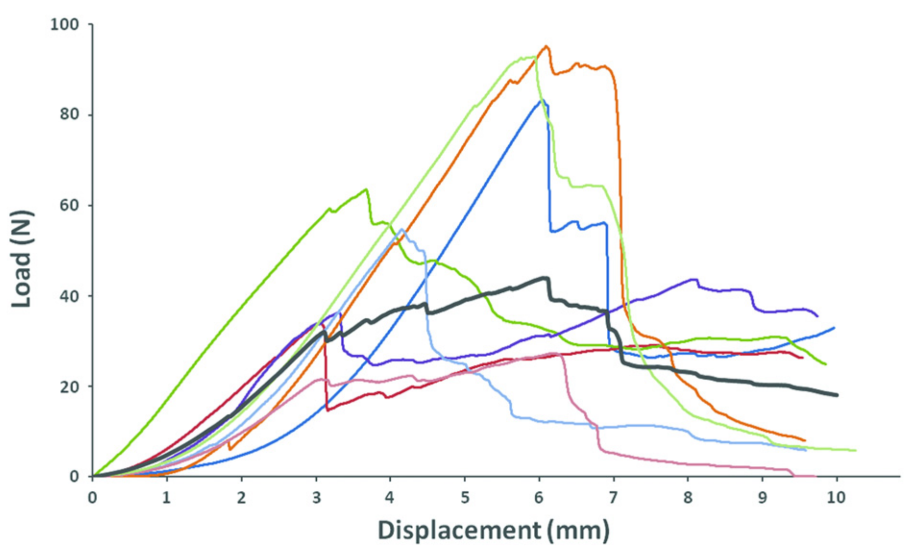

Fig. 2. Individual load–displacement responses of each specimen. The heavy black curve indicates the average load–displacement response for all specimens.

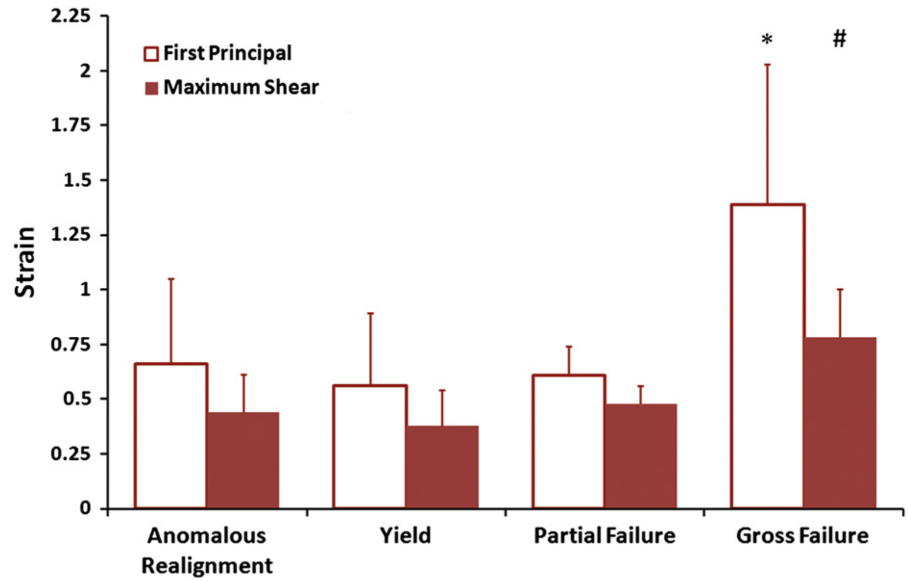

Fig. 3. Average (±SD) first principal strains and maximum shear strains at the first occurrence of anomalous fiber realignment, yield, partial failure, and gross failure. Both types of strain are significantly higher (*$p<0.05$; #$p<0.03$) at gross failure than at the detection of anomalous fiber realignment, yield, and partial failure.

capsular ligament in tension are also lower than in retraction (Siegmund et al., 2001; Winkelstein et al., 2000) and may be due to the general organization and orientation of the collagen fibers in the ligament. The fibers may be more aligned along the direction of joint tension; such an orientation would cause them to become elongated and support load at lower tensile displacements, but during a joint retraction which is not aligned with their primary orientation, they do not support load until the joint undergoes larger excursions (Quinn and Winkelstein, 2011).

The initial detection of anomalous fiber realignment was at 2.95±1.66 mm (Table 1), which is within the previously reported range of retraction excursions that the facet joint experiences during whiplash (Cusick et al., 2001; Deng et al., 2000; Luan et al., 2000; Panjabi et al., 1998; Pearson et al., 2004; Siegmund et al., 2001; Stemper et al., 2004; Stemper et al., 2005; Sundararajan et al., 2004; Yoganandan et al., 1998; Yoganandan et al., 2002). Rear-impact simulations of cadavers estimate retraction of the facet joint in the lower cervical spine to be between 2.2 and 4.25 mm (Deng et al., 2000; Luan et al., 2000; Sundararajan et al., 2004). Similarly, studies of isolated motion segments and cervical spines report that the facet joint undergoes between 1.07 and 3.20 mm of retraction (Cusick et al., 2001; Siegmund et al., 2001; Stemper et al., 2004; Stemper et al., 2005; Yoganandan et al., 1998; Yoganandan et al., 2002). The displacement (2.95±1.66 mm) at the onset of anomalous fiber realignment in the current study is in range of the joint displacements reported in those whiplash studies. Based on those reports, we previously imposed facet joint retraction up to 2.5 mm together with the same approach as in this study to track collagen fiber organization during loading to evaluate if microstructural damage occurs during and after those whiplash-like retractions (Quinn and Winkelstein, 2011). Although no microstructural changes were found *during* retraction up to 2.5 mm, reduced ligament stiffness, increased laxity, and unrecovered strain were all detected *after* the retraction (Quinn and Winkelstein, 2011). In the current study, anomalous fiber realignment was detected at an average displacement of 2.95±1.66 mm, but in three of the specimens it was observed below 2.5 mm of retraction (Table 1). This difference may be due to the fact that more of the ligament was preserved and the ligament stiffness is greater or due to variability in the ligament properties between the donors in the two studies. Regardless, considering the prior retraction study and our current study, the finding that the occurrence of fiber alignment exhibits variability among specimens is consistent with the biomechanical and clinical literature, which supports the varied individual responses that have been reported in this type of injury (Lord et al., 1996; Radanov et al., 1995; Siegmund et al., 2001; Winkelstein et al., 2000). Of note, the current study used facet capsules from only three different donor specimens (Table 1) which may bias the findings.

Gross failure of the facet capsule occurred at a lower force and displacement than previously reported for this joint (Fig. 2; Table 1). Siegmund et al. (2001) found the failure load (94±31 N) and displacement (8.1±1.5 mm) for the cervical capsule in retraction to be approximately 50% greater. In that study, the ligament was dissected only to remove surface musculature; in our study extensive specimen dissection was performed to facilitate light transmission through the ligament to measure fiber alignment (Fig. 1). In order to maximize light transmission of the capsular ligament, fine dissection was more extensive and included removal of the surface musculature, synovial tissue, and light-obstructing articular bone (Fig. 1). Although none of the specimens were overtly damaged during the specimen preparation, removal of musculature on the surface of the ligament, synovial tissue inside the capsule, or removal of the bone may have weakened the capsule. The increased capsular tissue removal in our study also reduces the amount of tissue available to support load. Although it is not known how such preparation would affect the onset of anomalous fiber realignment, it would result in the lower failure load that we observe here. The rate of loading in this study is an order of magnitude greater than the Siegmund study, which may affect the microstructural responses of the ligament (Siegmund et al., 2001). Despite all of these differences, the load–displacement curves in our study exhibit the typical relationships and failure characteristics (Fig. 2) of this tissue (Siegmund et al., 2001).

Microstructural changes in fiber alignment can occur before any detectable mechanical events during facet retraction. Fiber realignment was detected in several specimens prior to their yield or partial failure, and both events were detected in one specimen prior to detection of fiber realignment (Table 1). This suggests that previously defined injury thresholds that are based on the traditional failure metrics may not actually define the onset of microstructural injury to the cervical facet capsule. Furthermore, due to the remaining articular bone and synovial tissue inside the capsule that impede light transmission in this study, imaging data could not be acquired or analyzed at the ligament insertions due to inadequate SNR in those regions (Fig. 1). The ligament area with acceptable SNR was approximately 3.66 ± 2.25 mm^2, which is only a fraction of the entire facet capsule (Fig. 1). As such, there may have been undetected anomalous fiber realignment during loading, and anomalous fiber realignment may have occurred prior to yield or partial failure in other specimens but without detection.

This study has demonstrated that microstructural changes in fiber alignment in the cervical facet capsular ligament occur within the reported range of retraction during whiplash-like joint motions. But, anomalous fiber realignment occurs prior to any yield or failure of the ligament. It is possible that anomalous fiber realignment may even occur at lower thresholds than detected in the current study. However, given the unique anatomy of the facet joint and its hard and soft tissue, current techniques do not enable such detection. Nevertheless, identifying the onset of microstructural tissue changes *during* retraction provides an improved framework over traditional injury metrics for understanding how mechanical loading relates to the onset of capsular ligament injury in the absence of visible tissue rupture.

Conflict of interest statement

There are no conflicts with either author.

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