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Morphologic and biomechanical comparison of spinous processes and ligaments from scoliotic and kyphotic patients

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ABSTRACT

The spinous processes and supraspinous and interspinous ligaments (SSL and ISL, respectively) limit flexion and may relate to spinal curvature. Spinous process angles and mechanical properties of explanted human thoracic posterior SSL/ISL complexes were compared for scoliosis ($n=14$) *vs.* kyphosis ($n=8$) patients. The median thoracic coronal Cobb angle for scoliosis patients was 48°, and sagittal angles for kyphosis patients was 78°. Spinous processes were gripped and four strain steps of 4% were applied and held. Percent relaxation was calculated over each step, equilibrium load data were fit to an exponential equation, and a Kelvin model was fit to the load from all four curves. Failure testing was also performed. Median ligament complex dimensions from scoliosis and kyphosis patients were, respectively: ISL width = 16.5 mm and 16.0 mm; SSL width = 4.3 mm and 3.8 mm; ISL+SSL area = 17.2 mm and 25.7 mm; these differences were not significant. Significant differences did exist in terms of spinous process angle *vs.* spine axis (47° for scoliosis and 32° for kyphosis) and SSL thickness (2.1 mm for scoliosis and 3.0 mm for kyphosis). Fourth-step median relaxation was 42% for scoliosis and 49% for kyphosis. Median linear region stiffness was 42 N/mm for scoliosis and 51 N/mm for kyphosis. Median failure load was 191 N for scoliotic and 175 N for kyphotic ligaments. Differences in loading, relaxation, viscoelastic and failure parameters were not statistically significant, except for a trend for greater initial rate of relaxation (T1) for scoliosis ligaments. However, we found significant morphological differences related to the spinous processes, which suggests a need for future biomechanical studies related to the musculoskeletal aspects of spinal alignment and posture.

1. Introduction

Idiopathic scoliosis and Scheuermann's kyphosis are developmental conditions leading to the deformity of the adolescent spine. Advanced cases of spinal deformity may require spinal fusion. While fusion usually arrests the progression of deformity, fusion also limits the flexibility of the spine and is attributed to degenerative changes of adjacent motion segments levels later in life. Because even the secondary biological and mechanical stages of these diseases are poorly understood, the development of targeted treatments remains difficult. Optimally, non-fusion treatment is desirable.

Scoliosis patients often have hypokyphotic thoracic spines relative to normal adolescent population (de Jonge et al., 2002). One may speculate that this is due to taut ligaments of the posterior elements in scoliosis patients relative to lax ligaments in Schuermann's patients. The authors have noted a qualitative relationship between spine deformity and quality of the supraspinous and interspinous ligaments (SSL and ISL, respectively) during surgical treatment. Specifically, the ISL and SSL in scoliotic patients appear thick and the spinous processes appear relatively perpendicular to the long axis of the spine. Conversely, the spinous processes in kyphotic subjects tend to be angled downward, and the ISL and SSL tend to appear thin and hypoplastic.

Quantifying such a relationship in these structures would demonstrate a correlation between biomechanical ligament properties and deformity. Though it is understood that such a link in itself cannot determine causation, establishing a connection between ligament properties and spinal deformity would identify a biological or mechanical connection that could be explored in future studies. Such studies might investigate causation through animal models, explore *in vivo* ligament differences using medical imaging, biochemical or histological analysis, improve mathematical models, or evaluate treatment by ligament modification or augmentation.

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To our knowledge, no comparative study has analyzed the SSL/ISL complex using rigorous biomechanical analysis techniques, and no study has biomechanically compared these ligaments as formed in the presence of scoliosis to those formed in the presence of kyphosis. A pilot study by the lead author investigated mechanical testing and analysis methods for the evaluation of posterior spinal ligaments in a porcine model. The goal of the present study was to apply these methods to the human SSL/ISL complex to describe possible differences in the viscoelastic properties between scoliotic and kyphotic patients. Although the SSL/ISL unit represents an inhomogenous and locally anisotropic tissue (Aspden et al., 1987), samples in this study were tested uni-axially in their natural configuration in order to compare these clinically obtained tissues, which act together *in vivo*.

On the basis of possible functional differences and visually observed differences, this study hypothesized that the ISL/SSL complexes would differ both morphologically and in terms of their mechanical performance. Evaluation of these hypotheses was performed by making *in vitro* and *in vivo* dimensional measurements, and by stress-relaxation testing and load-to-failure testing. Mechanical performance data were evaluated both in terms of structural performance (load–displacement) and material properties (stress–strain) to separate load response differences due to differing morphology.

2. Methods

2.1. Clinical measurements

Preoperative standing coronal and sagittal spinal radiographs were measured for each subject to determine the degree of their scoliosis and kyphosis. The Cobb method was used over the entire length of the curve and across the local curve (the region of the tissue specimens). MRIs from all patients were reviewed to confirm that there were no traumatic or congenital conditions. Axial images were measured to determine the size of the spinous process and the total transverse sagittal length of the vertebra. Axial images allow measurements to be obtained while taking into account axial rotation. Specifically, T2 weighted images were used for measurements after confirming that the images were parallel to the intervertebral disc and endplates. T1 weighted images were also used in 5 cases in which there was better delineation between the tissues at the anterior vertebral bodies. The transverse length of the spinous process was determined as the distance from the posterior margin of the canal to the posterior tip of the spinous process, and the vertebral length was determined as the distance from the anterior vertebral margin to the posterior tip of the process. Due to the caudal alignment of the spinous processes on a given axial image, the anterior reference point would usually be one vertebral level below the level of the posterior process measurement point. This required verification that there was no change in spinous process length from one vertebral level to the adjacent level being measured. The spinous process "Lever Arm" was the spinous process length measured at the tested level (apex of the spinal curve) from the spinous process–lamina junction to the tip of the spinous process in a direction perpendicular to the long axis of the corresponding motion segment. The vertebral body depth was measured along the same axis from the anterior margin to posterior margin of the vertebral body, Fig. 1.

2.2. Tissue procurement

After internal review board approval, 14 adolescent idiopathic scoliosis and 8 Scheuermann kyphosis patients undergoing posterior spinal surgery for treatment of their deformity had tissue excised at the apex of their curvature. The tissue obtained consisted of three to four adjacent spinous processes with intervening ligaments. The technique entailed scoring the junction of the base of the spinous process to laminar junction and then using small osteotomes or gouges in a direction tangential to the lamina to release the spinous processes from the laminae. Muscle and fascia were carefully removed from these specimens. The time from tissue harvest to freezing was less than 60 min. All tissue was double-wrapped in airtight plastic bags and frozen at −20 °Celsius (C), where it was stored until the time of testing.

2.3. Tissue preparation and measurement

Specimens were thawed, placed in 0.9% phosphate-buffered saline (PBS, Fisher Scientific, BP665-1), and refrigerated for approximately 24 h before testing. Specimen width and thickness were measured using a digital caliper in the locations indicated in Fig. 1. Cross-sectional area was calculated assuming an elliptical cross-sectional shape for the supraspinous ligament, and a rectangular cross-sectional shape for the much wider interspinous ligament. Special grips, shown in Fig. 2, were designed to allow testing of the central level of multiple-level specimens. For a four-level specimen (*e.g.*, T7–T10), the outer levels (between T7 and T10) are fixed first, followed by the inner levels (between T8 and T9), which are fixed with the specimen under 1 N of applied axial loading for testing of the central ligament (*e.g.*, T8–T9). Pilot testing revealed the importance of measuring only the ligamentous region of the ISL when determining the initial length of the ligament, and so the interspinous process ligament length was measured on scaled fluoroscopic images acquired with the ligament under 1 N of axial tension, exclusive of the weight of the tissue. Ligament length was measured at three points across the spinous processes, and the average of these three points was used as the initial, unloaded length of the specimen.

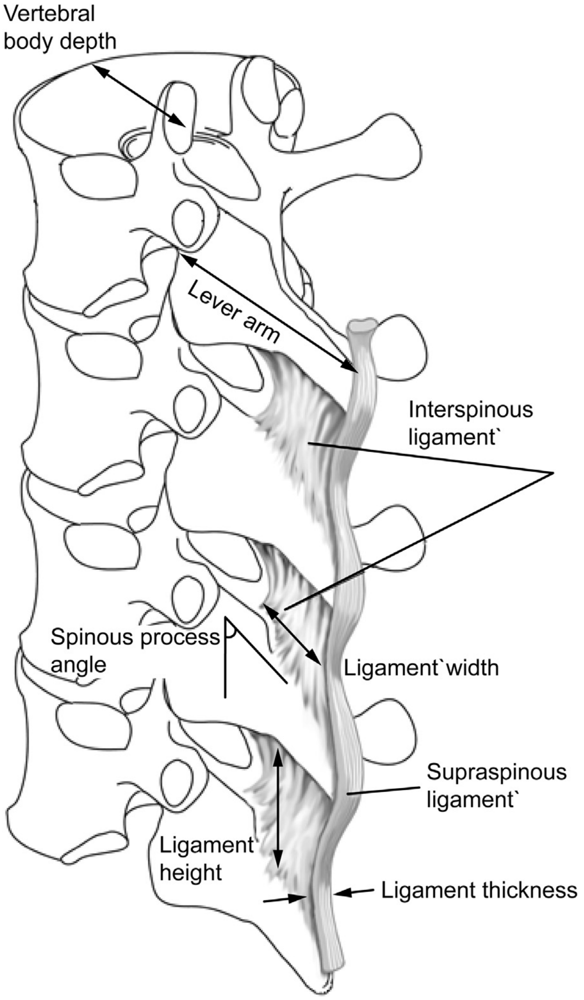

Fig. 1. Schematic identification of measured morphologic parameters.

2.4. Stress relaxation testing

In developing the mechanical test protocol, a balance was sought between minimal test time and rigorous description of the mechanical properties of the system. An incremental step relaxation protocol consisting of four stretch steps from 1.04 to 1.16 with a 1000-second relaxation period was chosen to evaluate viscoelastic properties (Fig. 3). The magnitude of this stretch is similar to that seen using *in vitro* flexibility tests (Panjabi et al., 1982) and is well below the estimated failure strain of these ligaments. The relaxation period was chosen as it allowed the load to approach equilibrium in pilot tests. A video strain measurement system was used during pilot testing, but it was found that surface strains did not necessarily correlate linearly with subsurface strains owing to the presence of a fine membrane on the surface of the ligaments. Furthermore, it was the net displacement of the spinous processes that was of the most interest clinically. For this reason, crosshead displacement was used to calculate the net stretch of the ligament.

Stress relaxation experiments were conducted in a PBS bath to ensure hydration and at body temperature (37 ± 1 °C). Displacements were applied to the bone–