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Interpedicular kinematics in an *in vitro* biomechanical assessment of a bilateral lumbar spondylolytic defect

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ABSTRACT

Background: A spondylolytic defect in lumbar vertebra is a common condition during early childhood and adolescence, and is considered a precursor to spondylolisthesis. This study examined whether a bilateral spondylolytic defect in lumbar spine intrinsically results in increased intervertebral translations during different bending motions.
Methods: Seven fresh frozen cadaveric kangaroo lumbar (L1–L6) spine specimens were tested in a kinematic spine simulator; first in their intact state, followed by creating a bilateral spondylolytic defect at L4 and retesting. In addition to recording global and segmental range of motions, the pedicles at L3, L4, and L5 vertebrae were digitized bilaterally and virtually tracked throughout testing. Interpedicular kinematic metrics were employed to capture any changes in translatory motions during flexion–extension, bilateral bending, and axial torsion testing modes.
Findings: Following the defect, range of motion at the defect level (L4–L5) increased significantly in all the three motion planes. At L4–L5, normalized interpedicular displacement increased significantly in flexion–extension (median change +156%) and bilateral bending (median change +58%) motions, but changes in bending-plane and out-of-plane intervertebral translations were not significant in any of the testing modes.
Interpretation: In the absence of any significant changes in bending-plane and out-of-plane intervertebral translations at L4–L5, changes in interpedicular displacement would directly correspond with the stretching of posterior annulus of the L4–L5 intervertebral disc. A bilateral spondylolytic defect at L4 may result in significant overstretching of the posterior annulus of the L4–L5 disc during flexion–extension and bilateral bending motions.

1. Introduction

Spondylolysis, an osseous defect of the pars interarticularis of the vertebral arch, occurs in nearly 6% of the population (with some ethnic variations) particularly during childhood and adolescence (Fredrickson et al., 1984; Morita et al., 1995; Simper, 1986). While the majority of cases are developmental in nature without any known cause, the defect is prominent amongst athletes involved in sports requiring repetitive flexion–extension of the spine, such as gymnasts, football linemen and weightlifters (Ferguson et al., 1974; Jackson et al., 1976; Rossi and Dragoni, 1990; Standaert and Herring, 2000).

Most commonly affecting the L5 and L4 vertebrae, spondylolysis is postulated to arise from an accumulation of repetitive microtrauma (Farfan et al., 1976; Standaert and Herring, 2000). The inferior facets of the cephalad vertebra and the superior facets of the caudal vertebra impose contact stresses on the lamina of the index vertebra during lumbar extension, which may induce a stress fracture. This more commonly occurs in people with congenitally weak or dysplastic pars interarticularis during early childhood when the posterior arch is not completely ossified and the intervertebral disc is still very elastic, making the pars susceptible to fatigue failure (Roche and Rowe, 1951; Simper, 1986; Wiltse and Jackson, 1976).

Spondylolysis can progress to spondylolisthesis, but progression is uncommon in the presence of <30% slippage at prognosis, and rarely occurs after adolescence (Fredrickson et al., 1984; Seitsalo et al., 1991). In a 45 year follow-up evaluation study of 500 first-grade school children, Beutler et al. (2003) found that bilateral spondylolysis was more prevalent (73%) than unilateral spondylolysis (27%). The authors further found that unilateral spondylolysis never progressed to spondylolisthesis or disability, and in some cases self healing of the defect was also observed (Beutler et al., 2003).

From a biomechanical standpoint, it remains unclear whether a bilateral spondylolytic defect in lumbar spine intrinsically results in increased intervertebral translations during physiologic bending motions, or does the defect induces secondary changes in the load distribution and motion patterns amongst spinal elements, or a combination of both which may eventually lead to spondylolisthesis. A few biomechanical *in vitro* studies have quantified kinematic changes following a bilateral spondylolytic defect and immediate stability offered by various surgical treatment procedures, mostly using conventional metrics viz. range of motion (ROM), linear and angular extensions

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(Deguchi et al., 1999; Fan et al., 2010; Mihara et al., 2003). Additional metrics may however be necessary to capture full extent of the three dimensional trajectories traced by vertebral bodies, and any changes in intervertebral translatory motions following the defect. In this biomechanical *in vitro* assessment of a bilateral spondylolytic defect in lumbar spine, interpedicular metrics proposed by Cook et al. (2012) were further developed to capture bending-plane and out-of-plane projections of intervertebral translations.

The tests were performed on cadaveric kangaroo lumbar spine segments, which like other mammalian spines have morphological adaptations to accommodate specific biomechanical demands (Boszczyk et al., 2001). Despite perceived morphological differences, Alini et al. (2008) reported similarities in median axial torsion range of motion (ROM) between kangaroo and human lumbar spine segments. Kangaroo lumbar spines have been used previously in an *in vitro* biomechanical study to test the efficacy of a nucleus replacement implant (Sabet et al., 2010). Bipedal locomotion, comparable adult stature and mass, upright posture, and similarities in vertebral anatomy are some of the factors that make kangaroo an ideal animal model for the study of human lumbar spine (Brown et al., 1992; Hopwood, 1976; Kostuik, 1992).

The main objectives of this study were:

a) Using conventional metrics (range of motion (ROM) and neutral zone (NZ)), to evaluate global and segmental (defect and cephalad level) kinematic changes following a bilateral spondylolytic defect in lumbar spine during bending motions of flexion-extension (FxEx), bilateral bending (LB) and axial torsion (AXT).
b) Using modified interpedicular kinematics, to further assess whether a bilateral spondylolytic defect in lumbar spine results in increased bending-plane and/or out-of-plane intervertebral translations during the three different bending motions.

2. Methods

2.1. Specimen preparation and in vitro testing

Fourteen fresh frozen lumbar spines (L1–L6) were obtained from kangaroo cadavers of undetermined age and sex (Maverick Biosciences, Dubbo, Australia). Specimens were first externally examined for any damage, and then screened for bony abnormalities or fractures under a C-arm X-ray scanner (Zeihm Solo Mobile C Arm, Nuremberg, Germany). Seven specimens were selected after screening, and stored in double plastic bags until preparation and testing. The specimens were thawed overnight at 4 °C refrigeration and then left at ambient conditions for approximately 2 hours prior to preparation and testing. Following thawing, muscles and loose connective tissues were removed, with care taken to preserve the ligaments and the intervertebral discs. The specimens were then mounted with very-fast curing polyurethane (Barnes Products, Sydney, Australia) at the L1 and L6 vertebrae such that the L4–L5 disc was always horizontal. Three motion-capturing rigid bodies ('L'-shaped plexiglass plates with four non-collinear infrared light-emitting diodes) were mounted on the L3, L4, and L5 vertebrae with customized stainless-steel brackets and timber screws. A layer of Vaseline Dry Skin Conditioning Lotion (Vaseline Intensive Care —Unilever, London, UK) was applied prior to attachment to prevent dehydration during testing.

Testing was performed in a six-degrees-of-freedom kinematic spine simulator (Bose ElectroForce Systems, Framingham, USA). Each specimen was tested in the intact state (D_0) by applying non-destructive, unconstrained pure moments of ± 5 Nm (sinusoidal, 0.01 Hz) in the three anatomical bending planes. Two preconditioning cycles were used to overcome inherent viscoelasticity in the specimens, and data from the third cycle were used for analyses. After testing the specimen in the intact state, approximately 2 mm-wide spondylolytic defects were created in the pars interarticularis region bilaterally at L4 (D_1 state) using an oscillating saw (Bosch Power Tools, Stuttgart, Germany), followed by biomechanical testing (Fig. 1).

Although follower loads are sometimes used in *in vitro* biomechanical studies to simulate compressive forces in the spine, they were not employed in this study. For follower loads, the path of the loading cable must pass through the instantaneous center of rotation of each intervertebral segment, which is often difficult to achieve in motions other than FxEx (Goel et al., 2006; Patwardhan et al., 2003). A non-optimized follower load path can cause significant intervertebral rotations interfering with the motion due to pure moments.

Three-dimensional inter-segmental motion was recorded using 12 infrared markers and an opto-electronic motion tracking device (Optotrak Certus-Northern Digital, Waterloo, Canada), while global motion was recorded directly from the kinematic spine simulator. In addition to the real markers, virtual markers were also defined to track the motion of virtual landmarks at pedicles. Using manufacturer supplied 4 marker digitizing probe, the pedicles at L3, L4, and L5 vertebrae were digitized bilaterally relative to their respective rigid bodies so that the digitized points could be virtually tracked throughout testing (Fig. 2a). Interpedicular kinematic parameters were based on the coordinate data obtained by tracking these digitized points. The raw kinematics data in Cartesian coordinates were collected using the NDI First Principles data acquisition software (Northern Digital, Waterloo, Canada), and used to evaluate interpedicular position vectors ($\mathbf{r_1}$ and $\mathbf{r_2}$) and interpedicular travel (IPT) vector (Fig. 2). In the Cartesian system, the bending-plane projection of the IPT vector was represented in terms of two bending-plane coordinate components. To combine the two components into one, the IPT vector in Cartesian coordinates was converted into Cylindrical coordinates using a code written in Matlab (v. R2011b, Mathworks, Natick, USA), such that the radial component in the new system represented the bending-plane projection of the IPT vector and the axial component represented the out-of-plane projection. The bending plane Cartesian coordinate axes were used to define the r, and the θ axes for the Cylindrical coordinate system, and the out-of-plane Cartesian coordinate axis defined the z axis.

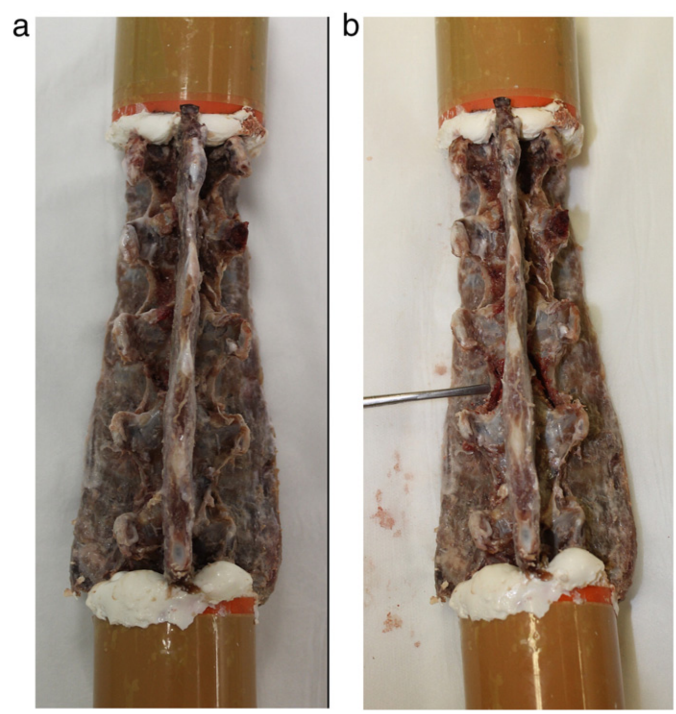

Fig. 1. a) Intact specimen; b) specimen after creating a bilateral spondylolytic defect at the L4 vertebra.