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Biomechanical Analysis of Acute Proximal Junctional Failure After Surgical Instrumentation of Adult Spinal Deformity: The Impact of Proximal Implant Type, Osteotomy Procedures, and Lumbar Lordosis Restoration*

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Abstract

Study design: Computer biomechanical simulations to analyze risk factors of proximal junctional failure (PJF) following adult scoliosis instrumentation.
Objective: To evaluate the biomechanical effects on the proximal junctional spine of the proximal implant type, tissue dissection, and lumbar lordosis (LL) restoration.
Summary of Background Data: PJF is a severe proximal junctional complication following adult spinal instrumentation requiring revision surgery. Potential risk factors have been reported in the literature, but knowledge on their biomechanics is still lacking to address the issues.
Methods: A patient-specific multibody and finite-element hybrid modeling technique was developed for a 54-year-old patient having undergone instrumented spinal fusion for multilevel stenosis resulting in PJF. Based on the actual surgery, 30 instrumentation scenarios were derived and simulated by changing the implant type at the upper instrumented vertebra (UIV), varying the extent of proximal osteotomy and the degree of LL creation. Five functional loads were simulated, and stresses and strains were analyzed for each of the 30 tested scenarios.
Results: There was 80% more trabecular bone with stress greater than 0.5 MPa in the UIV with screws compared to hooks. Hooks allowed 96% more mobility of the proximal instrumented functional unit compared to screws. The bilateral complete facetectomy along with posterior ligaments dissection caused a significant increase of the range of motion of the functional unit above the UIV. LL creation increased the flexion moment applied on the proximal vertebra from 7.5 to 17.5 Nm, which generated damage at the bone-screw interface that affected the screw purchase.
Conclusion: Using hooks at UIV and reducing posterior proximal spinal element dissection lowered stress levels in the proximal junctional spinal segment and thus reduced the biomechanical risks of PJF. LL restoration was associated with increased stress levels in postoperative functional upper body flexion.

Keywords: Spine deformity; Instrumentation; Proximal junctional failure; Biomechanical modeling

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Introduction

One of the complications of both adolescent and adult spinal fusion surgery is the postoperative development of proximal junctional kyphosis (PJK), an abnormal kyphotic deformity of the spinal segment proximally adjacent to the instrumentation [1,2].

The proximal junctional spinal segment (PJSS) was defined as the spinal segment between the caudal endplate of the upper instrumented vertebra (UIV) and the cephalad endplate of the noninstrumented vertebra two levels above the UIV (UIV+2) [1]. The PJK is abnormal if the angle of the PJSS is equal to or greater than 10° and at least 10° greater than the preoperative measurement [1]. The definition of PJK, its incidence, and causes are variable in the literature [3]. In adult spinal deformity patients, the postoperative proximal junctional changes are frequently clinically symptomatic and can lead to the need for revision surgery [4-6].

Based on the severity of PJK, a subset of patients has been identified with a more severe form of PJK that was referred to as proximal junctional failure (PJF) [6,7]. The pathologic changes to PJF may occur early after the initial surgery and can be in the forms of compromised structural integrity, neurologic deficit [7], topping-off syndrome (junctional compression fracture, subluxation, retrolisthesis, focal kyphosis, and disc height loss) [8], proximal junctional acute collapse [9], and fractures at the top of long segmental instrumentation constructs [10], and would need to be addressed through revision surgery. Advanced age (eg, >75 years), osteopenia, preoperative comorbidities, sagittal balance, fusion to the sacrum, level of upper instrumented vertebra (UIV), proximal junctional dissection, and use of pedicle screw at UIV have been associated with the risks of PJF [5,7,9-16]. A retrospective review of a large adult spinal deformity database revealed that the strongest PJF predictors were age, lower instrumented vertebra (LIV), UIV, preoperative sagittal vertical axis (SVA), implant type at UIV, preoperative pelvic tilt (PT), and preoperative difference between pelvic incidence (PI) and lumbar lordosis (LL) [17]. Based on these baseline demographic, radiographic, and surgical factors, a computer expert-system-like model was built that can predict PJF and clinically significant PJK with 86% accuracy based on 510 adult spinal deformity patients with 2-year follow-up [17]. However, biomechanical studies on individual identified risk factors are very limited. The pathomechanisms of PJK were studied using multibody numerical modeling and design of experiment techniques [18,19], which provided useful biomechanical facts by assessing the resultant proximal junctional force, moment and kyphotic angle as functions of UIV, proximal implant type, osteotomy procedure, transition rod diameter, sagittal balance, and sagittal rod curvature. A hybrid multibody and finite-element modeling technique was developed and a preliminary model was tested; the model allowed simulation of spinal instrumentation and postoperative loads, which constitutes an effective tool to further investigate proximal junctional failure pathomechanisms [20]. However, stresses across the vertebral bone, intervertebral disc, intervertebral ligaments, facet joints, bone-implant interface, implants, and rods are yet to be evaluated in order to acquire fundamental biomechanical knowledge necessary to improve construct design, instrumentation configuration, and surgical techniques.

The objective of this study was to develop a detailed patient-specific computational model and characterize stresses across the PJSS associated with different implant types at UIV, osteotomy procedures, and LL creation in adult spinal instrumentations.

Methods

A hybrid computational modeling technique was developed to characterize the biomechanical stresses across the intervertebral structures and bone−implant interface of the PJSS. A previously developed multibody model (MBM) [18,19] was first refined to simulate patient-specific spinal instrumentation, compute the instrumentation correction, simulate different physiological loads and movements, and estimate the resultant forces and moments within the PJSS. Then, a highly detailed finite-element model (FEM) of three vertebrae at the PJSS was created to further investigate PJF pathomechanisms, and perform detailed stress and failure analyses across the bone-implant interface and within the vertebral bone, intervertebral discs and ligaments, and facet joints. The modeling framework is illustrated in Figure 1. The modeling and simulation details are presented in the following subsections.

Patient-specific spine geometric model

A three-dimensional (3D) geometric model of the spine was built for a 54-year-old patient having undergone spinal fusion instrumentation and subsequently having had PJF. This was done using the patient's preoperative posteroanterior (PA) and lateral (LAT) plain radiographs (Figure 2) and 3D multiview reconstruction techniques [21]. The process began with the identification, on both radiographs, of key anatomical landmarks of each vertebra, typically pedicle, vertebral endplate middle and corner points, and transverse and spinous process extremities. The two-dimensional (2D) coordinates of these landmarks on the two radiographs allowed the determination of their 3D coordinates in space, which was done using self-calibration and optimization algorithms [21,22]. The reconstruction process was completed by registering detailed vertebral geometric models using the 3D coordinates of the key landmarks and a free-form deformation technique [21,22]. Average accuracy for pedicles and vertebral bodies is 1.6 mm (standard deviation 1.1 mm) and 1.2 mm (standard deviation 0.8 mm), respectively [22].

Patient-specific MBM

Base model

Each of the vertebrae from T1 through L5 and the pelvis was modeled as a rigid part using its reconstructed geometry. These rigid parts were connected through flexible elements