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Instrumentation Strategies to Reduce the Risks of Proximal Junctional Kyphosis in Adult Scoliosis: A Detailed Biomechanical Analysis

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Abstract

Study Design: Biomechanical analysis of proximal junctional kyphosis (PJK) through numerical simulations.
Objectives: Assessment of the effect of sagittal alignment, the upper instrumented vertebral level (UIV), and 4 other surgical variables on biomechanical indices related to the PJK risks.
Summary of Background Data: Despite retrospective clinical studies, biomechanical analysis of individual parameters associated with PJK is lacking to support instrumentation strategies to reduce the PJK risks.
Methods: Instrumentations of 6 adult scoliosis cases with different operative strategies were simulated (1,152 simulations). Proximal junctional (PJ) angle and flexion loads were evaluated against the sagittal alignment and the proximal instrumentation level.
Results: Instrumenting 1 more proximal vertebra allowed the PJ angle, proximal moment, and force to be reduced by 18%, 25%, and 16%, respectively. Shifting sagittal alignment by 20 mm posteriorly increased the PJ angle and proximal moment by 16% and 22%, and increased the equivalent posterior extensor force by 37%. Bilateral complete facetectomy, posterior ligaments resection, and the combination of the 2 resulted in an increase of the PJ angle (by 10%, 28%, and 53%, respectively), flexion forces (by 4%, 12%, and 22%, respectively), and proximal moments (by 16%, 44%, and 83%, respectively). Transverse process hooks at UIV compared with pedicle screws allowed 26% lower PJ angle and flexion loads. The use of proximal transition rods with proximal diameter reduced from 5.5 to 4 mm slightly reduced PJ angle, flexion force, and moment (less than 8%). The increase in sagittal rod curvature from 10° to 40° increased the PJ angle (from 6% to 19%), flexion force (from 3% to 10%), and moment (from 9% to 27%).
Conclusions: Simulated posteriorly shifted sagittal alignment was associated with higher PJK risks, whereas extending instrumentation proximally allowed a lower mechanical risk of PJK. Preserving PJ intervertebral elements and using a more flexible anchorage at UIV help reduce the biomechanical risks of PJK.

Keywords: Proximal junctional kyphosis; Adult scoliosis; Surgical simulation; Biomechanical modeling; Spinal deformity

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Introduction

One of the undesirable consequences of spinal instrumentation for deformity treatment is proximal junctional kyphosis (PJK) [1,2]. Proximal junctional kyphosis is an abnormal kyphotic deformity of the proximal junctional spinal segment (PJSS) between the inferior end plate of the upper instrumented vertebra (UIV) and the superior end plate of (UIV + 2) greater than or equal to 10°, and 10° greater than the preoperative value [2]. The PJK prevalence is between 20% and 39% in adult instrumentations [1,3-5], between 26% and 35% in adolescent idiopathic scoliosis (AIS) instrumentations [2,6,7], and about 30% in instrumentations for Scheuermann kyphosis [8]. PJK reportedly accounted for 51.9% of unplanned readmissions within 90 days from surgery at a single institution from 2006 through 2011 among patients who received a spine fusion for the treatment of adult spinal deformity [9]. In AIS and Scheuermann kyphosis instrumentations, posterior elements disruptions were thought to be important factors of PJK [8,10]. A similar hypothesis was brought forward based on findings that the incidence of PJK in posterior instrumentations was higher than that in anterior instrumentations [3,7]. Some clinical studies found that the incidence of PJK was higher in all–pedicle screw instrumentations compared with hook and hybrid constructs, which suggests that PJK might be associated with high mechanical stresses because of the high-rigidity instrumentation systems [2,5,6,10,11]. Fusion levels, especially the inclusion of the sacrum, were thought to have an important role in PJK [3,5,12]. Other risk factors include higher correction forces applied intraoperatively to restore the sagittal alignment [3,6], age over 55 years [5], accelerated joint capsule degeneration [3], thoracoplasty [1], obesity [13], poor bone quality [12,13], and preoperative comorbidities [12].

The effects of proximal dissection, implant type, rod curvature, and proximal diameter of transition rods have been investigated through numerical simulations [14]. However, the biomechanical role of sagittal alignment and fusion levels is unclear. PJK risk analyses have mainly been performed through retrospective clinical and limited biomechanical studies; studies on the effects of additional independent variables need to be conducted. The objectives of this study were to further assess the biomechanical effects of independent variables involved in PJK and identify its potential biomechanical risk factors.

Materials and Methods

This study was performed through numerical simulations of spinal instrumentations and postoperative functional loadings of 6 adult scoliosis patients using a previously validated patient-specific spine modeling technique [14-17]. Modeling and simulation details are provided in the following subsections.

Biomechanical modeling of patient-specific scoliotic spine

The three-dimensional (3D) spine geometries of the 6 adult scoliosis patients were reconstructed using their calibrated plain radiographs and 3D reconstruction techniques [18,19]. In brief, posteroanterior and lateral radiographs were taken with the patient wearing a calibration plate carrying radiopaque pellets. The calibration pellets and 14 anatomical landmarks (2 on the tips of each pedicle and 4 on the periphery and 1 at the center of each vertebral end plate) were manually identified on each vertebra. Coordinates of these pellets and anatomical landmarks were computed using a self-calibration and optimization algorithm [19]. For each vertebra, a detailed vertebral geometry model was registered using those landmarks and a freeform deformation technique [19]. The reconstruction accuracy is 3.3 mm on average (standard deviation, 3.8 mm) when considering all landmarks, but much better for the pedicles (1.6 ± 1.1 mm) and vertebral bodies (1.2 ± 0.8 mm) [20]. The reconstruction variations of a given scoliotic spine in terms of Cobb angles (0.6° or less), kyphosis, and lordosis (6.7° or less) are within the error levels reported for equivalent 2D measurements used by clinicians [20,21].

Vertebrae and pelvis were modeled as rigid bodies based on the assumption that the bone deformation was negligible compared with intervertebral displacement during instrumentation and under functional loadings. The intervertebral elements, primarily the intervertebral disc, intervertebral ligaments, and the facet joints, were represented with flexible connectors that used parametric curves to relate the intervertebral displacement to the intervertebral load. Intervertebral load–displacement data were acquired through mechanical tests on cadaveric spines [22,23]. Then, these parametric curves were adjusted to the patient's specific spinal flexibility by tuning the defining data such that side bending simulations reproduced the Cobb angles measured on the patient's side bending radiographs [15,24,25].

At the distal end, boundary conditions were applied by fixing the pelvis. At the proximal end, spring elements linked with the global frame of reference were introduced at the first 3 thoracic vertebrae to globally represent the posterior extensor–flexor muscle actions needed to counterbalance the gravity and maintain a given posture. The mechanical properties of these springs were determined through multiple runs of simulations such that the spine attained equilibrium at a given sagittal alignment. The resulting forces were interpreted as an estimate of the resultant extensor–flexor forces needed to maintain this given sagittal alignment. Gravitational forces were modeled by applying to each vertebra a gravitational force whose magnitude was specifically proportional to the body weight, as reported in Pearsall's anthropometric model [26] (Table 1). The application point was positioned anteriorly with respect to the vertebral center of mass as reported in Kiefer et al. [27] (Table 1).