Push or Pull, That Is the Question -
Understanding Anterior Vertebral Body Tethering Through Stresses in the Vertebral Growth Plates

Minhao Zhou[1], Yousuf Abubakr[1], Max H. Twedt[3], Ellen M. Leiferman[4], Thomas D. Crenshaw[4], James Sypherd[5], Susan M. Hamman[5], Matthew A. Halanski [5,6], Grace D. O'Connell[1, 2]

[1]University of California-Berkeley, Berkeley, CA, [2]University of California-San Francisco, SF, CA, [3]University of Nebraska Medical Center, Omaha, NE, [4]University of Wisconsin-Madison, Madison, WI, [5]Phoenix Children's Hospital, Phoenix, AZ, [6]University of Arizona, Phoenix, AZ
halanski@arizona.edu/g.oconnell@berkeley.edu

Disclosures: The authors have nothing to disclose.

INTRODUCTION: Idiopathic scoliosis is among the most common spinal disorders in children, affecting up to 5% of the adolescent population [1]. With its capability to control curve progression and low revision rate, posterior spinal fusion (PSF) has been the gold standard for adolescent idiopathic scoliosis [2-3]. However, PSF is a highly invasive procedure with notable biomechanical concerns due to the loss of mobility and growth at the fused spinal levels [4]. Utilizing growth modulation, anterior vertebral body tethering (AVBT) harnesses the patient's growth potential to correct spine deformity and has been examined as a mobility- and growth-friendly alternative to PSF. Unfortunately, AVBT has yet to yield consistent clinical outcomes. Compared to PSF, the AVBT cohort showed significantly more residual deformity after five years, with more than 25% of the patients eventually requiring PSF [3]. Thus, there is a need to better understand how different intraoperative parameters might affect vertebral growth behavior to improve AVBT efficacy. To do this, we combined a spontaneous kyphotic porcine model as an analog for human spine deformity with a finite element model of the bone-disc-bone motion segment to examine the effect of postoperative disc heights on growth plate stress distributions [5]. We hypothesized that a reduced postoperative disc height suggests excessive compression on the vertebral growth plates due to tethering, indicating compromised differential growth capabilities.

METHODS: Finite element models of bovine caudal disc motion segments were created based on our previous work (**Fig. 1A**) [6]. Boundary and loading conditions were defined such that a motion segment of a 10° scoliotic angle was corrected by simulated tethering in the form of rotation and translation applied through the top vertebral body, mimicking AVBT procedures (**Fig. 1A**). Simulated tethering aimed to realign the motion segment with different disc heights after the realignment. Model-predicted intradiscal pressure and tether load were compared to the kyphotic porcine model data and data in the literature for validation [5-7]. Fluorochrome labeling with Alizarin complexone and oxytetracycline was performed to track the growth modulation at the vertebral growth plates. Disc geometry (i.e., mid-sagittal disc height) and growth plate stress distributions, which were compared to growth plate growth modulation data measured in bovine caudal vertebrae [8], were evaluated after the simulated tethering.

RESULTS: Model-predicted intradiscal pressure and tether load agreed well with both kyphotic porcine model data and reported literature data (**Fig. 1B & C**). A torque about the y-axis combined with displacements along the x- and z-axes was required or motion segment realignment (**Fig. 1A**). Fluorochrome labeling was able to track the vertebral growth plate differential growth over a 10-14-day time frame (**Fig. 1D**). Model predictions demonstrated that tethering procedures that maintained the mid-sagittal disc height generated an effective differential growth stress gradient across the vertebral growth plates (i.e., facilitated and reduced growth at the convex and concave sides of the growth plates with minimum arrested growth, **Fig. 1E**). While reducing the disc height by ~20% still generated a differential growth stress gradient, 50%+ of the growth plates were in arrested growth (**Fig. 1E**). Further compressing the disc was expected to shut down the growth modulation mechanisms, as almost the entire growth plates were under arrested growth.

DISCUSSION: This study demonstrates that the long-term results of AVBT heavily depend on the tether-induced growth plate stress magnitudes and their relationship to facilitated, reduced, or arrested growth with growth modulation. Current AVBT procedures rely heavily on segmental compression for deformity correction [9]. Findings from the current work highlight that the growth plates are subjected to arrested growth under large tether load (i.e., excessive compression to the growth plates), which might help explain the lack of long-term differential growth-based curve correction observed in the current clinical setting, including significant residual deformity, high revision rates due to overcorrection or curve progression [10-12], and insignificant differential growth of the deformed spine [13]. While additional data are needed to validate kyphotic porcine model differential growth data against model predictions, future work will determine whether this modeling approach can be used to predict AVBT outcomes with different surgical planning decisions (e.g., the potential benefits of exploring a distractor-oriented 'push'-based tethering setup to help prevent excessive compression applied to the vertebral growth plates).

SIGNIFICANCE/CLINICAL RELEVANCE: AVBT provides a promising growth- and mobility-friendly alternative to PSF to correct spinal deformities in the adolescent population. Findings from this study suggest that successful long-term AVBT outcomes require accounting for the applied tether load to understand the impact of tethering on vertebral growth plate stress distributions and growth modulation behavior.

REFERENCES: [1] Konieczny+, 2013; [2] Larsen+, 2019; [3] Newton+, 2020; [4] Martin+, 2014; [5] Halanski+, 2018; [6] Zhou+, 2021; [7] Lalande+, 2020; [8] Stokes et al; [9] Wong+, 2019; [10] Newton+, 2018; [11] Kuznia+, 2020; [12] Shin+, 2021; [13] Farivar+, 2023.
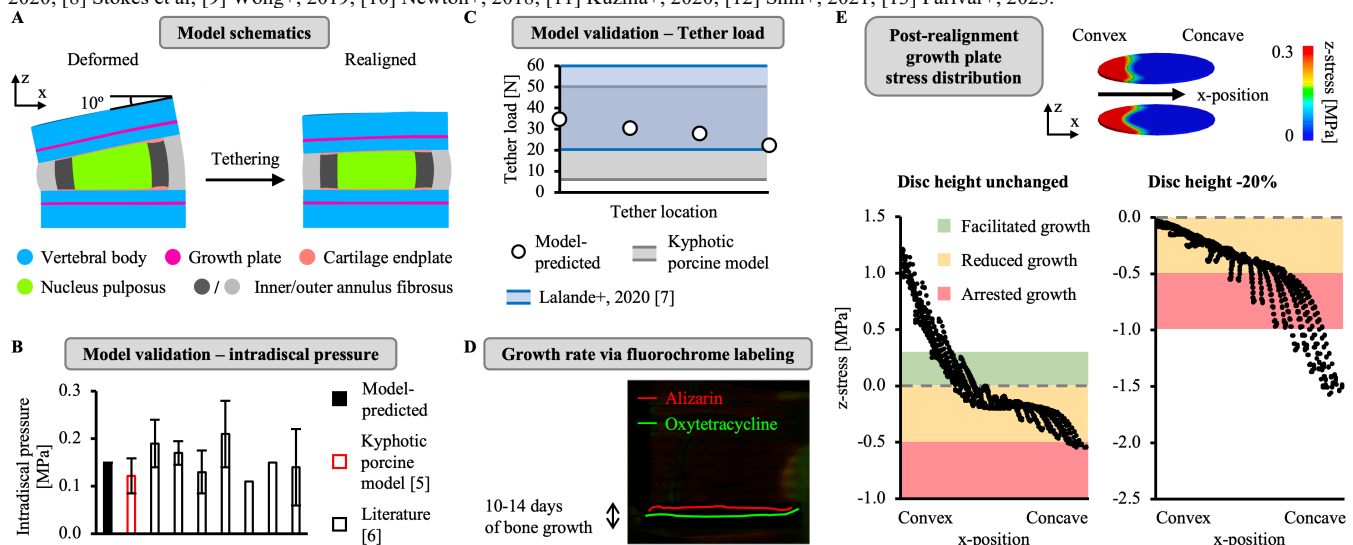
Fig. 1: (A) Schematics of the novel structure-based motion segment FEM demonstrating in silico deformity correction from a deformed (left) to a realigned state (right). (B & C) Model-predicted intradiscal pressure and tether load compared to kyphotic porcine model data and literature data [5-7]. (D) Fluorochrome labeling showing vertebral growth within a 10-14-day time frame. Oxytetracycline was administered 3-7 days after Alizarin to label and determine bone growth occurred during the time frame. (E) Model-predicted growth plate z-stress distributions with unchanged and 20% reduced post-realignment disc height. Stress-based tissue growth predictions are determined based on data from [8].