

Quantifying 3D Spinal Deformity Corrective Moment and Spine Stiffness in Children with Spinal Muscle Atrophy

Dennis E. Anderson^{1,2}, Lennert Plasschaert^{2,3,4}, Hiroko Matsumoto^{2,3,4}, Ryan Murdock⁵, Brian Snyder^{1,2,3}

¹Beth Israel Deaconess Medical Center, Boston, MA, USA; ²Harvard Medical School, Boston, MA, USA; ³Boston Children's Hospital, Boston, MA, USA;

⁴Ghent University Hospital, Ghent, Belgium; ⁵Thinks Works, PBC, Chicago, IL, USA

Email: dennis.earl.anderson@gmail.com

Disclosures: Dennis Anderson (N), Lennert Plasschaert (N), Hiroko Matsumoto (N), Ryan Murdock (N), Brian Snyder (N)

INTRODUCTION: Neuromuscular spinal deformity (NMSD), prevalent in ~90% of children afflicted by spinal muscular atrophy (SMA), is a multi-planar, 3D, helical distortion of the vertebra and rib cage, owing to warping, twisting and bending induced by the differential orientation of the posterior facets (coronal plane for thoracic spine, sagittal plane for lumbar spine) and soft tissue connections (muscles, ligament, intervertebral disc (IVD)). While the deformity is best described in a helical coordinate system, bi-planar X-rays (Figure 1) obtained in a cartesian anatomic coordinate system portray the complex 3D spinal deformity as scoliosis when projected onto the coronal plane and kyphosis when projected in the sagittal plane. Most of the spine deformity occurs predominantly in the non-osseous IVD, with subsequent deformity of the bony vertebrae developing later, after significant spinal deformity has already occurred. NMSD is often accompanied by pelvic obliquity and rib cage distortion that contribute to physical disability, cardiopulmonary compromise, reduced health-related quality of life, and early mortality. Spinal bracing provides a non-operative treatment for spinal deformity that may delay or reduce the need for corrective spine surgery by superimposing asymmetric corrective forces and bending moments on the dynamic forces and moments that the spine is typically exposed during daily activities, inducing correction of spinal deformity through viscoelastic CREEP. Bracing is effective in managing adolescent idiopathic scoliosis [1], but prior studies of its effectiveness in SMA [2,3] are limited by methodological constraints and have not included modern 3D thoraco-lumbar-sacral-orthosis (TLSO, Figure 1). Effective treatment of NMSD using a 3D TLSO requires careful consideration of the 3D nature of spine pathoanatomy, the stiffness of the deformity, and planning where to place and direct corrective bending moments to effectively "straighten" the deformity. The aim of this study was to produce biomechanical estimates of 3D NMSD stiffness and corrective moment magnitude and orientation as a function of patient age and BMI to individualize the corrective moments applied to the distorted spine by the TLSO.

METHODS: This single-center, IRB approved, retrospective study included patients with SMA being treated by halo gravity traction (HGT) for severe spine deformity prior to spinal instrumentation. Biplanar seated spine x-rays were analyzed in the coronal and sagittal plane before and after HGT. In each view the Cobb angle of the major curve, the number of vertebrae subtended by the curve and the offset (cm) of the curve apex from the C7 plumb line were measured. Assuming a single 3D deformity when the apices of the curves on bi-planar images were coincident within 3 vertebral levels, the 3D deformity angle θ_M was calculated from the scoliosis Cobb (θ_S), and kyphosis Cobb (θ_K): $\theta_M = 2 \times \tan^{-1}(\sqrt{\tan^2(\theta_S/2) + \tan^2(\theta_K/2)})$. The moment arm for the axial distraction moment applied by HGT force (N) was calculated from the hypotenuse of the distances of the apex of the deformity in the coronal and sagittal planes to the C7 vertical plumb line. The distraction moment applied to the global deformity was corrected by subtracting the moment due to the body mass above the curve apex, estimated for each patient using age-specific musculoskeletal models [4]. The orientation of the applied corrective moment was calculated from the angle produced by the offset distance of the 3D curve apex from the C7 plumb line in the axial plane, where 0° indicates 100% extension moment and 90° a lateral bending moment. Deformity stiffness was calculated from the applied corrective moment and the corresponding change in θ_M before vs. after application of HGT ($\Delta\theta_M$). The change at each IVD was estimated by distributing the total $\Delta\theta_M$ among the number of vertebrae subtended by the curve, assuming a normal distribution and that the greatest change occurred at the curve apex. Non-linear stiffness of IVD was assumed, using a cubic form [5]. Associations of corrective moment magnitude, orientation, and IVD stiffness with age and modified BMI were examined using linear regressions. Only linear elastic component of stiffness was examined in these analyses.

RESULTS: 3D NMSD was analyzed for 20 patients (15 male, 5 females, mean±SD age 8±4 years). Characteristic of SMA, spine pathoanatomy was thoracic and thoracolumbar, with the apices ranging anatomically from T6 – T12. Prior to HGT $\theta_M = 124 \pm 19^\circ$, improving ~40% to $75 \pm 16^\circ$ with HGT. The applied HGT load was 125 ± 51 N, or $55 \pm 10\%$ body weight, corresponding to a corrective moment of 16 ± 10 N-m (range 6.7–41.1 N-m), at an orientation angle of $53 \pm 17^\circ$ (range 21–80°). Elastic IVD stiffness was 1.11 ± 0.88 N-m/° (range 0.26 – 4.01 N-m/°). Corrective moment magnitude ($p < 0.001$), moment orientation ($p = 0.018$) and stiffness ($p = 0.002$) increased with age (Table 1, Figure 2). Corrective moment magnitude ($p < 0.001$) and stiffness ($p = 0.027$) varied with BMI, but moment orientation did not ($p = 0.709$).

DISCUSSION: While these SMA patients had severe spine deformity, being treated with HGT prior to surgery, this biomechanical analysis provides proof of concept for determining 3D NMSD stiffness and the necessary corrective moment that must be applied to straighten the deformity when planning surgery or designing a TLSO. The *in-vivo* estimation of global deformity and IVD stiffness is novel. Published point estimates for elastic IVD stiffness, based on cadaveric testing in adult spines [5], range from 0.89 – 3.55 N-m/° in the lower thoracic spine (T6 – T12). The stiffnesses estimated here are similar but generally lower, which is reasonable as the patients are children. This analysis incorporated several assumptions to estimate spinal mechanics. While a non-linear form was used for IVD stiffness, assumptions were made of uniformity of stiffness among IVD levels in sagittal vs coronal planes of motion. Moreover, IVD stiffness is altered by compressive loading [5], thus distraction HGT could affect IVD stiffness and observed angular change differently than a pure moment would. Finally, the analysis did not account for axial rotations, as this is less reliably evaluated from planar x-rays.

SIGNIFICANCE/CLINICAL RELEVANCE: *In-vivo* quantitative data on 3D global deformity stiffness and the required 3D corrective moments are limited, particularly for patients with SMA. Using known axial distractive forces applied to the deformed spine and corresponding radiographic changes in 3D curvature we quantified the stiffness of NMSD and estimated the applied corrective moments. These data can be used to inform treatment, determining whether the curve is too stiff for bracing, and guiding 3D TLSO design to optimize multi-planar spine deformity correction in neuromuscular patients with early onset scoliosis.

REFERENCES: 1. Weinstein et al. N Engl J Med. 369(16):1512-1521, 2013. 2. Morillon et al. Ann Readapt Med Phys. 50(8):645-50, 2007. 3. Kling et al. Clin Orthop Relat Res. 159:208-210, 1981. 4. Schmid et al. J Biomech, 102:109305, 2020. 5. Zhang et al. J Biomech, 100: 109579, 2020.

Table 1: R² values of associations with Age and Modified BMI

	Age	Modified BMI
Moment Magnitude	0.57	0.51
Moment Orientation	0.27	0.01
Linear Stiffness	0.41	0.24



Figure 1: Analysis of bi-planar x-ray to quantify 3D deformity can support 3D TLSO design.

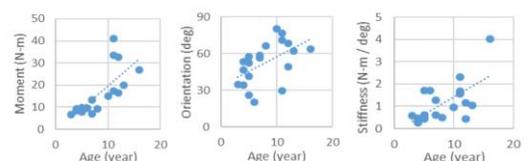


Figure 2: Plots and linear regression lines of Moment Magnitude, Moment Orientation (0 = extension, 90 = lateral), and Linear Intervertebral Stiffness versus Patient Age.