

The Moments That Matter: Paraspinal Muscle Architecture and Spinal Loading in Adolescent Idiopathic Scoliosis

Phoebe Duncombe¹, Taylor JM. Dick¹, Bart Bolsterlee^{2,3}, Maree T. Izatt^{4,5}, Robert D. Labrom^{4,5}, Kylie Tucker¹

¹ The University of Queensland, Brisbane, Australia; ² Neuroscience Research Australia, Sydney, Australia; ³University of New South Wales, Sydney, Australia; ⁴Biomechanics and Spine Research Group at the Queensland University of Technology, Brisbane, Australia; ⁵Orthopaedics Department, Queensland Children’s Hospital, Brisbane, Australia
phoebe@duncombe.net.au

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INTRODUCTION: Adolescent idiopathic scoliosis (AIS) is characterized by an asymmetrical spinal curvature that develops rapidly during adolescence [1]. The magnitude and direction of the forces applied to the skeleton during development are key moderators of growth [2]. Muscle moments are determined from the product of i) the magnitude of the mechanical forces generated by muscles and ii) the direction and distance that these forces are applied to vertebrae [3]. Here, we aim to quantify the potential moments generated by multifidus and longissimus muscles in flexion-extension, lateral bending, and axial rotation directions at 10 vertebral levels and to determine whether these moments differ between adolescents with AIS and age-matched controls with symmetrical spines.

METHODS: T1-weighted and diffusion-tensor MRI scans were conducted on female participants with either primary-right-thoracic AIS (n=29, mean±SD age: 13.3±1.8 years, Lenke 1A-C) or typically developing spines (controls: n=16, mean±SD age: 13.3±1.8 years). Only female participants were included due to the higher prevalence and greater curve severity of AIS in females [1]. Using anatomically constrained fibre tractography (an MRI post-processing technique to visualize a muscle’s 3D fascicle architecture), multifidus and longissimus fascicles were reconstructed from the 5th thoracic (T5) to the 2nd lumbar vertebra (L2). Muscle fascicle length, physiological cross-sectional area (PCSA = muscle volume/fibre length), moment arm, maximal isometric force ($F = PCSA \times \text{Specific tension}$) and muscle moment-generating potential were determined. Linear mixed-effects models were used, and between-group effects (AIS vs Control) were evaluated using Wald t-tests on the fixed effects, with statistical significance set at $\alpha = 0.05$. Effect sizes were quantified using Hedges-corrected Cohen’s d with 95% confidence intervals. Ethics approval was granted by both hospital and university human research ethics committees.

RESULTS SECTION: Muscle moment asymmetries were identified in AIS compared to controls for: multifidus in lateral bending, with greater left-directed moments at T5-T9 and right-directed moments at L1-L2 (Figure 1A); and axial rotation with a rightward bias moment at T6 and a leftward bias moments from T8-T12 (Figure 1B); and longissimus in lateral bending, with greater right-directed moments only at T12; and axial rotation with a rightward bias moment at T10 and a leftward bias moment at T12. All $p < 0.05$.

Counterfactual modelling (to explain causation and predicted moment outcomes) indicated that the lateral-bending moment asymmetry is primarily attributable to the muscle fascicle moment arm, which is related to spine curvature. In contrast, axial rotation moment differences were attributed to the force-generating capacity of the paraspinal muscles. Moderate associations ($R > 0.40$) with scoliosis curve angle were most evident in multifidus, particularly in lateral bending and axial rotation on the right side. Collectively, these findings implicate multifidus as the dominant contributor to muscle-related moment asymmetry in AIS.

DISCUSSION: This study provides evidence that the moment-generating potential of paraspinal muscles are asymmetrical in AIS, and that these asymmetries are associated with altered muscle force generation and moment arms along the spine. Our findings provide evidence that the paraspinal muscles may not simply mirror the spinal deformity but actively contribute to its progression by producing imbalanced forces within the range capable of modulating vertebral growth [4]. This supports the hypothesis that muscle-driven mechanical loading contributes to the vicious cycle of AIS progression. These interpretations should be considered in light of key limitations, including the restricted imaging field of view, cross-sectional study design, reliance on adult biopsy data for specific tension estimates, and the assumption of symmetrical maximal muscle activation.

SIGNIFICANCE/CLINICAL RELEVANCE: Adolescents with idiopathic scoliosis exhibit muscle- and vertebral-level-specific asymmetries in paraspinal muscle-generated forces and moment-generating potential, suggesting that these muscles may function as active contributors rather than passive responders in curve progression. These findings highlight the potential to identify markers of muscle-focused dysfunction and develop targeted, muscle-specific interventions to resist further asymmetry and mitigate AIS progression.

REFERENCES: [1] Negrini, S et al. (2016). *Scoliosis Spinal Disord*, 13(1): 3; [2] Stokes IAF. et al. (1996) *Spine* 21, 1161-1167; [3] Crouzier M. et al. (2020) *Med Sci Sports Exerc*. 52(5):1076-1087. [4] Frost, H.M., 1990. *The Anatomical record* 226, 423-432.

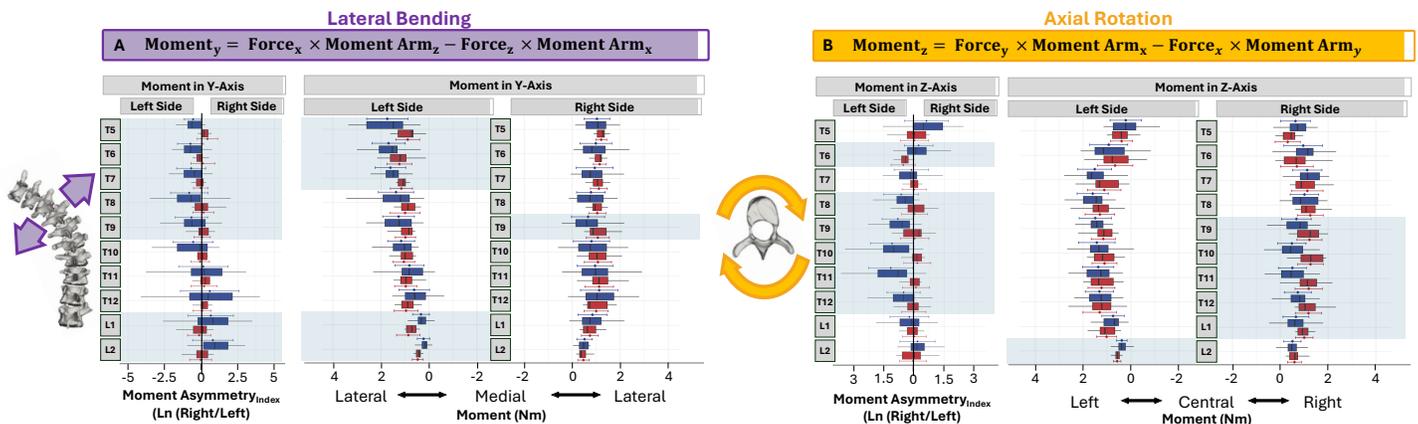


Figure 1: Comparison of AIS (Blue) and Control (Red) groups multifidus moment Asymmetry_{index} and left and right-side muscle moment potential by vertebral level of origin. Mean (♦) and SD (L). Boxplot: Median and IQR. n=16-29. Significant between-group differences highlighted in blue shading, $p < 0.05$.