The Role of Mechanical Loading in Proximal Junctional Failure: Influence of Gravity and Sagittal Alignment

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INTRODUCTION: Proximal Junctional Failure (PJF) is a well-recognized complication in adult spinal deformity (ASD) surgery, with an incidence of ~10% within two years postoperatively. Mechanical loading above the UIV has been implicated in junctional failure mechanisms, but its role in PJF onset and progression remains unclear. This study aims to investigate the relationship between mechanical loading from gravity at the UIV and the occurrence of proximal failure.

METHODS: This study is a retrospective review of prospectively collected data. ASD surgically treated with a posterior fusion from pelvis to at least L1, with a minimum of 2-year follow-up were retrospectively analyzed. A validated mechanical model estimating the gravity line (GL) in the sagittal plane was applied to three sagittal alignment configurations: preoperative, postoperative, and simulated postoperative without PJK (Figure 1). GL-to-disc distances were measured and compared between upper thoracic (UT: T2-T5) and lower thoracic (LT: T9-T11) UIVs. Proximal failure was defined as a proximal extension of instrumentation or severe radiographic PJK (PJA >28°, ΔPJA >22°). GL-to-UIV distances were analyzed in patients with and without proximal failure. Mechanical loading at the UIV was estimated before and after PJA reciprocal changes.

RESULTS:

678 patients were included (64 ± 10 yo; 81% F). SRS classification indicated moderate-to-severe deformities (38.9% N, 36.6% L, 22.4% D; PI-LL Modifier: 22.3% +, 52.2% ++; SVA Modifier: 31.1% +, 38.5% ++). Proximal failure occurred in 14.9% (6.2% proximal extension, 9.3% severe PJK.

With surgical realignment, pre-to-post analysis revealed distinct trends in spinal alignment relative to the gravity line (GL), with the thoracic spine moving further from the GL while the thoracolumbar spine moved closer (Figure 2). Postoperatively, thoracic spines in LT patients were closer to the GL, whereas thoracolumbar spines in UT patients were closer to the GL, except at T7-T8 (p=0.924), the crossover point. However, after numerically removing PJA reciprocal changes, no significant differences were detected at T3-4 to T7-8 and L3-4 to L5-S1 (p>0.05), suggesting similar shapes between UT and LT groups. For UT patients, the GL-to-UIV distance was significantly greater in those with proximal failure, both before and after accounting for PJA reciprocal changes (Before: 44 ± 17mm vs. 52 ± 17mm, p=0.046; After: 57 ± 25mm vs. 74 ± 26mm, p<0.001). In LT patients, the GL-to-UIV distance was significantly greater only after accounting for PJA reciprocal changes (Before: 51 ± 23mm vs. 51 ± 21mm, p=0.874; After: 71 ± 22mm vs. 95 ± 25mm, p<0.001). After stratification by UIV position, mechanical loading at the UIV differed between patients with and without proximal failure (Table 1). Patients with proximal failure exhibited greater anterior tangential forces and larger bending moments compared to those without (p<0.05). After accounting for PJA reciprocal changes, these differences disappeared, except for the UT bending moment, which remained significant (p=0.017).

DISCUSSION AND CONCLUSION: Proximal failure affected 14.9% of patients, with 6.2% requiring proximal extension and 9.3% developing severe PJK. PJA reciprocal changes increased the distance between the GL and UIV, with this effect being more pronounced in patients with proximal failure, leading to altered mechanical loading. While gravity-induced mechanical loading does not appear to initiate proximal failure, it may amplify focal deformities and reciprocal changes, even at early follow-up.

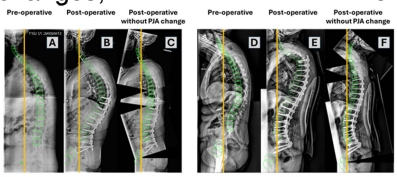

Figure 1: Example of gravity line (yellow line) estimation on pre-operative (A & D), post-operative (B & E) and post-operative without PJA reciprocal change (C & F), stratified by UIV position (Lower Thoracic A,B & C versus Upper Thoracic D, E & F).

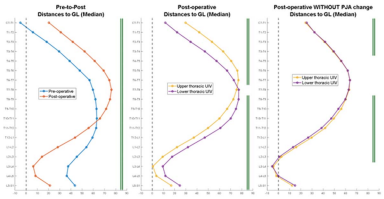

Figure 2: Graphical representation of the Median value of the distance to GL at each disc. Black dotted line represent the gravity line. Green double-line signal a significant difference (p<0.05)

		Upper Thoracic UIV (T2-5)			*Lower Thoracic UIV (T9-11)*		
		No Failure (N=241)	Failure (N=34)	p-value	No Failure (N=304)	Failure (N=64)	p-value
Real	F_N	99.6+/-29.8	93+/-18.6	0.080	192.4+/-48.4	181.8+/-44.8	0.106
	F_T	46.6+/-24.1	58.2+/-19.2	***0.008****	-24.6+/-25.1	-8.8+/-30.8	***0.000****
	M	6.5+/-3.1	7.9+/-2.6	***0.017****	13+/-6.1	15.7+/-6.9	***0.002****
Virtual	F_N	105+/-29.8	104.3+/-18.4	0.850	190+/-48	179.1+/-44.4	0.094
	F_T	35.2+/-20.3	33.1+/-20.8	0.576	-39.4+/-25.2	-38.2+/-23.6	0.073
	M	4.2+/-2.9	2.9+/-2.9	***0.017****	7.2+/-5.8	6+/-5.5	0.123

Table 1: Mechanical loading at the UIV differed between patients with and without proximal failure