Enhancing Interfragmentary Compression with Divergent Locking Screws: A Biomechanical and Cadaveric Study of Insertion Order and Screw Angulation

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INTRODUCTION: Achieving robust interfragmentary compression is critical for successful arthrodesis, particularly in midfoot joints where nonunion and hardware complications remain prevalent. Traditional lag screws often require predrilled trajectories that may be suboptimal in small, comminuted, or osteopenic bones. Recent innovations in polyaxial plating systems permit locking screw insertion at non-perpendicular angles, potentially transforming the compressive mechanics of plate-based fixation. However, the specific influence of screw trajectory and insertion order on compression and contact area has not been systematically evaluated. This study quantifies the effect of screw angulation and sequence on interfragmentary compression in a controlled surrogate model and cadaveric second tarsometatarsal (TMT) fusion constructs, aiming to identify reproducible techniques that enhance mechanical stability without additional hardware or procedural complexity.

METHODS:

Two experimental series were conducted using both surrogate and cadaveric models. In Series 1, foam bone surrogates (Sawbones, Pacific Research Labs) were fixed with either a 15°-capable polyaxial plate (VariAx, Stryker) or a 30°-capable plate (Arsenal, Enovis). Screws were inserted at uniform angles (0°, 15°, or 30°) across all four holes. In Series 2, all constructs used the 30° plate to evaluate five screw angle configurations: (1) the first and second screws angled at 30°, the third screw (non-locking) perpendicular, and the fourth screw angled at 30°; (2) the first and second screws angled at 30° with the third and fourth screws perpendicular; (3) the first, second, and third screws perpendicular with only the fourth screw angled at 30°; (4) the first and second screws perpendicular with the third and fourth screws angled at 30°; and (5) all screws angled at 30° away from the fracture line. Interfragmentary compression (N) and contact area (mm²) were measured post-tightening using TekScan pressure film.

Twelve fresh-frozen cadaveric lower-extremity specimens (mean age 67.8 ± 7.0 years; 14 male, 10 female) were prepared by exposing the second TMT joint, removing cartilage, and fenestrating subchondral bone. Plates were dorsally applied under fluoroscopic guidance. Two paired comparisons were made: (a) all screws 0° vs. all screws 30°, and (b) cuneiform screws 0° with metatarsal screws 30° vs. all screws 0°. Compression and contact area were recorded after metatarsal screw insertion stages.

Statistical analysis included two-way ANOVA for Series 1 (screw angle × plate type), one-way ANOVA for Series 2, and repeated-measures ANOVA for cadaveric comparisons. Significant interactions were explored using Fisher's LSD post hoc tests ($\alpha = 0.05$).

RESULTS:

In Series 1, compression rose in a dose-dependent fashion with screw angulation: 0° = 44.7 ± 30.0 N, 15° = 94.8 ± 21.2 N, and 30° = 156.0 ± 27.0 N ($p < 0.001$). Contact area increased in parallel: 0° = 22.1 ± 12.3 mm², 15° = 103.8 ± 23.7 mm², 30° = 211.0 ± 24.4 mm². Plate type had no significant effect with the exception of maximum allowable angle ($p = 0.81$).

Screw angle configuration exerted a pronounced influence on construct mechanics ($p < 0.001$ for compression). Introducing angled screws in the first bone fragment only (Group 2) produced the lowest compression (58.9 ± 23.9 N). In contrast, angling both screws within the second bone fragment, either exclusively (Group 4) or in combination with angulation in the first fragment (Group 5), resulted in marked gains: Group 4 = 162.7 ± 51.9 N ($p < 0.01$ vs Group 2) and Group 5 = 198.2 ± 44.6 N ($p < 0.001$ vs Group 2). No significant differences in contact area were noted between groups ($p = 0.086$, Figure 3C). These findings isolate the second-fragment screw orientation as the principal driver of interfragmentary compression and contact optimization.

Cadaveric testing confirmed these findings. Constructs with all 30° screws had a 14.7-fold increase in compression vs. all 0° (49.4 ± 35.1 N vs. 3.4 ± 3.8 N; $p < 0.001$) and 3.8-fold increase in contact area (47.8 ± 28.9 mm² vs. 12.8 ± 7.3 mm²; $p < 0.001$). Constructs with 30° screws in the metatarsal yielded 3.9-fold higher compression (118.1 ± 88.3 N vs. 30.3 ± 38.9 N) and doubled contact area (53.3 ± 19.1 mm² vs. 26.2 ± 30.3 mm²; $p < 0.001$).

DISCUSSION AND CONCLUSION: This study demonstrates that screw divergence is a powerful biomechanical lever for enhancing interfragmentary compression and contact area in TMT fusion. The benefits were most pronounced when angled screws were inserted into the second bone fragment after securing the plate to the first, likely due to improved fragment approximation and parallel force vectors along the fusion interface. These findings support a simple and efficient intraoperative technique for improving fixation stability using existing polyaxial plates, without added hardware, surgical time, or complexity. Particularly in high-risk populations – such as patients with midfoot pathology – this technique may

offer a valuable means to reduce the risk of nonunion. Future clinical studies are warranted to determine whether these biomechanical improvements translate into higher fusion rates, faster healing, and improved patient outcomes.