Biomechanical Comparison of Seven Occipital-Cervical Fixation Constructs using Finite Element Analysis

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INTRODUCTION:

Surgery of the occipitocervical (OC) junction may be indicated when this region is either rendered unstable or when there is compression of neurological structures. While various OC constructs exist, there is no consensus regarding the optimal design. Prior biomechanical studies often use outdated fixation techniques or cadaveric specimens with variable bone quality. This study uses finite element analysis (FEA) to evaluate modern OC constructs under standardized conditions.

METHODS:

Seven bilateral OC constructs were modeled per ASTM F2706 guidelines, spanning C1 with fixation in C2 and C3 (Figure 1). Constructs varied in screw number, clamp configurations, keel plate use, and screw diameter (Table 1, Figure 2). A ramping flexion torque of 6.12 Nm simulated physiologic loading. Construct stiffness and screw pullout forces were calculated. The Multi-Attribute Utility Theory (MAUT) score was applied to balance bending stiffness against pullout forces.

RESULTS: Construct E, composed of medial 1-hole and 2-hole clamps, demonstrated the highest MAUT utility score (0.79), offering superior stiffness (820 N.mm/deg) with moderate screw pullout forces (78 N). Constructs using keel plates had higher peak pullout forces (up to 117 N), but lower overall stiffness (Table 2). Stress analysis showed rod notching at implant interfaces, predicting potential fatigue failure (Figure 3). Screw diameter increase from 4.5 mm to 5.0 mm had minimal biomechanical impact.

DISCUSSION AND CONCLUSION:

Our FEA methodology overcomes limitations of previous cadaveric studies by standardizing material properties and simulating physiologic loads. The findings support medial clamp-based constructs for optimal biomechanical performance. This study is the first to use a combined utility score to holistically rank OC fixation designs.

Constructs using medial clamps and independent rod anchoring provide the most favorable balance of stiffness and force distribution in OC fixation. Findings may guide implant selection, particularly in patients with compromised bone quality.

Figure 1: Occipital-cervical construct design with simplified bilateral blocks and screws following the testing setups described in ASTM F2706-18 and ISO 12189-2008.
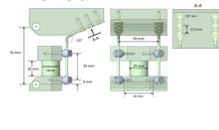

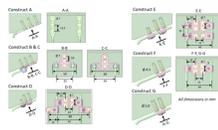Figure 2: The seven designs of occipital fixation as modeled.

Figure 3: Von-Mises stress distribution in occipital rods with maximum stress of 800 MPa or higher (TAN yield stress).
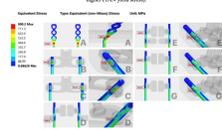
Table 1: Occipital Fixation Designs.

Construct	Occipital Components	Occipital Screws (major thread diameter x length)
A	Occiput Rod 3.5 mm (x2)	4.5 mm x 14 mm screw (x3)
B	50 mm 3-Hole Keel Plate (x1)	4.5 mm x 14 mm screw (x3)
C	60 mm 3-Hole Keel Plate (x1)	4.5 mm x 14 mm screw (x3)
D	1-Hole Clamp (x2) [lateral fixation] 2-Hole Clamp (x2) [medial fixation]	4.5 mm x 14 mm screw (x4) 4.5 mm x 8 mm screw (x4)
E	1-Hole Clamp (x2) [medial fixation] 2-Hole Clamp (x2) [medial fixation]	4.5 mm x 14 mm screw (x4) 4.5 mm x 8 mm screw (x4)
F	2-Hole Clamp (x2) [medial fixation]	4.5 mm x 14 mm screw (x4)
G	2-Hole Clamp (x2) [medial fixation]	5.0 mm x 14 mm screw (x4)

Table 2: Balanced ranking of construct performance using the Multi-Attribute Utility Theory (MAUT) method for data normalization.

Construct	Normalized Bending Stiffness	Normalized Maximum Pullout Reaction Force	MAUT Utility Score (0-1)
E	1.00	0.57	0.79
D	0.69	0.57	0.63
A	0.06	1.00	0.53
B	0.90	0.00	0.45
G	0.02	0.44	0.23
F	0.00	0.41	0.21
C	0.30	0.07	0.19