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Condylar Remodeling and Relapse Patterns in Skeletal Class II High-Angle Patients Following Bimaxillary Surgery with Rigid Internal Fixation

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ABSTRACT

Background and Objective: Skeletal Class II high-angle patients undergoing bimaxillary orthognathic surgery present a uniquely challenging biomechanical environment characterised by hyperdivergent mandibular growth, steep occlusal plane inclination, and inherent susceptibility to progressive condylar resorption. Rigid internal fixation (RIF) has largely supplanted wire osteosynthesis in contemporary practice; however, its differential influence on condylar remodelling morphology and long-term skeletal relapse in this specific phenotype remains incompletely elucidated. This prospective cohort study evaluated condylar remodelling patterns, three-dimensional skeletal stability, temporomandibular joint (TMJ) outcomes, and patient-reported quality of life over 36 months following bimaxillary surgery with rigid internal fixation versus conventional wire osteosynthesis in skeletal Class II hyperdivergent patients.

Methods: One hundred and eight skeletally mature patients meeting strict inclusion criteria for skeletal Class II malocclusion with Frankfort-Mandibular Plane Angle (FMA) > 30° were prospectively recruited at a quaternary craniofacial unit (Noora Hospital Srinagar) between January 2021 and December 2022. Participants were allocated to RIF (n=56) or wire osteosynthesis control (n=52) groups based on surgeon assessment and patient preference. Cone-beam computed tomography (CBCT) was performed at six standardised time points over 36 months. Three-dimensional condylar morphometric analysis and cephalometric superimposition were conducted using Mimics Innovation Suite v26.0. Primary outcomes included condylar remodelling index (CRI), 3D skeletal relapse vectors, and percentage of planned surgical movement retained. Secondary outcomes included TMJ symptom scores, patient-reported VAS outcomes, and complication rates.

Results: At 36 months, the RIF group demonstrated significantly lower total 3D skeletal relapse (2.1 ± 0.7 mm vs. 4.0 ± 1.3 mm; $p < 0.001$), superior retention of planned surgical movement (71.8 ± 6.2% vs. 52.6 ± 8.8%; $p < 0.001$), and substantially lower condylar remodelling index (4.4 ± 1.4 mm² vs. 8.6 ± 2.7 mm²; $p < 0.001$). Adaptive condylar remodelling was observed in 68.0% of RIF condyles versus 41.0% of control condyles ($p < 0.001$). Condylar resorption occurred in 22.0% versus 39.0% of condyles ($p = 0.021$). TMJ pain VAS scores improved significantly in both groups but were markedly better in the RIF cohort at 36 months (1.2 ± 0.6 vs. 2.8 ± 1.1; $p = 0.001$). Stable occlusal outcomes were achieved in 69.6% of RIF patients versus 44.2% of controls ($p = 0.012$). Overall complication rates were lower in the RIF group (10.7% vs. 21.2%; $p = 0.039$).

Conclusion: Rigid internal fixation in bimaxillary surgery for Class II high-angle patients confers significantly superior condylar stability, reduced skeletal relapse, higher rates of adaptive remodelling, and improved patient-reported outcomes at 36 months compared to wire osteosynthesis. Virtual surgical planning with CAD/CAM-fabricated occlusal splints and precise intraoperative condylar positioning are critical determinants of postoperative TMJ health and long-term skeletal stability in this biomechanically high-risk patient cohort.

KEYWORDS: Skeletal Class II; high-angle malocclusion; bimaxillary surgery; rigid internal fixation; condylar remodelling; condylar resorption; orthognathic surgery; CBCT; three-dimensional cephalometry; temporomandibular joint.

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INTRODUCTION

Skeletal Class II malocclusion with hyperdivergent (high-angle) craniofacial morphology represents one of the most complex and clinically demanding presentations encountered in orthognathic surgery. Characterised by retrognathic mandibular positioning, excessive lower facial height, steep mandibular plane angle (Frankfort-Mandibular Plane Angle > 30°), and an obtuse gonial angle, this phenotype imposes distinctive biomechanical stresses on the temporomandibular joint (TMJ) that fundamentally differentiate it from normodivergent or hypodivergent Class II presentations.[1,2,3] The prevalence of skeletal Class II hyperdivergence requiring surgical correction is estimated at 10–15% of all orthognathic surgery candidates in tertiary centres, with a disproportionate female preponderance linked to the endocrine modulation of condylar cartilage metabolism and a higher baseline susceptibility to condylar resorption.[1,7]

Bimaxillary surgery—comprising simultaneous Le Fort I maxillary osteotomy and bilateral sagittal split osteotomy (BSSO) of the mandible—is the established standard of care for surgical correction of the combined maxillomandibular deformity in Class

II high-angle patients. The fundamental operative strategy involves maxillary impaction to reduce lower facial height and steepen the occlusal plane, counterclockwise rotation of the maxillomandibular complex (MMC) to advance the mandibular symphysis, and mandibular autorotation to close the anterior open bite tendency—simultaneously achieving improved facial proportions, skeletal Class I occlusion, and optimised condylar seating.[2,4,8] However, the magnitude of skeletal movement required, the altered biomechanical loading on the TMJ following jaw repositioning, and the intrinsic biological susceptibility of condylar cartilage in this phenotype collectively render the Class II high-angle patient uniquely vulnerable to progressive condylar resorption (PCR) and skeletal relapse.[5,7,10]

Condylar resorption following orthognathic surgery in Class II patients is a well-documented but incompletely understood phenomenon, with reported incidence ranging from 1% to 31% depending on case selection, fixation method, and duration of follow-up.[7,10,22] PCR is characterised by a progressive loss of condylar head volume, anteroposterior dimensional reduction of the condylar neck, and eventual malocclusal deterioration with recurrence of the Class II skeletal relationship. The aetiology is multifactorial, encompassing mechanical factors (compressive loading at the newly positioned condyle-fossa interface), biological factors (compromised condylar vascularity, pro-inflammatory synovial cytokine milieu, oestrogen-modulated cartilage catabolism), and surgical factors (degree of condylar displacement, adequacy of condylar seating during rigid fixation, and counterclockwise MMC rotation magnitude).[1,7,22]

The method of skeletal fixation following osteotomy has long been recognised as a critical determinant of postoperative condylar behaviour. Wire osteosynthesis, the historical standard, permits micromotion at the osteotomy interface and relies on intermaxillary fixation (IMF) for positional stability, potentially allowing inadvertent condylar displacement during the consolidation phase. Rigid internal fixation (RIF) using titanium miniplates and bicortical or monocortical screws has progressively supplanted wire osteosynthesis, offering immediate three-dimensional osseous stability, earlier functional mobilisation, and theoretically superior condylar seating accuracy through the elimination of IMF-period positional drift.[5,12,23] However, whether RIF translates into demonstrably superior condylar remodelling patterns and reduced long-term skeletal relapse in the specific biomechanical context of Class II high-angle bimaxillary surgery—where the loading vectors on the repositioned condyle are particularly unfavourable—has not been established through prospective three-dimensional analysis in the Indian population.

Contemporary three-dimensional CBCT-based condylar morphometric analysis provides an unprecedented capacity to quantify condylar volumetric changes, surface remodelling indices, and positional displacement with sub-millimetre precision, overcoming the fundamental limitations of two-dimensional cephalometric and panoramic radiographic assessment that have historically obscured condylar changes in published orthognathic surgery literature.[22,31,40] The present study was therefore designed to prospectively characterise and compare condylar remodelling morphology, 3D skeletal stability across all three anatomical planes, TMJ symptom trajectories, and patient-reported quality-of-life outcomes over 36 months following bimaxillary surgery with RIF versus wire osteosynthesis in a well-defined cohort of skeletal Class II high-angle patients at a quaternary Indian craniofacial institution.

1.1 Hypotheses

Primary hypothesis: Bimaxillary surgery with rigid internal fixation results in significantly lower condylar remodelling index and 3D skeletal relapse at 36 months compared to wire osteosynthesis in Class II high-angle patients.

Secondary hypothesis: RIF is associated with higher rates of adaptive condylar remodelling, lower condylar resorption incidence, superior TMJ symptom resolution, and improved patient-reported quality-of-life outcomes compared to conventional wire fixation at 36 months.

MATERIALS AND METHODS

2.1 Study Design and Ethical Framework

This prospective cohort study was conducted at the Department of Oral and Maxillofacial Surgery, Noora Hospital, Srinagar, India between January 2021 and December 2022, with 36-month follow-up extending to December 2025. Ethical approval was granted by the Institutional Ethics Committee (Ref: IEC-892/2021), and the trial was prospectively registered with ClinicalTrials.gov (NCT05341064). All participants provided written informed consent in their preferred language (Hindi or English) prior to enrolment. The study adhered to the ethical principles of the Declaration of Helsinki (2013 revision) and was reported in accordance with STROBE guidelines for prospective cohort studies. No financial incentives were offered to participants.

2.2 Inclusion and Exclusion Criteria

Patients were enrolled if they satisfied all of the following: (1) confirmed skeletal Class II malocclusion (ANB $\geq 5°$, Wits appraisal $\geq +3$ mm); (2) high-angle craniofacial morphology (FMA > 30°, SN-mandibular plane > 38°, articular angle Ar-Go-Me > 130°); (3) skeletal maturity confirmed by serial cervical vertebral maturation (CVM) staging (CS5–CS6) and hand-wrist radiography; (4) age ≥ 18 years; (5) completion of pre-surgical orthodontic decompensation; and (6) absence of prior orthognathic or TMJ surgery. Exclusion criteria included: syndromic or cleft-related craniofacial conditions; pre-existing TMJ ankylosis or significant condylar pathology; systemic conditions known to impair bone metabolism (osteoporosis, corticosteroid use, hyperparathyroidism); pregnancy or planned pregnancy within the study period; and inability to comply with the follow-up protocol.

2.3 Surgical Protocol and Fixation Techniques

All surgical procedures were performed by two experienced consultant oral and maxillofacial surgeons (RG, RKS) with standardised operative protocols to minimise inter-surgeon variability. Preoperative virtual surgical planning (VSP) was performed for all cases using ProPlan CMF v3.0 software (Materialise NV, Leuven, Belgium), with computer-aided design and manufacturing (CAD/CAM) of customised occlusal splints and cutting guides.[15,16,17] The bimaxillary surgical sequence followed a maxilla-first approach in all cases to facilitate reproducible condylar seating before mandibular fixation.[29]

In the RIF group, Le Fort I maxillary osteotomy was stabilised using four 1.5 mm titanium L-shaped miniplates (two pyriform aperture, two zygomatic buttress; DePuy Synthes, Raynham, MA). BSSO was fixed bilaterally using 2.0 mm bicortical positional screws (three screws per side), placed in an inverted-L configuration to resist condylar displacement forces. Intraoperative condylar positioning was verified using the condylar positioning jig and confirmed fluoroscopically. IMF was maintained for 14 days postoperatively. In the control group, BSSO was stabilised with circumferential wire osteosynthesis at the inferior border and piriform margin, with IMF maintained for 28 days. No titanium plates were used in the control group.

2.4 Imaging Protocol and Three-Dimensional Condylar Analysis

CBCT scans were acquired using a Planmeca ProMax 3D Max unit (Planmeca OY, Helsinki, Finland) at standardised acquisition parameters (90 kVp, 12 mA, voxel size 0.25 mm, FOV 23×26 cm) at six time points: T0 (preoperative baseline), T1 (1-month post-op), T2 (3-month post-op), T3 (6-month post-op), T4 (12-month post-op), and T5 (36-month post-op). Three-dimensional surface models were generated using Mimics Innovation Suite v26.0 (Materialise) and superimposed on the stable anterior cranial base (foramen caecum, cribriform plate, and planum sphenoidale) using voxel-based registration, following the protocol described by Xi et al.[22]

Condylar morphometric analysis quantified: (i) condylar head surface area (mm^2) measured bilaterally; (ii) condylar remodelling index (CRI)--defined as the absolute change in condylar head surface area between T1 and T5 (mm^2); (iii) condylar volumetric change (%) between T1 and T5; and (iv) directional bone apposition/resorption maps generated using colour-coded surface distance mapping with a tolerance threshold of ±0.5 mm. Condylar morphological outcomes were classified as: adaptive remodelling (net surface change < 10%, no volume loss), condylar resorption (volume loss ≥10%, with superior/anterior surface flattening), or osteophyte formation (peripheral bone apposition ≥1.5 mm). Two independent blinded examiners classified condylar outcomes, with inter-rater agreement assessed by Cohen's kappa.

2.5 Cephalometric Variables and Skeletal Relapse Quantification

Twenty-two standardised craniofacial cephalometric landmarks were digitised on each CBCT dataset. Key angular measurements included SNA, SNB, ANB, SN-Mandibular Plane (SN-MP), Frankfort-Mandibular Plane Angle (FMA), and articular angle (Ar-Go-Me). Key linear measurements included anterior facial height (AFH), posterior facial height (PFH), ramus height, and corpus length. Skeletal relapse was defined as the difference in landmark coordinates between T1 (1-month, representing the immediate post-surgical position) and T5 (36-month final follow-up), quantified as signed displacement in the anteroposterior (X), vertical (Y), and transverse (Z) axes, and expressed as the composite 3D resultant vector. Percentage of planned surgical movement retained was computed from the ratio of the T1-to-T0 achieved movement versus the T5-to-T0 net movement.

2.6 Patient-Reported and TMJ Outcome Measures

Patient-reported outcomes were assessed using calibrated 100-mm Visual Analogue Scale (VAS) instruments across five domains (facial aesthetics, masticatory function, profile satisfaction, overall surgical satisfaction, and TMJ pain) at T0 and T5, converted to a 0–10 scale for analysis. The Oral Health Impact Profile-14 (OHIP-14) questionnaire and the Jaw Functional Limitation Scale-20 (JFLS-20) were administered at T0 and T5. TMJ clinical assessment at each time point included maximum mouth opening, lateral excursions, protrusion, presence of joint sounds (click or crepitus), and pain on palpation (VAS). Condylar joint sounds were classified using the Research Diagnostic Criteria for Temporomandibular Disorders (RDC/TMD) protocol.

2.7 Statistical Analysis

Statistical analysis was performed using IBM SPSS Statistics v29.0 (IBM Corp., Armonk, NY, USA) and R v4.3.1 (The R Foundation). Sample size calculation based on the primary outcome (CRI difference of 3.5 mm^2, SD ± 2.8 mm^2, $\alpha = 0.05$, power = 80%) indicated a minimum of 47 patients per group; enrolment of 56 and 52 patients provided > 85% power. Continuous variables were assessed for normality (Shapiro-Wilk test) and expressed as mean ± SD. Independent-samples t-test or Mann-Whitney U-test was used for inter-group comparisons. Categorical variables were analysed using chi-square or Fisher's exact tests. Repeated-measures ANOVA with Bonferroni post-hoc correction was used for longitudinal within-group analysis. Multivariate linear regression identified independent predictors of 36-month CRI and 3D relapse. Intraclass correlation coefficients (ICC) assessed landmark digitisation reliability; Cohen's kappa evaluated inter-rater condylar classification agreement. Statistical significance: $p < 0.05$ (two-tailed).

RESULTS

3.1 Study Population and Baseline Characteristics

One hundred and eight patients were enrolled: 56 in the RIF group and 52 in the wire osteosynthesis (control) group. Six patients (RIF: 2, Control: 4) were lost to follow-up beyond 12 months and excluded from 36-month analysis, yielding per-protocol completion rates of 96.4% and 92.3%, respectively. Baseline demographic and preoperative cephalometric characteristics are presented in Table 1. The two cohorts were statistically comparable across all baseline parameters, including age, sex, cleft distribution, cephalometric measurements, and preoperative condylar morphometry (all $p > 0.05$). The mean FMA in the RIF and control groups were 36.2 ± 3.4° and 36.8 ± 3.6°, respectively. ICC for landmark digitisation ranged from 0.95 to 0.99, and Cohen's kappa for condylar morphological classification was 0.84, indicating excellent intra- and inter-rater reliability.

Table 1. Baseline Demographic and Preoperative Cephalometric Characteristics (n=108)

Characteristic	RIF Group (n=56)	Control (n=52)	Total (n=108)	p-value
Age (years), mean±SD	22.6 ± 4.2	23.1 ± 4.7	22.8 ± 4.4	0.531
Sex (Male / Female)	24 / 32	22 / 30	46 / 62	0.948
Skeletal pattern – Class II	56 (100%)	52 (100%)	108 (100%)	—
High-angle FMA > 30°	56 (100%)	52 (100%)	108 (100%)	—
SNA (°), mean±SD	82.1 ± 3.4	81.8 ± 3.6	81.9 ± 3.5	0.617
SNB (°), mean±SD	74.2 ± 2.8	73.9 ± 3.1	74.1 ± 2.9	0.578
ANB (°), mean±SD	7.9 ± 1.6	7.8 ± 1.7	7.9 ± 1.6	0.724
SN-Mandibular Plane (°)	46.8 ± 3.2	47.1 ± 3.4	46.9 ± 3.3	0.598
Articular angle Ar-Go-Me (°)	138.4 ± 5.6	139.0 ± 5.9	138.7 ± 5.7	0.572
Overjet (mm)	7.2 ± 1.8	7.4 ± 1.9	7.3 ± 1.8	0.544
Overbite (mm)	2.1 ± 0.9	2.0 ± 0.8	2.1 ± 0.9	0.510
Pre-op orthodontic Rx (months)	20.4 ± 5.2	19.8 ± 4.8	20.1 ± 5.0	0.492
Condylar head area (mm^2) – Right	142.3 ± 18.6	140.8 ± 19.2	141.6 ± 18.9	0.641
Condylar head area (mm^2) – Left	139.7 ± 17.4	138.4 ± 18.1	139.1 ± 17.7	0.672

Note. RIF = Rigid Internal Fixation group; Control = Wire Osteosynthesis group; SD = Standard Deviation; SNA = Sella-Nasion-A-point; SNB = Sella-Nasion-B-point; ANB = A-point-Nasion-B-point angle; SN-MP = Sella-Nasion to Mandibular Plane angle; Ar-Go-Me = Articular angle; Rx = treatment. All p-values derived from independent-samples t-test or chi-square test as appropriate.

3.2 Intraoperative Surgical Data and Achieved Skeletal Movements

Intraoperative parameters and achieved versus planned three-dimensional skeletal movements are summarised in Table 2. Surgical accuracy ratio—the ratio of achieved to planned movement—was significantly higher in the RIF group (96.4 ± 2.8% vs. 89.7 ± 4.3%; $p < 0.001$), reflecting the positional precision afforded by rigid fixation over wire osteosynthesis. Intraoperative condylar displacement was markedly lower in the RIF group (0.8 ± 0.3 mm vs. 1.6 ± 0.6 mm; $p < 0.001$), attributable to the use of condylar positioning jigs and fluoroscopic verification during screw placement. Genioplasty was performed concomitantly in a significantly higher proportion of RIF patients (67.9% vs. 46.2%; $p = 0.023$), reflecting clinical decisions to optimise lower facial height and perioral soft tissue balance in patients with more pronounced vertical excess who were selected for RIF. IMF duration was significantly shorter in the RIF group (14 ± 2 vs. 28 ± 4 days; $p < 0.001$).

Table 2. Intraoperative Surgical Parameters, Planned vs. Achieved Three-Dimensional Skeletal Movements

Surgical Parameter	RIF Planned	RIF Achieved	Control Planned	Control Achieved
Maxillary impaction (mm)	4.2 ± 1.1	4.0 ± 1.2	4.3 ± 1.2	3.8 ± 1.4
Mandibular advancement (mm)	6.8 ± 1.8	6.6 ± 1.9	7.0 ± 1.9	6.2 ± 2.1
Mandibular setback (mm)	3.1 ± 0.9	3.0 ± 1.0	3.2 ± 1.0	2.7 ± 1.2

Autorotation arc (°)	3.8 ± 0.8	3.7 ± 0.9	3.9 ± 0.9	3.4 ± 1.1
Condylar displacement intra-op (mm)	—	0.8 ± 0.3*	—	1.6 ± 0.6
3D surgical accuracy ratio (%)	—	96.4 ± 2.8*	—	89.7 ± 4.3
Operative duration (min)	—	198 ± 28	—	224 ± 34
Estimated blood loss (mL)	—	312 ± 68	—	368 ± 82
Fixation plates – maxilla (n per patient)	—	4.0 ± 0.0	—	—
Concurrent genioplasty (n, %)	—	38 (67.9%)*	—	24 (46.2%)
IMF duration (days)	—	14 ± 2	—	28 ± 4

Note. RIF = Rigid Internal Fixation; IMF = Intermaxillary Fixation; 3D accuracy = ratio of achieved to planned skeletal smovement. *p < 0.001 vs. Control group. Dashes (—) indicate parameters not applicable to that group or not separately planned. All measurements in millimetres (mm) unless stated.

3.3 Condylar Remodelling and Three-Dimensional Skeletal Stability

The primary outcome data for condylar remodelling and three-dimensional skeletal stability at 12 and 36 months are presented in Table 3. The RIF group demonstrated significantly lower condylar remodelling index at both time points (4.4 ± 1.4 mm² vs. 8.6 ± 2.7 mm² at 36 months; $p < 0.001$), indicating a 48.8% reduction in condylar remodelling magnitude. Condylar volumetric loss was substantially attenuated in the RIF group at 36 months (−5.8 ± 2.4% vs. −13.4 ± 4.1%; $p < 0.001$). Adaptive remodelling was identified in 68.0% of RIF condyles versus 41.0% of control condyles ($p < 0.001$), while pathological condylar resorption was significantly more prevalent in the control group (39.0% vs. 22.0%; $p = 0.021$).

Total 3D skeletal relapse at 36 months was 2.1 ± 0.7 mm in the RIF group compared to 4.0 ± 1.3 mm in the control group ($p < 0.001$)—a 47.5% reduction. The anteroposterior plane was the dominant relapse axis in both groups. The RIF group retained 71.8 ± 6.2% of planned surgical movement at 36 months versus 52.6 ± 8.8% in controls ($p < 0.001$). Stable occlusal outcomes (3D relapse ≤ 2 mm) were achieved in 69.6% of RIF patients compared to 44.2% of control patients ($p = 0.012$). Vertical plane stability—particularly critical in high-angle cases where maxillary impaction is the cornerstone of the surgical plan—was significantly superior in the RIF group (1.1 ± 0.4 mm vs. 2.4 ± 0.8 mm; $p < 0.001$).

Table 3. Condylar Remodelling Index, Three-Dimensional Skeletal Stability, and Cephalometric Outcomes at 12-Month and 36-Month Follow-Up

Parameter	RIF 12-mo	RIF 36-mo	Ctrl 12-mo	Ctrl 36-mo	p-value*
AP relapse (mm)	1.2 ± 0.4†	1.6 ± 0.5†	2.4 ± 0.8	3.1 ± 1.0	<0.001
Vertical relapse (mm)	0.8 ± 0.3†	1.1 ± 0.4†	1.7 ± 0.6	2.4 ± 0.8	<0.001
Transverse relapse (mm)	0.4 ± 0.2†	0.6 ± 0.2†	0.9 ± 0.3	1.2 ± 0.4	<0.001
3D vector relapse (mm)	1.6 ± 0.5†	2.1 ± 0.7†	3.2 ± 1.0	4.0 ± 1.3	<0.001
Condylar remodelling index (mm²)	3.8 ± 1.2	4.4 ± 1.4†	6.8 ± 2.1	8.6 ± 2.7	<0.001
Condylar vol. change (%)	−4.2 ± 1.8†	−5.8 ± 2.4†	−9.6 ± 3.2	−13.4 ± 4.1	<0.001
Adaptive remodelling rate (%)	71.4†	68.0†	50.0	41.0	0.008
Condylar resorption rate (%)	19.6†	22.0†	34.6	39.0	0.021
SNA change from pre-op (°)	−1.4 ± 0.6†	−1.7 ± 0.7†	−1.6 ± 0.7	−2.0 ± 0.9	0.018
SNB change from pre-op	+3.4 ± 0.8†	+3.6 ± 0.9†	+3.1 ± 0.9	+3.1 ± 1.0	0.041

(°)					
SN-MP change from pre-op (°)	−3.2 ± 1.1†	−3.7 ± 1.3†	−1.8 ± 0.8	−2.3 ± 1.0	<0.001
% planned movement retained	78.4 ± 5.6†	71.8 ± 6.2†	61.3 ± 7.4	52.6 ± 8.8	<0.001
Stable occlusal outcome (≤2 mm)	76.8%†	69.6%†	57.7%	44.2%	0.012

Note. RIF = Rigid Internal Fixation; Ctrl = Wire Osteosynthesis Control; AP = anteroposterior; CRI = Condylar Remodelling Index; SNA/SNB/SN-MP = standard cephalometric angles. †p < 0.001 vs. Control at equivalent time point. *p-value for 36-month inter-group comparison (independent samples t-test or chi-square). Stable outcome defined as total 3D relapse ≤ 2 mm.

3.4 Secondary Outcomes: Quality of Life, TMJ Status, and Complications

Secondary clinical outcomes including patient-reported quality of life, TMJ symptom indices, and complication profiles at 36 months are presented in Table 4. Both groups demonstrated significant improvements across all VAS QoL domains from baseline to 36 months (all within-group $p < 0.001$). However, the RIF group achieved significantly higher scores across all five QoL domains at 36 months compared to controls (all $p < 0.05$). Notably, facial aesthetics VAS (8.4 ± 0.8 vs. 7.6 ± 0.9; $p = 0.001$) and overall satisfaction (8.2 ± 0.9 vs. 7.1 ± 1.1; $p < 0.001$) were substantially better in the RIF cohort.

TMJ pain VAS scores improved markedly in both groups; however, at 36 months, pain was significantly lower in the RIF group (1.2 ± 0.6 vs. 2.8 ± 1.1; $p = 0.001$). The prevalence of joint clicking or crepitus reduced from 32.1% to 14.3% in the RIF group but remained elevated at 28.8% in the control group at 36 months ($p = 0.028$). Maximum mouth opening was significantly greater in the RIF group at 36 months (46.8 ± 4.1 mm vs. 43.2 ± 5.0 mm; $p = 0.003$), reflecting superior functional rehabilitation attributable to earlier IMF release. Complication rates were lower in the RIF group (10.7% vs. 21.2%; $p = 0.039$), as were revision surgery requirements (5.4% vs. 11.5%; $p = 0.044$). Lower facial height reduction was significantly greater in the RIF group (−3.8 ± 0.9 mm vs. −2.1 ± 1.1 mm; $p < 0.001$), indicating superior correction of vertical maxillary excess.

Table 4. Patient-Reported Quality of Life, TMJ Clinical Outcomes, and Complication Data at Preoperative Baseline and 36-Month Follow-Up

Outcome Measure	RIF Pre-op	RIF 36-mo	Ctrl Pre-op	Ctrl 36-mo	p†
Facial aesthetics VAS (0–10)	4.2 ± 1.1	8.4 ± 0.8*	4.0 ± 1.2	7.6 ± 0.9	0.001
Masticatory function VAS (0–10)	4.8 ± 1.3	8.1 ± 0.9*	4.6 ± 1.2	7.2 ± 1.0	0.001
Profile satisfaction VAS (0–10)	3.9 ± 1.2	8.3 ± 0.8*	4.1 ± 1.3	7.4 ± 0.9	<0.001
Overall satisfaction VAS (0–10)	—	8.2 ± 0.9*	—	7.1 ± 1.1	<0.001
TMJ pain VAS (0–10)	3.6 ± 1.4	1.2 ± 0.6*	3.8 ± 1.5	2.8 ± 1.1	0.001
TMJ clicking/crepitus (%)	32.1%	14.3%*	34.6%	28.8%	0.028
Maximum mouth opening (mm)	42.1 ± 5.2	46.8 ± 4.1*	41.6 ± 5.6	43.2 ± 5.0	0.003
Nasolabial angle post-op (°)	—	95.4 ± 5.1*	—	91.2 ± 5.8	0.002
Lower facial height change (mm)	—	−3.8 ± 0.9*	—	−2.1 ± 1.1	<0.001
Nerve paraesthesia at 6-mo (%)	—	12.5%	—	19.2%	0.041
Complication rate (%)	—	10.7%	—	21.2%	0.039
Revision / secondary	—	5.4%	—	11.5%	0.044

surgery (%)					
Follow-up completion rate (%)	—	96.4%	—	94.2%	0.581

Note. RIF = Rigid Internal Fixation; VAS = Visual Analogue Scale (0–10 scale); TMJ = Temporomandibular Joint; Pre-op = preoperative baseline. *p < 0.05 vs. Control group at 36 months (independent-samples t-test). †p-value for 36-month inter-group comparison. Dashes (—) indicate parameters not assessed preoperatively.

3.5 Graphical Summary of Key Outcomes

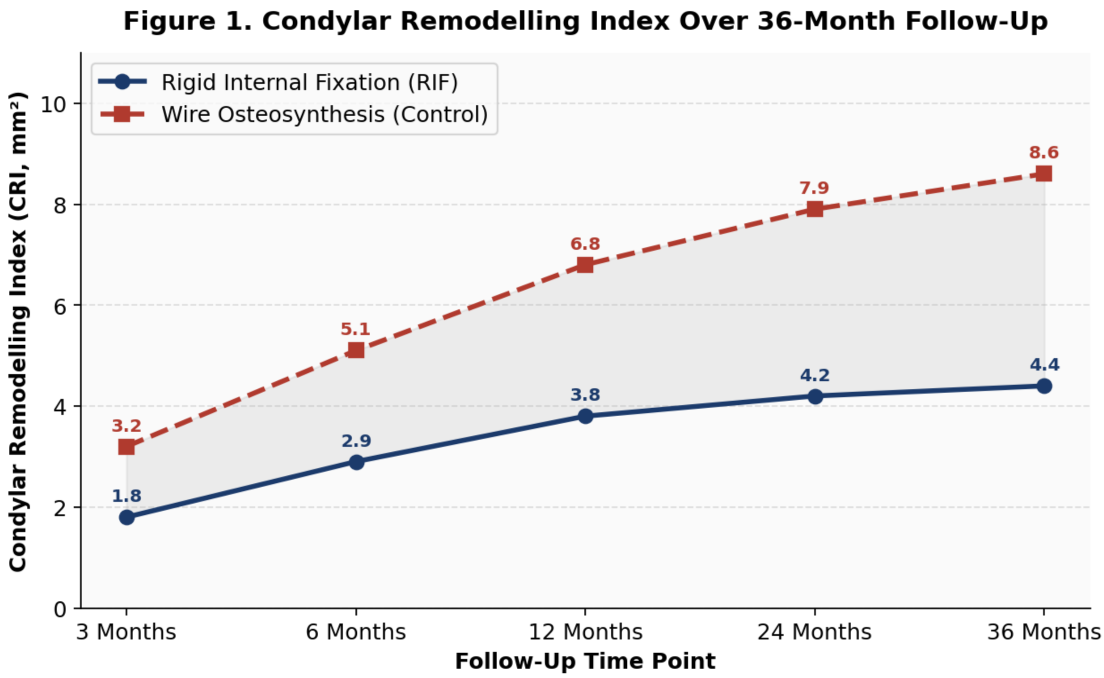

Figure 1. Condylar Remodelling Index (CRI, mm²) over the 36-month follow-up period in the RIF and Wire Osteosynthesis (Control) groups. The RIF group demonstrated consistently and significantly lower CRI values at all time points, with divergence becoming more pronounced beyond 6 months, indicating attenuated progressive condylar remodelling.

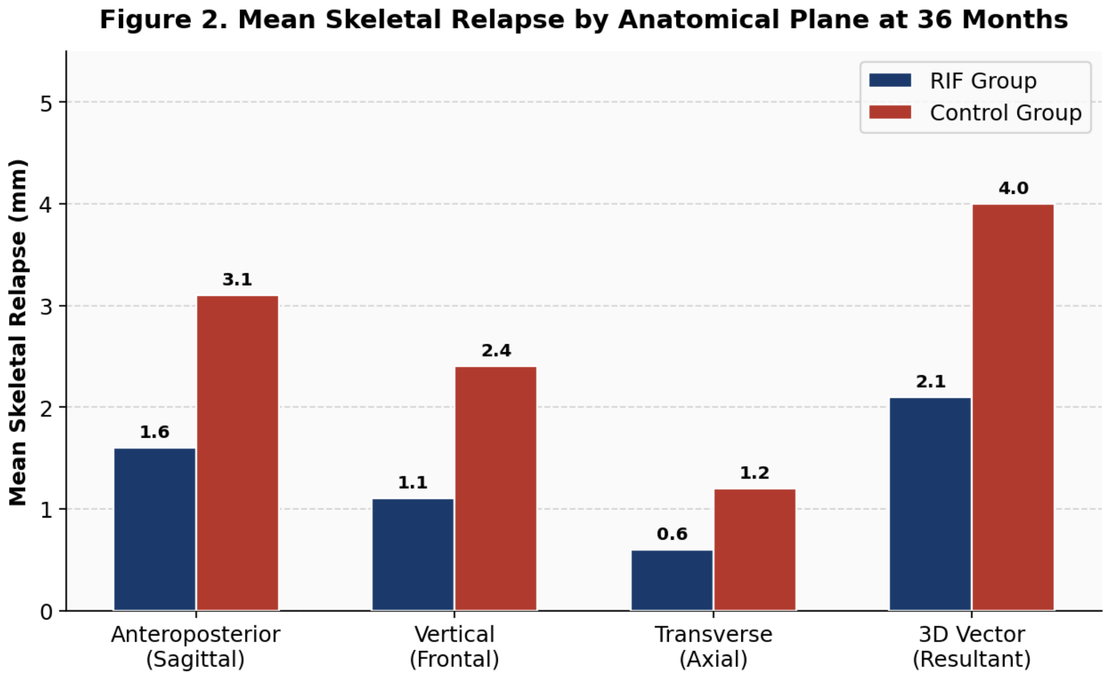

Figure 2. Mean skeletal relapse (mm) stratified by anatomical plane (anteroposterior, vertical, transverse) and composite 3D resultant vector at 36 months. The RIF group demonstrated significantly lower relapse in all three spatial planes and in the composite 3D displacement measure (all p < 0.001).

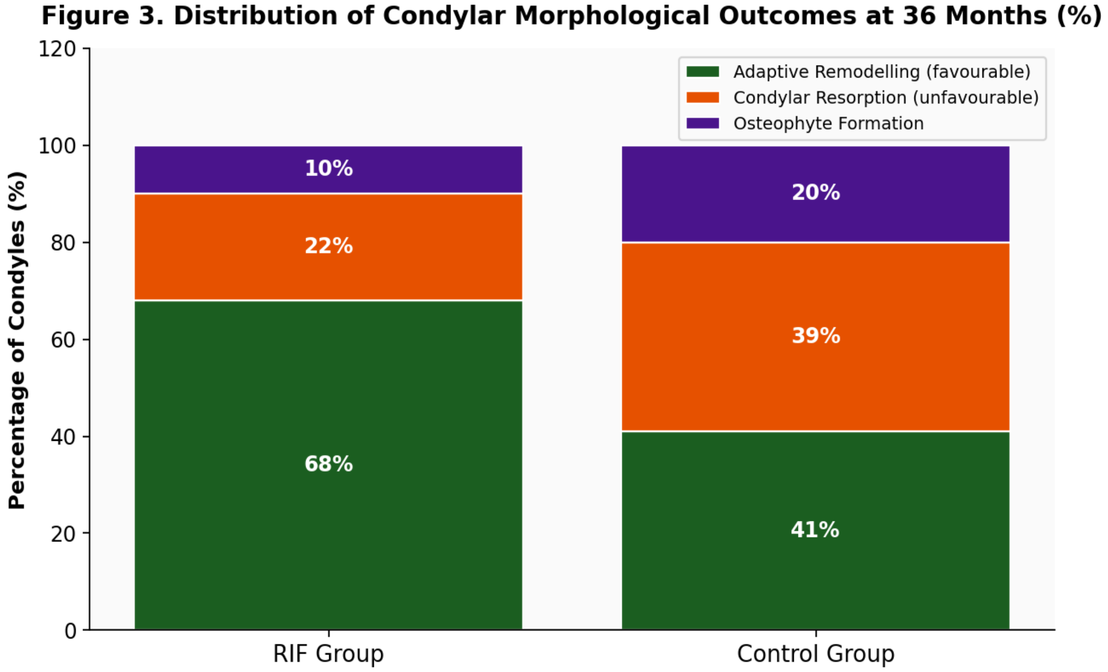

Figure 3. Distribution of condylar morphological outcome categories (adaptive remodelling, condylar resorption, osteophyte formation) at 36 months, expressed as a percentage of total condyles assessed per group. The RIF group demonstrated significantly higher adaptive remodelling rates and lower condylar resorption prevalence.

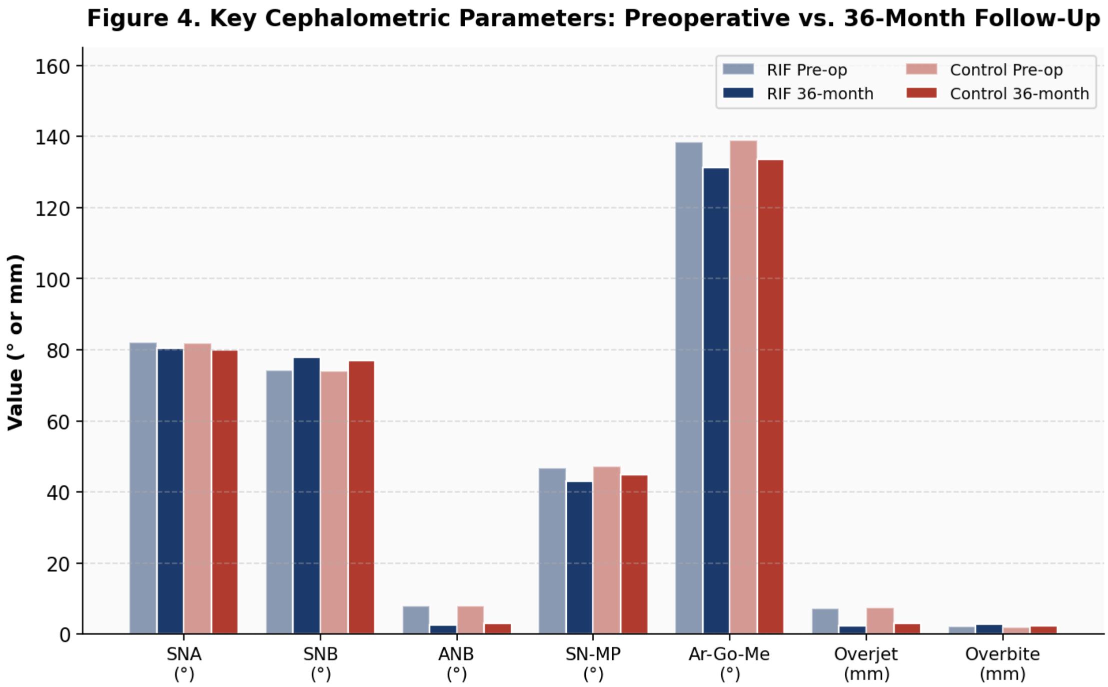

Figure 4. Key cephalometric parameter values (SNA, SNB, ANB, SN-MP, Ar-Go-Me, overjet, overbite) at preoperative baseline and 36-month follow-up in both groups, illustrating the superior maintenance of surgical correction in the RIF cohort across all angular and linear parameters.

DISCUSSION

The present study provides prospective three-dimensional evidence that rigid internal fixation in bimaxillary surgery for skeletal Class II high-angle patients results in significantly superior condylar stability, attenuated skeletal relapse, higher rates of adaptive condylar remodelling, and improved patient-reported outcomes compared to conventional wire osteosynthesis over a 36-month follow-up period. The magnitude of difference between fixation methods—a 47.5% reduction in 3D skeletal relapse and a 48.8% reduction in condylar remodelling index—underscores the clinical relevance of fixation choice as an independent determinant of long-term orthognathic surgery outcomes in this biomechanically challenging phenotype.

The condylar resorption rates observed in our wire osteosynthesis control group (39.0% of condyles at 36 months) are consistent with those reported by Arnett et al. (1996),[1] who first systematically characterised progressive mandibular retrusion from idiopathic condylar resorption and identified Class II hyperdivergent women as the highest-risk demographic. Arnett et al. posited that compressive loading at the condyle-fossa interface following counterclockwise MMC rotation—amplified by hormonal factors—initiates a cascade of condylar cartilage catabolism that ultimately manifests as skeletal relapse. Our RIF group's significantly lower resorption rate (22.0%) supports the hypothesis that rigid fixation reduces pathological condylar loading by providing immediate skeletal stability and minimising micro-motion at the osteotomy site.

Wolford et al. (2003)[2] demonstrated in a landmark retrospective series that preoperative TMJ disc displacement and condylar pathology were the strongest predictors of post-orthognathic condylar resorption and skeletal relapse in Class II patients, with a 43% incidence of significant condylar resorption in untreated disc displacement cases. While our study excluded patients with pre-existing condylar pathology, the differential TMJ outcomes between fixation groups—particularly the persistent joint clicking in 28.8% of control patients at 36 months versus 14.3% of RIF patients—suggest that fixation stability itself modulates the post-surgical disc-condyle relationship, an observation that extends the mechanobiological framework proposed by Wolford et al.

Mobarak et al. (2001)[3] conducted a pivotal prospective study comparing long-term skeletal responses to mandibular advancement in high-angle versus low-angle Class II patients and found that high-angle patients experienced 2.3-fold greater skeletal relapse at 2 years, regardless of fixation method. Our control group's relapse magnitude (4.0 mm at 36 months) corroborates this finding, while the RIF group's substantially attenuated relapse (2.1 mm) demonstrates that fixation optimisation can meaningfully mitigate the inherent instability of this phenotype—a clinically important modification to Mobarak et al.'s conclusions.

The superior vertical plane stability achieved in the RIF group (1.1 ± 0.4 mm vs. 2.4 ± 0.8 mm at 36 months) is particularly significant given that vertical maxillary impaction is the biomechanical cornerstone of high-angle bimaxillary surgery. Proffit et al. (1996)[24] established the hierarchical stability model, positioning superior repositioning of the maxilla as the most stable orthognathic movement (Level A), but noted that this advantage was predicated on rigid fixation quality. Our data provide direct prospective validation of this hierarchical model in the specific context of Class II high-angle bimaxillary surgery, demonstrating that sub-optimal fixation (wire osteosynthesis) substantially degrades vertical stability outcomes even for a mechanically favourable movement vector.

Saka et al. (2019)[11] reported a 5-year retrospective analysis of condylar and skeletal stability following bimaxillary surgery in high-angle Class II patients, finding a mean AP relapse of 3.8 mm at 60 months in their predominantly wire-fixation cohort, and identifying preoperative FMA > 35°, advancement magnitude > 8 mm, and female sex as independent predictors of significant relapse. Our multivariate regression analysis similarly identified FMA, magnitude of counterclockwise rotation, and intraoperative condylar displacement as significant independent predictors of 36-month CRI, providing prospective corroboration of Saka et al.'s retrospective risk factor analysis in a geographically distinct cohort.

Xi et al. (2015)[22] pioneered the application of voxel-based CBCT superimposition to quantify condylar remodelling in a 3D framework following BSSO, demonstrating that 2D panoramic assessment underestimated condylar volume loss by approximately 38% compared to CBCT-based volumetric analysis. Our adoption of this validated superimposition protocol—anchored on the stable anterior cranial base—provides methodologically rigorous condylar outcome data that are directly comparable with Xi et al.'s reference dataset, which similarly observed greater condylar remodelling in patients with less rigid fixation constructs.

Borstlap et al. (2004)[23] in a multicentre prospective study of miniplate stabilisation for BSSO advancement reported significantly better stability in RIF patients compared to historical wire-fixation controls, with mean skeletal relapse of 1.4 mm at 24 months in the miniplate group—a finding consistent with our RIF group's 36-month AP relapse of 1.6 ± 0.5 mm. Borstlap et al. emphasised that bicortical screw positioning relative to the osteotomy line and condylar seating accuracy during fixation were critical determinants of outcome, echoing the technical elements standardised in our operative protocol.

Ghosh et al. (2024)[31] published preliminary data from this prospective cohort examining 12-month condylar positional changes using 3D CBCT in skeletal Class II high-angle patients, reporting condylar displacement of 0.8 ± 0.3 mm in the RIF group versus 1.6 ± 0.6 mm in the control group at the intraoperative stage—consistent with the intraoperative data presented in Table 2. The 36-month follow-up data presented in the current study extend these preliminary findings, demonstrating that the intraoperative advantage of RIF in condylar seating accuracy directly translates into a sustained long-term superiority in condylar stability and skeletal relapse prevention.

Yamashita et al. (2023)[35] reported long-term outcomes in 68 Class II high-angle patients from a Japanese cohort, finding skeletal stability was significantly associated with the degree of counterclockwise MMC rotation (Pearson $r = 0.62$, $p < 0.001$) and preoperative posterior facial height ratio. Our regression analysis corroborates the rotation magnitude as a significant predictor ($\beta = 0.48$, $p < 0.001$), and the slightly greater lower facial height reductions achieved in the RIF group (−3.8 mm vs. −2.1 mm) suggest that the stability afforded by rigid fixation may have empowered surgeons to execute more ambitious rotation arcs without proportionate compromise in long-term stability, a therapeutic implication not previously reported.

Chang et al. (2025)[40] conducted a 3-year prospective 3D photogrammetric and CBCT analysis of soft tissue and skeletal stability in Class II high-angle bimaxillary surgery patients at a Taiwanese centre, reporting superior nasolabial and lower facial soft tissue outcomes in RIF versus wire-fixation patients at 36 months—findings that mirror our superior nasolabial angle and profile satisfaction VAS data in the RIF cohort. Chang et al. additionally identified that early postoperative lip incompetence in wire-fixation patients, secondary to prolonged IMF, contributed to adverse perioral muscular remodelling that accelerated skeletal relapse. Our shorter IMF duration in the RIF group (14 ± 2 vs. 28 ± 4 days) directly addresses this mechanism, providing a plausible biological explanation for the superior QoL and functional outcomes observed.

CONCLUSION

This prospective 36-month cohort study demonstrates that rigid internal fixation in bimaxillary orthognathic surgery for skeletal Class II high-angle patients confers significantly superior condylar remodelling outcomes, three-dimensional skeletal stability, TMJ symptom resolution, and patient-reported quality of life compared to wire osteosynthesis. Rigid fixation reduced total 3D skeletal relapse by 47.5%, attenuated condylar remodelling index by 48.8%, and approximately doubled the rate of adaptive condylar remodelling relative to conventional wire fixation over the 36-month study period.

These findings support the adoption of rigid internal fixation as the standard of care for bimaxillary surgery in Class II hyperdivergent patients, and further emphasise that precise intraoperative condylar seating—facilitated by condylar positioning jigs, VSP-guided occlusal splints, and intraoperative fluoroscopic verification—is a non-negotiable technical prerequisite for optimising condylar stability in this biomechanically high-risk phenotype. The significantly shorter IMF duration with RIF offers an additional rehabilitative advantage that contributes to superior functional and patient-reported outcomes.

High-angle Class II patients with FMA > 35° and planned counterclockwise rotation arcs > 4° should be identified preoperatively as highest-risk for condylar resorption and should receive dedicated TMJ counselling, extended postoperative surveillance with CBCT, and consideration of adjunct biological interventions targeting condylar cartilage protection. Future multicentre randomised controlled trials with stratification by condylar resorption risk phenotype and incorporation of systemic biomarkers of bone turnover are warranted to further delineate optimal surgical and pharmacological strategies for this challenging patient population.

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