Research Article

Predicting The Outcome Of Comprehensive Occlusal And Temporomandibular Rehabilitation In Adults With Class II Malocclusion: Development And Internal Validation Of A Weighted Four-Domain Compensatory-Reserve Index

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Abstract

Objective. Angle's classification describes the occlusal contact but does not define how much dentoalveolar movement an adult can absorb, nor how the condylar position constrains the mechanics that may be used. The study aimed to identify pre-treatment determinants of a stable occlusal and temporomandibular result in adults with Class II malocclusion and to develop, weight and internally validate an interpretable prognostic index of dentoalveolar compensatory reserve.

Materials and Methods. A single-centre observational cohort of 129 adults aged 18–45 years with completed facial growth was stratified before outcome assessment into four clinical–morphological groups: dentoalveolar (n = 41), skeletal–dentoalveolar with mandibular retrognathism (n = 47), hypodivergent Class II division 2 (n = 26) and complicated forms (n = 15). Every patient underwent clinical, digital-model, lateral cephalometric, cone-beam computed tomographic (CBCT) and periodontal examination. CBCT quantified the Pullinger–Hollender condylar position index, its inter-side difference, intercondylar and intergonial width, and mandibular spatial asymmetry. The composite unfavourable endpoint at 24 months of retention combined occlusal relapse, incisor irregularity, new clinically relevant recession and forced abandonment of planned movement. The cohort was split, with strata preserved, into a development sample (n = 89) and a validation sample (n = 40).

Results. The unfavourable endpoint occurred in 38.2 % of the development and 37.5 % of the validation sample. Univariable odds ratios were highest for periodontal phenotype (OR = 3.43), Jarabak ratio (3.39), dehiscence and fenestration (3.18) and buccal plate thickness (2.71). After collapsing collinear variables into four domain modules, all remained independent (Nagelkerke $R^2 = 0.49$); the vertical and periodontal–alveolar modules carried the largest standardised coefficients ($\beta = 0.34$ and 0.32). The resulting weighted index ($0.18 \cdot M1 + 0.30 \cdot M2 + 0.24 \cdot M3 + 0.28 \cdot M4$) reached an area under the ROC curve of 0.86 (95 % CI 0.77–0.93), exceeding every single module. Across the three prognostic bands the unfavourable outcome rose from 9.7 % to 31.8 % and 66.7 % (trend $p < 0.001$). In the validation sample accuracy was 82.5 %, sensitivity 80.0 %, specificity 84.0 %, calibration slope 0.93. Where the delivered tactic matched the index recommendation, 24-month stability was 87.5 % versus 56.3 % ($p = 0.034$) and biologically risky incisor movement 8.3 % versus 43.8 % ($p = 0.012$).

Conclusions. Stability of comprehensive occlusal and temporomandibular rehabilitation in Class II adults is governed less by the magnitude of the sagittal discrepancy than by the vertical and periodontal–alveolar reserve available to compensate it. A four-domain weighted index computed before appliance placement separates favourable from unfavourable courses with good discrimination and calibration, and its dominant module converts the numerical grade into a specific mechanical restriction.

Keywords: Class II malocclusion; treatment outcome prediction; temporomandibular joint; condylar position; cone-beam computed tomography; dentoalveolar compensation; periodontal phenotype; orthodontic camouflage; risk stratification.

1. Introduction

Class II malocclusion remains the most frequent sagittal deviation reported in epidemiological surveys, and its share changes only modestly between dentition stages and world regions [1, 2]. The clinical label, however, is broader than the morphology behind it. Adult populations described in comparative craniofacial studies contain maxillary protrusion, mandibular retrognathism, hypodivergent division 2 configurations and asymmetric subdivisions, all of which produce the same distal molar relationship [3–6]. An identical occlusal photograph can therefore correspond to entirely different amounts of skeletal discrepancy, incisor compensation and alveolar bone available for movement.

Once growth is complete, correction of the sagittal step is achieved almost exclusively by dentoalveolar movement. The biological ceiling of that movement is set by the buccal cortical plate, the symphyseal morphology and the periodontal phenotype rather than by any angular norm. CBCT studies consistently link steeper incisor inclination and hyperdivergent patterns with thinner anterior mandibular bone [10–12], and long-term cohorts report gingival recession and loss of buccal coverage after labial incisor displacement [13–16]. An occlusally acceptable finish obtained at the cost of the alveolar envelope is not a successful rehabilitation.

The temporomandibular joint constitutes a second, largely independent constraint. Three-dimensional assessments show that the condyle in skeletal Class II with mandibular retrognathism tends to occupy a more posterior position within the fossa, with joint-space and morphological differences that vary further with the vertical pattern [7–9]. Such a position is not in itself pathological, yet it narrows the range of admissible mechanics: prolonged Class II elastics, molar extrusion and posterior mandibular rotation act on a joint that already has a reduced anterior reserve. Comprehensive rehabilitation of occlusion in the adult consequently has to be planned against both the alveolar and the articular envelope, and neither is visible in the Angle classification.

Contemporary prediction research has moved towards machine-learning decision support, and reviews of artificial intelligence in orthodontics confirm rapid growth in automated classification, landmark identification and outcome modelling [34–40]. These tools achieve high internal accuracy, but their outputs are difficult to translate into a specific instruction at the chairside, they require datasets that most clinical departments do not hold, and they rarely separate the reason for a high risk score from the score itself. What the treating orthodontist needs before bonding is narrower and more actionable: an estimate of how much compensation the individual patient can absorb, and of which anatomical domain will fail first if that limit is exceeded.

The present study was therefore designed around a domain-preserving rather than a purely predictive logic. Pre-treatment variables were grouped into four anatomically coherent modules — sagittal skeletal, vertical, dentoalveolar and periodontal–alveolar — each scored on an identical internal scale but weighted according to its independent contribution in multivariable analysis. The aims were: (i) to quantify the pre-treatment determinants of a stable occlusal and temporomandibular result at 24 months of retention; (ii) to construct and weight an integral index of dentoalveolar compensatory potential; (iii) to test its discrimination and calibration in an untouched validation sample; and (iv) to examine whether concordance between the delivered tactic and the index recommendation is associated with better occlusal and biological outcomes.

2. Materials and Methods

2.1. Study design and ethical approval

This was a single-centre observational cohort study with retrospective model development and internal validation, conducted at the Department of Orthodontics and Dental Prosthetics of Tashkent State Dental Institute. Patients were recruited between January 2017 and December 2020; active treatment and 24 months of retention monitoring were completed by December 2024. The choice of treatment tactic remained an ordinary clinical decision of the treating orthodontist and was in no way influenced by the mathematical analysis performed afterwards. Reporting follows the TRIPOD recommendations for prediction-model studies. The protocol conformed to the Declaration of Helsinki and to national radiation-safety regulations; all participants gave written informed consent for the use of anonymised clinical data. No radiographic examination was ordered for research purposes alone.

2.2. Participants

Eligible patients were 18–45 years old, had a permanent dentition, completed facial growth and an Angle Class II relationship. Completion of growth was confirmed by absence of body-height change over the preceding two years, a fully established permanent dentition and mature cervical vertebral morphology on the available cephalogram. A complete pre-treatment record set, finished orthodontic correction, digital models after the active phase and follow-up at 6, 12 and 24 months were required. Exclusion criteria were craniofacial syndromes and clefts, previous jaw fracture or orthognathic surgery, active generalised periodontitis, grade II–III tooth mobility, multiple anterior tooth loss, medication with a pronounced effect on bone remodelling, decompensated systemic disease, pregnancy at the time of imaging and inadequate record quality. Earlier orthodontic treatment did not preclude inclusion when documentation of the new course was complete.

2.3. Clinical–morphological stratification

Allocation to four groups was performed before outcome assessment and was based on the leading morphological component rather than on the occlusal contact alone. Group I (n = 41) comprised the dentoalveolar form with minimal skeletal disharmony: increased overjet, maxillary incisor protrusion or arch constriction with ANB and Wits close to reference. Group II (n = 47) comprised the skeletal–dentoalveolar form with mandibular retrognathism, defined by reduced SNB, increased ANB and Wits and a posterior pogonion. Group III (n = 26) comprised hypodivergent Class II division 2 with deep incisor overlap, incisor retrusion, an increased interincisal angle and a raised Jarabak ratio. Group IV (n = 15) comprised complicated forms: hyperdivergence, Class II subdivision asymmetry, thin periodontal phenotype, recession, dehiscence or fenestration. At least one constraint capable of altering safe mechanics was mandatory for allocation to Group IV.

2.4. Cephalometric analysis

Lateral cephalograms were taken in habitual occlusion. Sagittal relations were described by SNA, SNB and ANB (Steiner), the Wits appraisal (Jacobson) and the Beta angle; the simultaneous use of three appraisals reduces dependence on nasion position and occlusal-plane inclination [29]. Vertical morphology was characterised by SN–MP, the Björk sum, the Jarabak posterior-to-anterior facial height ratio, the gonial angle and occlusal-plane inclination. Incisor position was described by IMPA (Tweed), maxillary incisor inclination to the palatal plane, the interincisal angle and the distance of both incisors to the A–Pog line (Ricketts). Tracing was performed by one calibrated examiner; where the rami were doubly imaged, the mean contour was used.

2.5. Cone-beam computed tomography of the mandible and temporomandibular joints

CBCT was acquired with a 12 × 9 cm field of view and reconstructions oriented to the Frankfort horizontal and the midsagittal plane; all measurements were made at identical slice thickness. The central articular slice was selected through the greatest mediolateral dimension of the condyle. Anterior joint space was measured as the shortest distance from the anterior condylar contour to the fossa and posterior joint space from the posterior contour; right and left values were stored separately, and the Pullinger–Hollender index together with its inter-side difference was derived from them. Intercondylar width was taken between the most lateral condylar points and intergonial width between right and left gonion on coronal reconstruction. Mandibular spatial position was described by the pogonion-to-nasion-perpendicular distance and the deviation of menton from the midsagittal plane. The accuracy of cephalometric variables derived from or compared with CBCT reconstructions has been documented previously [30–33].

2.6. Periodontal and alveolar assessment

Gingival thickness, keratinised and attached gingival width were recorded in the mandibular anterior region. Periodontal phenotype was determined by probe transparency according to Kan and co-workers, recession was classified by Cairo, and dehiscence or fenestration was registered from CBCT. Buccal plate thickness was measured on CBCT at the mandibular incisors. Professional hygiene and caries treatment preceded appliance placement in every case.

2.7. Outcome definition

A stable result was defined at 24 months of retention as an increase in the PAR index of less than 4 points, an overjet increase below 1.0 mm, an increase in overbite below 1.0 mm, an increase in Little's irregularity index below 1.5 mm and the absence of new clinically relevant recession. The composite unfavourable endpoint was recorded when at least one of these thresholds was reached, or when a planned movement had to be abandoned because of insufficient osseous or periodontal reserve. Relapse was always computed relative to the state immediately after appliance removal.

2.8. Index construction

Each of the four modules contained three variables belonging to a single morphological domain. A variable scored 0 points when the reserve was adequate, 1 point in a borderline state and 2 points when the limitation was pronounced, so that a module summed from 0 to 6 and was then normalised as $M_j = (\Sigma b_j / 6) \times 100$. This gave all four blocks an identical internal range while leaving their weights unequal. The weights were taken from the relative contribution of each module in the multivariable model and were rounded to values convenient for chairside calculation while preserving their sum, giving the final expression $DACPI = 0.18 \cdot M1 + 0.30 \cdot M2 + 0.24 \cdot M3 + 0.28 \cdot M4$ on a 0–100 scale.

2.9. Statistical analysis

After the 24-month outcome had been established, the cohort was split with strata preserved into a development sample of 89 patients (Group I 28, II 32, III 18, IV 11) and a validation sample of 40 (13, 15, 8 and 4). The two parts did not differ in age ($p = 0.744$) or sex ($p = 0.681$), and the analytical files were held separately: the validation codes were unblinded only after predictor selection and the computation rule had been fixed. Continuous variables were compared by one-way analysis of variance with Tukey's test and categorical variables by Pearson's χ^2 or Fisher's exact test with Holm correction for pairwise comparisons. Univariable and multivariable logistic regression yielded odds ratios with 95 % confidence intervals; collinearity was assessed by Spearman correlation and variance inflation factors. Discrimination was expressed as the area under the ROC curve with bootstrap confidence intervals and compared by DeLong's test; calibration was described by slope, intercept, the Brier score and the Hosmer–Lemeshow statistic. Proportions in the validation sample were reported with Wilson confidence intervals. Significance was accepted at $p < 0.05$.

3. Results

3.1. Composition of the cohort

The 129 patients had a mean age of 29.8 ± 7.0 years; 82 were women and 47 men. Mean age in Groups I–IV was 29.1 ± 7.0, 30.3 ± 7.2, 30.0 ± 6.6 and 30.1 ± 7.5 years respectively, without difference ($F = 0.23$, $p = 0.877$), and the sex ratio was equally homogeneous ($\chi^2 = 0.25$, $p = 0.970$). Subsequent comparisons therefore required no age standardisation. Two baseline characteristics did separate the groups. Oral hygiene was poorer in Group IV (OHI-S 1.63 ± 0.58 versus 1.18–1.34 points elsewhere, $p = 0.025$), and the orthodontic treatment need expressed by the dental health component of IOTN was markedly asymmetric: grades 4–5 were recorded in 24.4 % of Group I but in 86.7 % of Group IV ($p < 0.001$). Caries experience did not differ ($p = 0.602$). Since every patient received professional hygiene and caries treatment before bonding, the hygiene difference did not carry over into the appliance phase.

Table 1. Demographic profile, referral pattern, oral hygiene and orthodontic treatment need in the compared groups

Characteristic	Category	Clinical–morphological group, n (%) I (n = 41)	II (n = 47)	III (n = 26)	IV (n = 15)	Total (n = 129)	p
Age	18–25 years	14 (34.1)	15 (31.9)	9 (34.6)	5 (33.3)	43 (33.3)	>0.999
	26–35 years	17 (41.5)	20 (42.6)	11 (42.3)	6 (40.0)	54 (41.9)	
	36–45 years	10 (24.4)	12 (25.5)	6 (23.1)	4 (26.7)	32 (24.8)	
Sex	Female	26 (63.4)	31 (66.0)	16 (61.5)	9 (60.0)	82 (63.6)	0.970
	Male	15 (36.6)	16 (34.0)	10 (38.5)	6 (40.0)	47 (36.4)	
Referral	First presentation	33 (80.5)	36 (76.6)	20 (76.9)	9 (60.0)	98 (76.0)	0.462
	Repeat presentation	8 (19.5)	11 (23.4)	6 (23.1)	6 (40.0)	31 (24.0)	
Previous orthodontics	Yes	6 (14.6)	8 (17.0)	5 (19.2)	5 (33.3)	24 (18.6)	0.447
Duration of the anomaly	More than 20 years	10 (24.4)	14 (29.8)	7 (26.9)	6 (40.0)	37 (28.7)	0.957
Oral hygiene	OHI-S, points, M ± σ	1.21 ± 0.48	1.34 ± 0.52	1.18 ± 0.44	1.63 ± 0.58	1.31 ± 0.51	0.025
Caries experience	DMFT, teeth, M ± σ	8.7 ± 3.9	9.4 ± 4.1	8.9 ± 3.6	10.2 ± 4.3	9.2 ± 4.0	0.602
IOTN dental health component	Grade 2	8 (19.5)	1 (2.1)	2 (7.7)	0 (0.0)	11 (8.5)	<0.001
	Grade 3	23 (56.1)	16 (34.0)	10 (38.5)	2 (13.3)	51 (39.5)	
	Grade 4	9 (22.0)	24 (51.1)	12 (46.2)	8 (53.3)	53 (41.1)	
	Grade 5	1 (2.4)	6 (12.8)	2 (7.7)	5 (33.3)	14 (10.9)	
IOTN aesthetic component	Points, M ± σ	5.4 ± 1.5	6.7 ± 1.4	6.1 ± 1.3	7.3 ± 1.2	6.2 ± 1.5	<0.001

Categorical variables were compared by Pearson's χ^2 or Fisher's exact test, continuous variables by one-way analysis of variance. OHI-S — simplified oral hygiene index; DMFT — decayed, missing and filled permanent teeth; IOTN — index of orthodontic treatment need.

3.2. Craniofacial, dentoalveolar, periodontal and temporomandibular architecture

Maxillary position relative to the anterior cranial base was similar across the cohort: SNA ranged from 81.6 ° to 82.7 ° without between-group difference ($p = 0.370$). The sagittal disharmony was therefore not driven by systematic maxillary prognathism. All three sagittal appraisals converged on the mandible: SNB fell to 75.5 ± 2.1 ° in Group II and 75.7 ± 2.6 ° in Group IV, ANB rose to 6.5 ± 1.6 ° and 7.0 ± 2.0 °, and the Beta angle fell to 22.9 ± 2.8 ° and 21.8 ± 3.4 ° ($p < 0.001$ for each). Agreement between three measurements taken from different reference planes makes an artefact of cranial-base inclination an unlikely explanation.

Vertical morphology separated Groups III and IV more sharply than any sagittal variable. SN–MP was 23.8 ± 3.8 ° in Group III and 41.5 ± 5.5 ° in Group IV, a range of 17.7 ° between two groups sharing the same distal molar relationship ($F = 60.54$, $p < 0.001$). The Jarabak ratio moved in mirror image, from 68.4 ± 2.6 % to 56.6 ± 3.2 %. Intrusion, molar extrusion and intermaxillary elastic traction cannot carry the same biomechanical meaning at the two ends of this range.

Incisor position revealed how much compensation had already been spent before treatment. IMPA averaged 101.0 ± 6.2 ° in Group II and 98.7 ± 7.8 ° in Group IV against 84.2 ± 5.4 ° in Group III, and the lower incisor already lay 5.8 ± 2.0 mm in front of A–Pog in Group II. Buccal plate thickness followed the reciprocal order, falling from 0.91 ± 0.25 mm in Group III to 0.58 ± 0.20 mm in Group II and 0.36 ± 0.16 mm in Group IV ($F = 25.01$, $p < 0.001$). In Group II a residual overjet of about 8 mm therefore had to be resolved through incisors that were already proclined and supported by roughly half a millimetre of bone.

Tomography of the joints added a constraint that none of the two-dimensional variables expressed. The Pullinger–Hollender index was −13.9 ± 9.2 % in Group II and −17.6 ± 10.7 % in Group IV against −3.5 ± 7.8 % and −1.8 ± 6.9 % in Groups I and III ($F = 21.95$, $p < 0.001$), indicating a relatively posterior condylar seat wherever mandibular retrognathism was present. The inter-side difference reached 22.4 ± 9.6 % in Group IV, more than three times the value of the other groups ($F = 28.17$, $p < 0.001$), consistent with the high proportion of Class II subdivision in that group and paralleled by a menton deviation of 4.2 ± 1.8 mm. A posteriorly seated condyle is not in itself a diagnosis of joint disease, but in combination with retrognathism and a distal occlusion it reduces the admissibility of mechanics that would displace the mandible further backwards.

Table 2. Skeletal, dentoalveolar, periodontal–alveolar and temporomandibular characteristics in the compared groups

Domain	Variable (unit)	Reference, M ± σ	Clinical–morphological group, M ± σ				F	p
			I (n = 41)	II (n = 47)	III (n = 26)	IV (n = 15)		
Sagittal skeletal	SNA angle, °	82.0 ± 2.0	82.4 ± 2.1	82.0 ± 2.3	81.6 ± 2.0	82.7 ± 2.8	1.06	0.370
	SNB angle, °	80.0 ± 2.0	78.9 ± 2.0	75.5 ± 2.1	77.3 ± 1.9	75.7 ± 2.6	21.40	<0.001
	ANB angle, °	2.0 ± 2.0	3.5 ± 1.3	6.5 ± 1.6	4.3 ± 1.4	7.0 ± 2.0	38.37	<0.001
	Wits appraisal, mm	0.0 ± 1.5	2.2 ± 1.4	5.7 ± 2.0	3.6 ± 1.5	6.1 ± 2.5	34.19	<0.001
	Beta angle, °	31.0 ± 4.0	28.8 ± 3.1	22.9 ± 2.8	26.4 ± 2.9	21.8 ± 3.4	36.84	<0.001
Vertical	SN–MP angle, °	32.0 ± 5.0	31.8 ± 4.2	35.8 ± 4.8	23.8 ± 3.8	41.5 ± 5.5	60.54	<0.001
	Björk sum, °	396.0 ± 6.0	396.7 ± 5.5	401.2 ± 6.1	386.7 ± 5.2	407.8 ± 7.0	51.47	<0.001
	Jarabak ratio, %	63.5 ± 2.5	63.3 ± 2.7	60.7 ± 2.8	68.4 ± 2.6	56.6 ± 3.2	69.30	<0.001
	Gonial angle, °	128.0 ± 5.0	128.1 ± 5.0	131.9 ± 5.4	121.7 ± 4.8	136.8 ± 6.1	32.98	<0.001
	Occlusal plane inclination, °	14.0 ± 4.0	14.8 ± 3.4	17.3 ± 3.9	9.8 ± 3.1	21.4 ± 4.6	37.76	<0.001

Domain	Variable (unit)	Reference, M ± σ	Clinical–morphological group, M ± σ				F	p
			I (n = 41)	II (n = 47)	III (n = 26)	IV (n = 15)		
Dentoalveolar	IMPA, °	90.0 ± 5.0	97.2 ± 5.8	101.0 ± 6.2	84.2 ± 5.4	98.7 ± 7.8	44.03	<0.001
	Upper incisor to palatal plane, °	110.0 ± 5.0	118.1 ± 6.5	120.6 ± 7.1	98.5 ± 6.0	116.0 ± 8.4	63.29	<0.001
	Interincisal angle, °	130.0 ± 6.0	115.3 ± 8.1	108.9 ± 8.8	149.1 ± 8.0	116.8 ± 10.6	128.51	<0.001
	Upper incisor to A–Pog, mm	3.5 ± 2.0	6.2 ± 2.0	7.0 ± 2.3	1.2 ± 1.7	6.4 ± 2.8	44.04	<0.001
	Lower incisor to A–Pog, mm	1.0 ± 2.0	4.4 ± 1.8	5.8 ± 2.0	−0.5 ± 1.5	4.1 ± 2.5	62.30	<0.001
Periodontal–alveolar	Gingival thickness, mm	1.20 ± 0.25	1.06 ± 0.23	0.95 ± 0.22	1.22 ± 0.25	0.68 ± 0.18	19.99	<0.001
	Keratinised gingiva width, mm	4.5 ± 1.0	4.1 ± 1.0	3.8 ± 1.0	4.7 ± 1.1	2.8 ± 0.8	12.12	<0.001
	Attached gingiva width, mm	3.0 ± 0.8	2.7 ± 0.9	2.3 ± 0.8	3.2 ± 0.9	1.4 ± 0.6	16.45	<0.001
	Buccal plate thickness (CBCT), mm	0.90 ± 0.30	0.72 ± 0.22	0.58 ± 0.20	0.91 ± 0.25	0.36 ± 0.16	25.01	<0.001
Temporomandibular and mandibular spatial (CBCT)	Pullinger–Hollender condylar position index, %	0.0 ± 8.0	−3.5 ± 7.8	−13.9 ± 9.2	−1.8 ± 6.9	−17.6 ± 10.7	21.95	<0.001
	Inter-side difference of condylar position, %	6.0 ± 4.0	7.2 ± 4.9	9.8 ± 6.1	6.3 ± 4.2	22.4 ± 9.6	28.17	<0.001
	Intergonial width, mm	94.0 ± 5.0	92.8 ± 4.9	90.2 ± 5.1	97.1 ± 4.7	88.7 ± 5.8	13.24	<0.001
	Intercondylar width, mm	112.0 ± 6.0	110.5 ± 5.3	108.1 ± 5.6	114.7 ± 5.1	106.5 ± 6.4	10.31	<0.001
	Pogonion to nasion perpendicular, mm	−2.0 ± 3.0	−3.1 ± 2.7	−8.2 ± 3.1	−4.0 ± 2.5	−8.8 ± 3.6	30.68	<0.001
	Menton deviation from midsagittal plane, mm	0.7 ± 0.5	1.0 ± 0.7	1.2 ± 0.8	0.9 ± 0.6	4.2 ± 1.8	53.38	<0.001

M — mean; σ — standard deviation. Between-group comparison by one-way analysis of variance with Tukey's test. A negative Pullinger–Hollender index denotes a relatively posterior condylar position within the fossa. CBCT — cone-beam computed tomography.

The soft-tissue and osseous envelope of the mandibular anterior segment showed the same gradient in categorical form. A thin periodontal phenotype was present in 38.8 % of the whole cohort but in 86.7 % of Group IV, where no patient had a thick phenotype ($\chi^2 = 28.58$, $p < 0.001$). Dehiscence was detected in 80.0 % and fenestration in 60.0 % of Group IV. Group II is the more instructive contrast: only 42.6 % of these patients had a thin phenotype on probe transparency, yet their mean buccal plate measured 0.58 mm and dehiscence was present in one third. The visible soft-tissue examination therefore under-reported the osseous limitation in precisely the group that required the largest incisor movement.

Table 3. Periodontal phenotype, gingival recession and osseous defects of the mandibular anterior region

Clinical or CBCT feature	Category	Clinical–morphological group, n (%)				p
		I (n = 41)	II (n = 47)	III (n = 26)	IV (n = 15)	
Periodontal phenotype (Kan)	Thin	13 (31.7)	20 (42.6)	4 (15.4)	13 (86.7)	<0.001
	Medium	21 (51.2)	21 (44.7)	11 (42.3)	2 (13.3)	
	Thick	7 (17.1)	6 (12.8)	11 (42.3)	0 (0.0)	
Gingival recession (Cairo)	None	29 (70.7)	30 (63.8)	22 (84.6)	3 (20.0)	<0.001
	RT1	10 (24.4)	12 (25.5)	4 (15.4)	6 (40.0)	
	RT2	2 (4.9)	5 (10.6)	0 (0.0)	5 (33.3)	
	RT3	0 (0.0)	0 (0.0)	0 (0.0)	1 (6.7)	
Dehiscence (CBCT)	Present	8 (19.5)	16 (34.0)	3 (11.5)	12 (80.0)	<0.001
Fenestration (CBCT)	Present	5 (12.2)	11 (23.4)	2 (7.7)	9 (60.0)	<0.001

Between-group differences were assessed by Pearson's χ^2 or Fisher's exact test with Holm correction for pairwise comparisons.

3.3. Occlusal result, mechanism of correction and 24-month stability

Treatment was completed in all 129 patients. The immediate occlusal result was acceptable everywhere, and the absolute PAR reduction did not differ between groups ($F = 1.87$, $p = 0.138$). What differed was the price of that result. Cephalometric superimposition showed that the skeletal contribution to overjet closure never exceeded 0.7 ± 0.4 mm, about 13.5 % of the total even in Group II, so that 83–92 % of the correction was dentoalveolar in every group. IMPA increased by 4.2 ± 3.1 ° in Group I but by 8.4 ± 4.0 ° in Group II and 10.1 ± 4.7 ° in Group IV. In Group II the mean final IMPA approached 109 °, a value that cannot be judged from the occlusal contacts alone.

Relapse at 24 months followed the amount of compensation rather than the initial severity. Across the whole cohort the dentoalveolar contribution correlated with the subsequent overjet increase at $r = 0.54$ ($p < 0.001$), the regression $y = 0.038 + 0.177x$ indicating roughly 0.18 mm of relapse for every additional millimetre of compensation. Compensation of 4 mm or more, achieved in 49 patients, was followed by a mean relapse of 0.93 ± 0.62 mm against 0.42 ± 0.42 mm below that threshold ($t = 5.18$, $p < 0.001$). The vertical dimension behaved differently: Group III remained the most stable sagittally (0.29 ± 0.26 mm) while showing the largest return of overbite (0.78 ± 0.42 mm). Horizontal and vertical relapse are therefore not interchangeable expressions of the same instability.

Table 4. Occlusal outcome, mechanism of dentoalveolar compensation and retention stability in the compared groups

Block	Variable (unit)	Clinical–morphological group, M ± σ				F	p
		I (n = 41)	II (n = 47)	III (n = 26)	IV (n = 15)		
Occlusal outcome	Active treatment duration, months	21.4 ± 3.8	24.8 ± 4.5	23.1 ± 4.2	28.3 ± 5.3	10.66	<0.001
	PAR index before treatment, points	26.5 ± 6.4	32.8 ± 7.2	29.6 ± 6.8	35.4 ± 8.1	8.78	<0.001
	PAR index after treatment, points	3.2 ± 1.8	5.8 ± 2.7	4.2 ± 2.1	8.7 ± 3.8	20.63	<0.001
	Absolute PAR reduction, points	23.3 ± 6.5	27.0 ± 8.1	25.4 ± 7.2	26.7 ± 9.7	1.87	0.138

Block	Variable (unit)	Clinical–morphological group, M ± σ I (n = 41)	II (n = 47)	III (n = 26)	IV (n = 15)	F	p
	Relative PAR reduction, %	87.3 ± 7.4	81.0 ± 10.7	85.0 ± 8.0	73.2 ± 15.7	—	—
	Overjet after treatment, mm	2.5 ± 0.5	2.9 ± 0.7	2.2 ± 0.5	3.3 ± 0.9	12.77	<0.001
	Overbite after treatment, mm	2.6 ± 0.6	2.9 ± 0.7	3.0 ± 0.7	2.8 ± 0.9	2.15	0.097
Mechanism of correction	Change in IMPA, °	4.2 ± 3.1	8.4 ± 4.0	7.1 ± 3.8	10.1 ± 4.7	12.98	<0.001
	Change in upper incisor inclination, °	−7.8 ± 4.2	−10.2 ± 4.8	8.6 ± 4.5	−8.9 ± 5.4	102.58	<0.001
	Skeletal contribution to overjet closure, mm	0.3 ± 0.2	0.7 ± 0.4	0.1 ± 0.1	0.4 ± 0.3	27.63	<0.001
	Dentoalveolar contribution to overjet closure, mm	3.4 ± 0.8	4.5 ± 1.1	0.5 ± 0.4	3.7 ± 1.2	108.31	<0.001
Stability at 24 months	Overjet relapse, mm	0.35 ± 0.31	0.83 ± 0.56	0.29 ± 0.26	1.21 ± 0.71	20.22	<0.001
	Overbite relapse, mm	0.28 ± 0.24	0.48 ± 0.35	0.78 ± 0.42	0.68 ± 0.47	12.22	<0.001
	Increase in Little's irregularity index, mm	0.55 ± 0.39	0.93 ± 0.56	0.72 ± 0.46	1.48 ± 0.81	12.31	<0.001
	PAR relapse, points	1.6 ± 1.1	3.5 ± 1.8	2.4 ± 1.4	5.2 ± 2.4	21.91	<0.001

PAR — peer assessment rating. A positive change in IMPA denotes labial tipping of the mandibular incisors; a negative change in upper incisor inclination denotes retraction. Relapse is expressed relative to the state immediately after appliance removal.

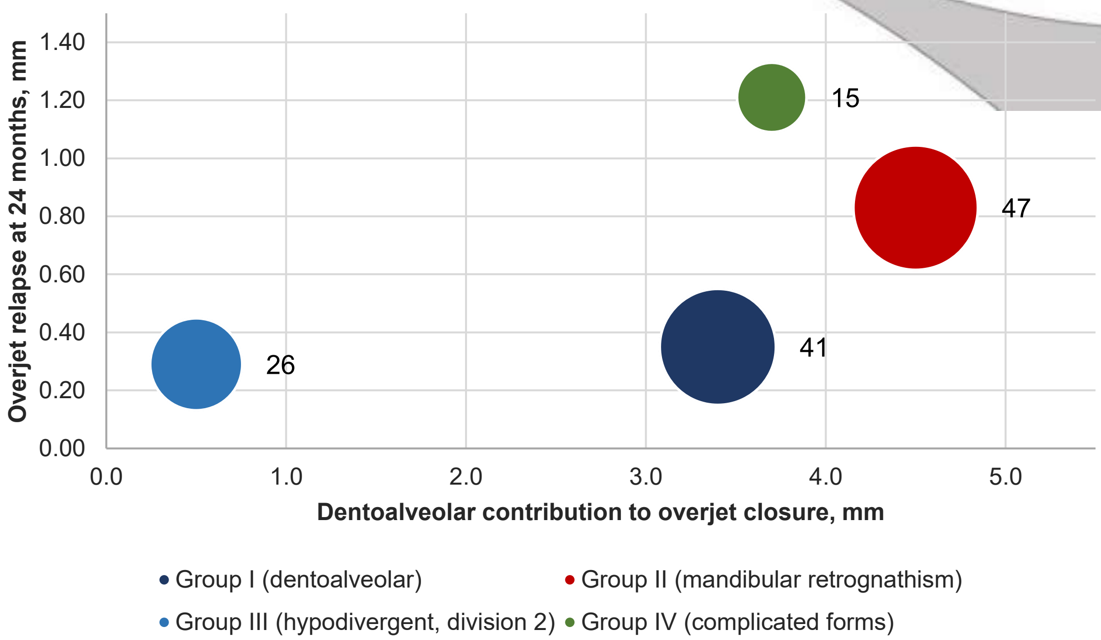

Figure 1. Relationship between the magnitude of dentoalveolar compensation and sagittal relapse at 24 months. Bubble area is proportional to group size. Group III achieved its result almost without horizontal compensation and relapsed least sagittally; Groups II and IV paid for the same occlusal correction with 3.7–4.5 mm of incisor movement and relapsed two to four times more.

3.4. Pre-treatment determinants of stability

The composite unfavourable endpoint occurred in 34 of 89 development-sample patients (38.2 %) and in 15 of 40 validation-sample patients (37.5 %; $\chi^2 = 0.01$, $p = 0.938$). Univariable analysis included only variables measurable before the choice of mechanics. Risk rose progressively with skeletal disharmony — 1.69 per degree of ANB, 1.37 per millimetre of Wits and 1.30 per degree of Beta-angle reduction — but the strongest associations belonged to the vertical and periodontal–alveolar domains. A 3-percentage-point fall in the Jarabak ratio multiplied the odds by 3.39 and a 5-degree increase in SN–MP by 2.84, while each 0.2 mm loss of buccal plate thickness multiplied them by 2.71 and each step of phenotype thinning by 3.43 (Figure 2).

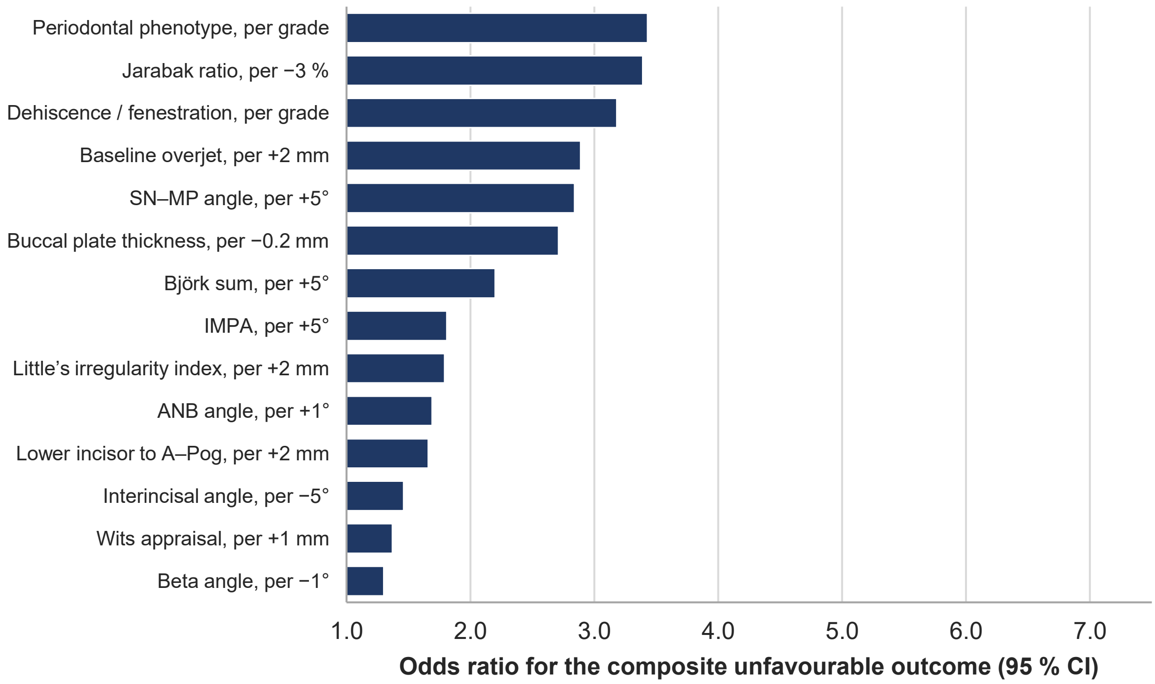

Figure 2. Univariable odds ratios with 95 % confidence intervals for the composite unfavourable 24-month outcome, development sample (n = 89). Increments are defined in the clinically unfavourable direction, so that every ratio exceeding unity denotes increasing risk. The four largest effects belong to the vertical and periodontal–alveolar domains rather than to the sagittal discrepancy itself.

Within each domain the variables were strongly interdependent: ANB correlated with Wits at $\rho = 0.89$ and with the Beta angle at $\rho = -0.89$, while SN–MP and the Jarabak ratio reached $\rho = -0.94$ and IMPA correlated with the position of the lower incisor at $\rho = 0.89$. Cross-domain correlations were far weaker — ANB with IMPA $\rho = 0.28$, ANB with buccal plate thickness $\rho = -0.36$ — so no single variable could stand for the others. Entering twelve collinear measurements into one equation was therefore replaced by a normalised score per domain. Variance inflation factors then lay between 1.42 and 2.18 and no module had to be dropped.

Table 5. Multivariable logistic model of the four domain modules (development sample, n = 89)

Predictor (per 10 normalised points)	B	Standardised coefficient β	OR	95 % CI OR	p	Share of explained variation, %
M1 — sagittal skeletal module	0.182	0.21	1.20	1.05–1.38	0.007	18.4
M2 — vertical module	0.278	0.34	1.32	1.14–1.52	<0.001	29.8
M3 — dentoalveolar module	0.215	0.27	1.24	1.07–1.43	0.004	23.7
M4 — periodontal–alveolar module	0.255	0.32	1.29	1.12–1.49	<0.001	28.1
Constant	−3.91	—	—	—	<0.001	—

B — unstandardised logistic regression coefficient; OR — odds ratio; CI — confidence interval. Nagelkerke $R^2 = 0.49$; Hosmer–Lemeshow $\chi^2 = 5.82$, $p = 0.668$; model $p < 0.001$.

All four modules retained significance after mutual adjustment. The vertical module carried the largest standardised coefficient ($\beta = 0.34$) and the periodontal–alveolar module was close behind ($\beta = 0.32$); their confidence intervals overlapped, so the two were treated as jointly dominant rather than ranked. The sagittal skeletal module made the smallest independent contribution ($\beta = 0.21$) although it remained significant. This ordering does not diminish the role of mandibular retrognathism. Skeletal disharmony determines how much compensation is required; stability depends on whether the vertical and periodontal–alveolar reserve is sufficient to deliver it. Normalising the standardised coefficients gave relative shares of 18.4, 29.8, 23.7 and 28.1 %, rounded for chairside use to 0.18, 0.30, 0.24 and 0.28.

3.5. Structure and diagnostic performance of the index

Table 6. Modular structure, scoring thresholds and weights of the dentoalveolar compensatory potential index

Module	Weight	Variable (unit)	0 points	1 point	2 points
M1 — sagittal skeletal	0.18	ANB angle, °	≤4	>4–7	>7
		Wits appraisal, mm	≤2	>2–5	>5
		Beta angle, °	≥27	22–<27	<22
M2 — vertical	0.30	SN–MP angle, °	≤32	>32–38	>38
		Björk sum, °	≤396	>396–402	>402
		Jarabak ratio, %	≥62	59–<62	<59
	0.24	IMPA, °	≤92	>92–98	>98

Module	Weight	Variable (unit)	0 points	1 point	2 points
M3 — dentoalveolar		Lower incisor to A–Pog, mm	≤3	>3–5	>5
		Interincisal angle, °	≥130	120–<130	<120
M4 — periodontal–alveolar	0.28	Buccal plate thickness, mm	>1.0	0.5–1.0	<0.5
		Periodontal phenotype (Kan)	Thick	Medium	Thin
		Dehiscence and fenestration	None	1–2 teeth	≥3 teeth

Every variable is scored before appliance placement. The module sum is divided by 6 and multiplied by 100, giving M_j on a 0–100 scale. The index is the weighted sum DACPI = 0.18·M1 + 0.30·M2 + 0.24·M3 + 0.28·M4. Interval limits are inclusive unless stated otherwise.

Each module discriminated acceptably on its own but none matched the composite. The vertical module reached an area under the ROC curve of 0.80, the sagittal skeletal module 0.78, the periodontal–alveolar module 0.75 and the dentoalveolar module 0.73. The weighted index reached 0.86 (95 % CI 0.77–0.93) with 82.4 % sensitivity and 80.0 % specificity at the point of maximum Youden index. By DeLong's test the index exceeded the dentoalveolar module ($p = 0.008$) and the periodontal–alveolar module ($p = 0.021$); the difference from the vertical module was smaller ($p = 0.068$), but combining four blocks improved the balance of sensitivity and specificity, and the optimum operating points of the individual modules lay in different regions of the curve (Figure 3).

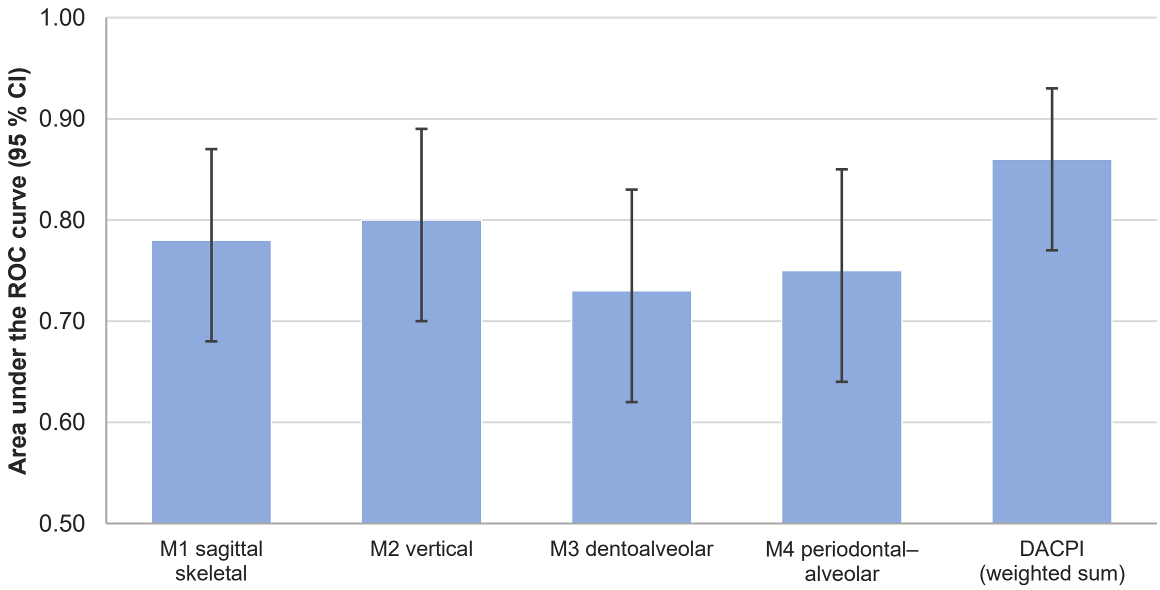

Figure 3. Discrimination of the individual modules and of the weighted index in the development sample (n = 89). Whiskers are bootstrap 95 % confidence intervals. No single anatomical domain reproduces the discrimination of the weighted combination.

Two cut-points were adopted for clinical grading: 33 separates adequate from limited reserve and 59 separates limited reserve from a doubtful prognosis. The choice was not made on the Youden index alone; the observed outcome frequencies, the need for greater sensitivity to periodontal and osseous risk and the interpretability of three equal-sense zones were all taken into account. Median index values were 35.3 points for stable and 70.7 points for unfavourable courses ($U = 389$, $p < 0.001$), with interquartile ranges of 20.0–51.7 and 58.0–83.3.

Table 7. Prognostic grading by index value and observed outcome frequencies (development sample, n = 89)

DACPI range	Prognostic grade	Patients, n	Stable result, n (%)	Unfavourable outcome or relapse, n (%)
0–33	Favourable	31	28 (90.3)	3 (9.7)
34–59	Conditionally favourable	22	15 (68.2)	7 (31.8)
60–100	Doubtful	36	12 (33.3)	24 (66.7)

Difference in the frequency of an unfavourable outcome between the three grades: $\chi^2 = 26.48$, $p < 0.001$; test for linear trend $\chi^2 = 24.31$, $p < 0.001$.

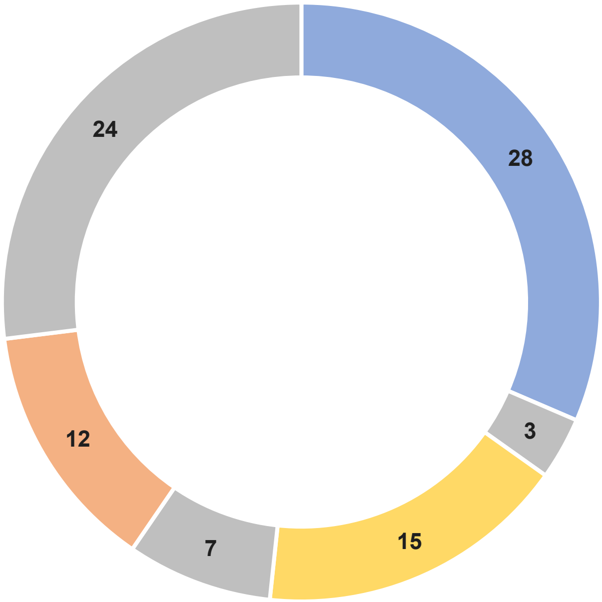

Figure 4. Distribution of the development sample across prognostic grades (inner ring: 31, 22 and 36 patients) and the outcome within each grade (outer ring; grey sectors denote unfavourable outcomes). The proportion of unfavourable courses rises from 9.7 % to 31.8 % and 66.7 % across the three zones.

Retention of a favourable result in one third of the doubtful zone does not contradict the purpose of the index. In several of those patients skeletal anchorage, restriction of proclination, periodontal preparation or a surgical–orthodontic route had already reduced the risk, so the delivered tactic itself modified the expected course. Conversely, the three unfavourable outcomes in the favourable zone were associated predominantly with breaches of the retention regimen and incomplete correction of the deep bite rather than with exhaustion of sagittal reserve.

3.6. Translation of the grade into a clinical route

The clinical route was formed in two steps. The total score defined whether dentoalveolar compensation was admissible; the dominant module defined which mechanical restriction applied. This separation prevents two opposite errors — excessive camouflage when the reserve is exhausted, and unwarranted referral for surgery when a high score arises from a single manageable component. Two patients with an identical score of 50 may require different mechanics: with M1 dominant the limitation concerns skeletal camouflage, with M4 dominant it concerns the direction of incisor movement and the need for periodontal preparation. The modular profiles of three documented courses illustrate this (Figure 5).

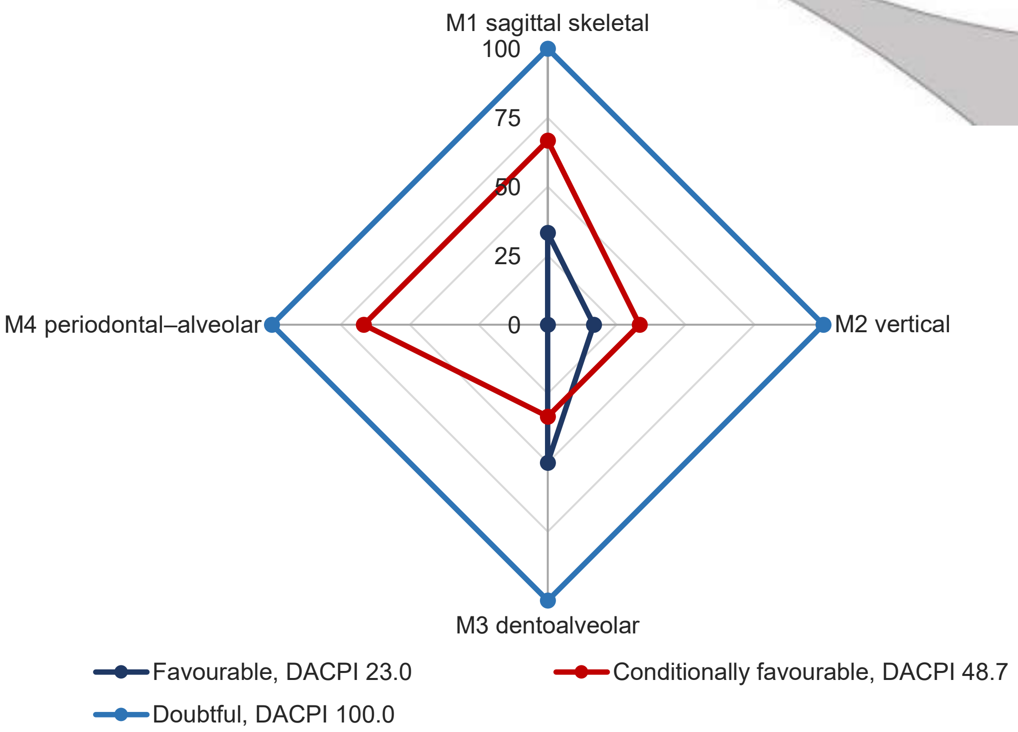

Figure 5. Normalised modular profiles of three documented courses. The favourable case carried its only limitation in the dentoalveolar domain and was treated by maxillary distalisation on skeletal anchorage with a final IMPA change of 2.1 °. The conditionally favourable case combined sagittal and periodontal–alveolar limitation and was treated without mandibular proclination. The doubtful case reached the ceiling in all four domains and was redirected to a surgical–orthodontic route. Equal total scores can conceal opposite mechanical requirements, which is why the profile is read together with the sum.

Table 8. Correspondence between prognostic grade, dominant module and the recommended clinical route

Grade	Dominant module	Recommended clinical route	Principal indications	Principal restrictions
0–33 Favourable	M1	Orthodontic camouflage with anchorage control; moderate distalisation or retraction of the maxillary arch	ANB up to 4–5°; adequate incisor and periodontal reserve	Planned large proclination of the mandibular incisors for the sake of a Class I contact alone
	M2	Vertically neutral mechanics; control of molar extrusion	SN–MP no higher than the borderline range; stable facial height	Prolonged Class II elastics without control of the vertical effect
	M3	Restricted change of incisor inclination with prescribed torque	IMPA and A–Pog distance retain reserve; interincisal angle not below 120°	Unplanned labial loss of mandibular incisor torque
	M4	Conventional correction with hygiene control	Bone thickness predominantly above 1 mm; thick or medium phenotype	Movement beyond the osseous envelope
	M1	Camouflage on skeletal anchorage;	Moderate skeletal disharmony;	Pronounced retrognathism with

Grade	Dominant module	Recommended clinical route	Principal indications	Principal restrictions
34–59 Conditionally favourable		limited distalisation, controlled retraction	refusal of surgery; acceptable profile	ANB > 7° and Wits > 5 mm without surgical consultation
	M2	Miniscrew anchorage, intrusion where indicated, exclusion of extrusive forces	Hyperdivergent tendency without gross facial disproportion	Prolonged intermaxillary traction that opens the mandibular plane
	M3	Extraction or distalisation mechanics preserving the position of the mandibular incisors	Initial proclination with adequate alveolar bone thickness	Additional proclination when IMPA > 98° and L1–A–Pog > 5 mm
	M4	Periodontal preparation, light forces, CBCT monitoring, skeletal anchorage	Thin phenotype and local defects with movement achievable inside the envelope	Buccal incisor movement without prior augmentation of tissue volume
60–100 Doubtful	M1	Surgical–orthodontic correction removing the skeletal discrepancy	ANB > 7°; Wits > 5 mm; Beta < 22°; pronounced profile disturbance	Full camouflage achieved by incisor tipping
	M2	Combined treatment with surgical control of the vertical proportions	SN–MP > 38°; Björk sum > 402°; Jarabak ratio < 59 %	Posterior tooth extrusion and prolonged Class II traction
	M3	No further incisor compensation; surgical route or a limited treatment objective	Inclination and position of the incisors already exhausted	Proclination of the mandibular anterior segment and loss of cortical coverage
	M4	Periodontal augmentation and surgical–orthodontic correction; minimal movement if the patient declines	Bone < 0.5 mm; thin phenotype; multiple dehiscences	Labial root movement without prior preparation

The route is refined according to the patient's complaints, facial profile, temporomandibular status, the magnitude of planned movement and informed consent. When two modules share the maximum value the restrictions of both are treated as mandatory.

3.7. Internal validation and concordance of the delivered tactic

Every patient had been treated according to decisions taken before the index existed, so its value was assessed retrospectively without interfering with the tactic actually chosen. Each validation-sample record was assigned an index value and a dominant module from pre-treatment data, and the computed recommendation was then compared with the treatment delivered. Twenty-four courses were classified as index-concordant and sixteen as index-divergent. The two subgroups did not differ at baseline in overjet, overbite, PAR, ANB, SN–MP, IMPA or buccal plate thickness (p > 0.20 throughout), so the difference in outcome reflects the degree of correspondence between treatment and prognosis rather than initial severity.

Table 9. Outcomes according to concordance between the delivered tactic and the index recommendation (validation sample, n = 40)

Outcome criterion	Index-concordant treatment (n = 24), n (%)	Index-divergent treatment (n = 16), n (%)	p
Planned occlusal result achieved	23 (95.8)	11 (68.8)	0.031
Result stable at 24 months	21 (87.5)	9 (56.3)	0.034
Periodontal or cortical plate complication	2 (8.3)	6 (37.5)	0.033
Biologically risky incisor movement	2 (8.3)	7 (43.8)	0.012
Forced change of the clinical route	1 (4.2)	5 (31.3)	0.021

Proportions were compared by Fisher's exact test. Complications comprised new or increased recession, radiographic signs of lost buccal bone coverage and the need to abandon a planned movement.

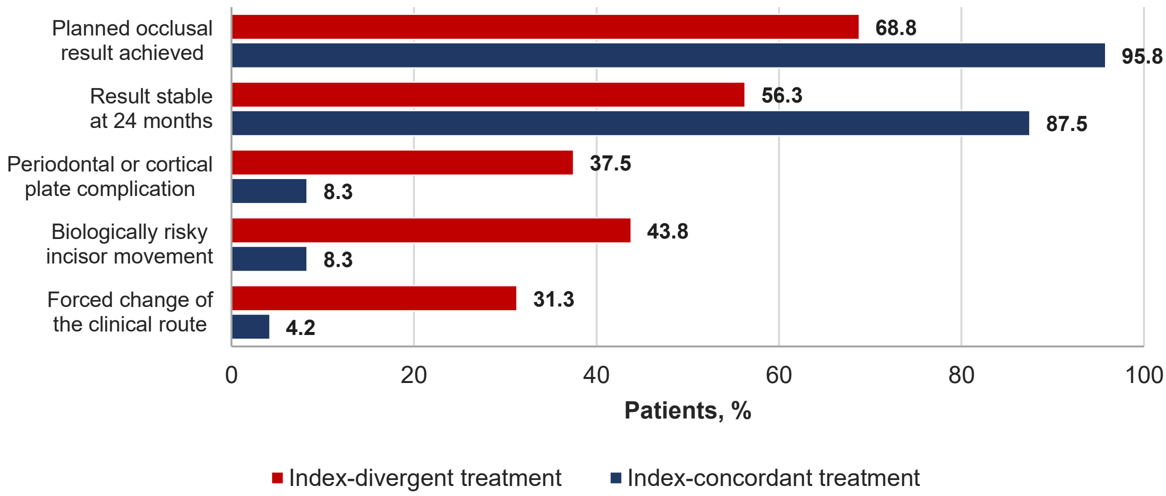

Figure 6. Outcomes of the validation sample according to concordance between the delivered tactic and the index recommendation. The effect is bidirectional: the two desirable criteria rise and the three undesirable criteria fall, which is difficult to explain by a milder initial condition in the concordant subgroup.

The absolute difference in the frequency of biologically risky movement reached 35 percentage points and in the frequency of complications 29 percentage points. Concordance was thus associated most strongly with precisely those outcomes that express the biological cost of camouflage. In the validation sample the model classified 33 of 40 courses correctly (Table 10). Negative predictive value reached 87.5 %, so a low score corresponded reliably to preservation of the result; positive predictive value was lower at 75.0 %, which is expected of an instrument designed not to declare relapse inevitable but to identify patients in whom camouflage must be restricted. Part of the positive predictions did not materialise as complications precisely because the tactic was modified.

Table 10. Diagnostic accuracy of the prognostic model in the validation sample

Metric	Value, %	Observations	95 % CI, %
Accuracy	82.5	33 of 40	68.1–91.3
Sensitivity	80.0	12 of 15	54.8–93.0
Specificity	84.0	21 of 25	65.3–93.6
Positive predictive value	75.0	12 of 16	50.5–89.8
Negative predictive value	87.5	21 of 24	69.0–95.7

A positive prediction denotes limited or exhausted compensatory reserve; a positive actual event denotes clinically relevant relapse, a complication or the need to change the route. Confidence intervals were computed by Wilson's method. Calibration slope 0.93, intercept 0.04, Brier score 0.16, Hosmer–Lemeshow p = 0.714.

Calibration held across the range and not merely on average. Where the computed probability was below 0.30 the observed proportion of unfavourable outcomes did not exceed 25 %, and above 0.70 it reached 79 %. Slight over-estimation of risk in the upper quintile is attributable to the more cautious or surgically oriented tactics that high-scoring patients received.

4. Discussion

The central finding of this cohort is that the stability of a comprehensive occlusal and temporomandibular rehabilitation in the adult Class II patient is governed less by the size of the sagittal discrepancy than by the reserve available to compensate it. The sagittal skeletal module remained an independent predictor, yet it accounted for only 18.4 % of the explained variation, while the vertical and periodontal–alveolar modules together accounted for 57.9 %. Expressed clinically: the discrepancy states how much movement is needed, the vertical pattern and the alveolar envelope state whether that movement can be delivered without cost.

This is consistent with the CBCT literature on the anterior mandible. Alveolar bone thickness has repeatedly been shown to decrease with steeper incisor inclination and with hyperdivergent facial patterns [10–12], and prospective follow-up after premolar extraction has documented measurable remodelling of the labial plate around mandibular incisors [15, 16]. Long-term cohorts report gingival recession years after appliance removal in a substantial minority of orthodontic patients [13, 14]. Our data add a quantitative bridge between those observations and treatment planning: every 0.2 mm reduction of buccal plate thickness multiplied the odds of an unfavourable 24-month course by 2.71, and each step of phenotype thinning by 3.43. Group II is the clinically instructive case, because a thin phenotype was recorded on probe transparency in fewer than half of these patients while their mean buccal plate measured 0.58 mm. Visual periodontal assessment alone under-reports the osseous limitation in exactly the patients who require the largest incisor movement.

The temporomandibular findings support treating the joint as an independent planning constraint rather than as a derivative of the occlusal class. A posteriorly seated condyle was characteristic of both retrognathic groups, and marked inter-side asymmetry was characteristic of the complicated group, mirroring three-dimensional analyses of condylar position and volume in skeletal Class II with different vertical patterns [7–9]. None of this constitutes a diagnosis of joint disease. Its planning significance is directional: when the condyle already occupies a relatively posterior position and the mandible is retrognathic, mechanics that rotate the mandible backwards or maintain prolonged Class II traction act against a reduced anterior reserve. This is why the vertical module, which governs precisely those mechanics, carried the largest independent weight, and why the route matrix restricts prolonged elastics and posterior extrusion whenever it dominates.

The mechanism data explain why the immediate occlusal result is a poor endpoint in adults. Absolute PAR reduction did not differ between groups, yet the skeletal contribution to overjet closure never exceeded 0.7 mm and 83–92 % of the correction was dentoalveolar. The amount of that compensation, not the initial severity, predicted relapse (r = 0.54), and the 4 mm threshold distinguished a mean relapse of 0.93 mm from 0.42 mm. Two patients finishing with identical PAR scores may therefore stand in entirely different positions with respect to the alveolar envelope. The divergence between sagittal and vertical relapse in Group III makes the same point from the opposite direction: the most sagittally stable group showed the greatest return of overbite.

Comparison with published mechanics is informative. Miniscrew-supported maxillary distalisation and aligner-based distalisation both achieve molar correction with limited anchorage loss [17–19, 21, 22], and overbite control with aligners has been examined specifically [20]. Our route matrix does not rank appliances; it constrains the direction and the anchorage of movement according to which reserve is exhausted. That is why the same appliance may be admissible under one modular profile and restricted under another. Alveolar decortication has been proposed to widen the biological envelope [23], and soft-tissue studies show that incisor retraction produces predictable but individually variable profile change [24–26]; airway consequences of premolar extraction appear limited [27, 28]. All of these belong downstream of the decision the index is designed to inform, which is whether compensation is admissible at all.

Contemporary prediction research is dominated by machine-learning approaches, including automated skeletal classification, landmark detection and decision support for orthognathic planning [34–40]. Those models frequently exceed the discrimination reported here. The trade-off is interpretability and transportability: a high risk probability from a neural model does not state which anatomical domain generated it, and reproducing it requires a comparable dataset. The present index is deliberately positioned differently. Twelve variables that are already measured in an ordinary diagnostic work-up are collapsed into four modules, each scored 0–2 per variable, and the result is a number accompanied by a named dominant limitation. The clinical output is not 'risk 0.71' but 'limited reserve, periodontal–alveolar module dominant', which maps directly onto a restriction of movement.

The concordance analysis is the most clinically direct result and also the most cautiously interpreted. Baseline comparability of the two subgroups and the bidirectional pattern of the differences — desirable outcomes higher, undesirable outcomes lower — argue against a simple confounding by initial severity. Nevertheless this was a retrospective comparison of tactics chosen for other reasons, and concordance may act in part as a marker of more conservative clinical judgement in general. The finding justifies a prospective trial, not a claim of causality.

Several limitations should be stated. The study was conducted in a single centre and validated internally by a stratified split rather than in an external population; the validation sample of 40 patients yields wide confidence intervals, particularly for sensitivity (54.8–93.0 %). Group IV contained only 15 patients, so the complicated forms are represented but not finely characterised. Radiographic follow-up was not repeated routinely for research purposes, so post-treatment buccal plate thickness was assessed only where clinically indicated. The joint assessment was positional and morphological; no instrumented functional or magnetic resonance evaluation of the disc was available, so the index constrains mechanics by joint position rather than by joint function. Finally, the composite endpoint combines occlusal and biological events of unequal weight, a design choice that increases the event rate and clinical relevance but prevents separate modelling of each component.

Future work should test the index externally, in centres with different treatment philosophies, and prospectively, with the recommendation issued before treatment rather than reconstructed afterwards. Adding functional joint variables and, in a larger sample, allowing the module weights to be re-estimated by penalised regression would be the natural next steps.

5. Conclusions

1. In adults with Class II malocclusion the immediate occlusal result is attainable across all morphological variants, but its stability is determined chiefly by the vertical and periodontal–alveolar reserve: these two domains accounted for 57.9 % of the explained variation against 18.4 % for the sagittal skeletal domain.
2. Correction in the completed dentition is almost entirely dentoalveolar, and the magnitude of that compensation — not the initial severity of the anomaly — predicts 24-month relapse; compensation of 4 mm or more more than doubled the mean sagittal relapse.
3. Condylar position and inter-side asymmetry, measurable on the diagnostic CBCT, differ systematically between morphological variants and constrain the admissible mechanics independently of the occlusal class; they should therefore enter the treatment plan rather than the differential diagnosis alone.
4. A weighted four-domain index computed before appliance placement discriminated stable from unstable courses with an area under the ROC curve of 0.86 in development and an accuracy of 82.5 % with a calibration slope of 0.93 in internal validation, outperforming every individual module.
5. Reading the total score together with the dominant module converts the prognosis into a specific mechanical restriction; where the delivered tactic corresponded to that restriction, 24-month stability was 87.5 % versus 56.3 % and biologically risky incisor movement 8.3 % versus 43.8 %.

Declarations

Ethics approval and consent to participate. The study was performed in accordance with the Declaration of Helsinki and approved by the institutional ethics committee of Tashkent State Dental Institute. All participants gave written informed consent for the use of anonymised clinical data.

Consent for publication. Written consent for publication of clinical material was obtained from the patients concerned.

Availability of data and materials. The anonymised dataset analysed during the current study is available from the corresponding author on reasonable request.

Competing interests. The authors declare that they have no competing interests.

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Authors' contributions. Nasimov E. E. — conception and design of the study, clinical management, drafting of the manuscript. Rasulova Sh. R. — cephalometric and tomographic analysis, interpretation of data. Kodirova S. U. — periodontal assessment, data acquisition. Sotivoldieva S. Z. — statistical analysis and construction of the index. Rakhmanova D. R. — retention follow-up, database curation. Sotivoldiev U. T. — critical revision for important intellectual content. All authors read and approved the final manuscript.

References

1. Alhammadi MS, Halboub E, Fayed MS, Labib A, El-Saaidi C. Global distribution of malocclusion traits: a systematic review. Dental Press J Orthod. 2018;23(6):40.e1–40.e10. doi:10.1590/2177-6709.23.6.40.e1-10.onl
2. Lombardo G, Vena F, Negri P, Pagano S, Barilotti C, Paglia L, et al. Worldwide prevalence of malocclusion in the different stages of dentition: a systematic review and meta-analysis. Eur J Paediatr Dent. 2020;21(2):115–22. doi:10.23804/ejpd.2020.21.02.05
3. Sivakumar A, Nalabothu P, Nguyen HT, Antonarakis GS. A comparison of craniofacial characteristics between two different adult populations with Class II malocclusion — a cross-sectional retrospective study. Biology. 2021;10(5):438. doi:10.3390/biology10050438
4. Ardani IGAW, Willyanti I, Narmada IB. Correlation between vertical components and skeletal Class II malocclusion in ethnic Javanese. Clin Cosmet Investig Dent. 2018;10:297–302. doi:10.2147/CCIDE.S188414
5. Perović T. The influence of Class II division 2 malocclusions on the harmony of the human face profile. Med Sci Monit. 2017;23:5589–98. doi:10.12659/MSM.905453
6. Freudenthaler J, Čelar A, Ritt C, Mitteröcker P. Geometric morphometrics of different malocclusions in lateral skull radiographs. J Orofac Orthop. 2017;78(1):11–20. doi:10.1007/s00056-016-0057-x
7. Al-Hadad SA, Alyafrusee ES, Abdulqader AA, Al-Gumaei WS, Al-Mohana RAAM, Ren L. Comprehensive three-dimensional positional and morphological assessment of the temporomandibular joint in skeletal Class II patients with mandibular retrognathism in different vertical skeletal patterns. BMC Oral Health. 2022;22(1):149. doi:10.1186/s12903-022-02174-6
8. Rivero-Millán P, Barrera-Mora JM, Espinar-Escalona E, González-del Pino CA, Martín-Salvador D, Llamas-Carreras JM. Comparison of condylar position in normal occlusion, Class II Division 1, Class II Division 2 and Class III malocclusions using CBCT imaging. J Clin Exp Dent. 2021;13(12):e1216–e1226. doi:10.4317/jced.58970
9. Ceratti C, Maspero C, Consonni D, Caprioglio A, Connelly S, Inchingolo F, et al. Cone-beam computed tomographic assessment of the mandibular condylar volume in different skeletal patterns: a retrospective study in adult patients. Bioengineering. 2022;9(3):102. doi:10.3390/bioengineering9030102
10. Dalaie K, Hajimiresmail YS, Safi Y, Baghban AA, Behnaz M, Rafsanjan KT. Correlation of alveolar bone thickness and central incisor inclination in skeletal Class I and II malocclusions with different vertical skeletal patterns: a CBCT study. Am J Orthod Dentofacial Orthop. 2023;164(4):537–44. doi:10.1016/j.ajodo.2023.02.021
11. Srebrzyńska-Witek A, Koszowski R, Różyło-Kalinowska I. Relationship between anterior mandibular bone thickness and the angulation of incisors and canines — a CBCT study. Clin Oral Investig. 2018;22(3):1567–78. doi:10.1007/s00784-017-2255-3
12. Foosiri P, Mahatumarat K, Panmekiate S. Relationship between mandibular symphysis dimensions and mandibular anterior alveolar bone thickness as assessed with cone-beam computed tomography. Dental Press J Orthod. 2018;23(1):54–62. doi:10.1590/2177-6709.23.1.054-062.oar
13. Morris JW, Campbell PM, Tadlock LP, Boley J, Buschang PH. Prevalence of gingival recession after orthodontic tooth movements. Am J Orthod Dentofacial Orthop. 2017;151(5):851–9. doi:10.1016/j.ajodo.2016.09.027
14. Gebistorf M, Mijuskovic M, Pandis N, Fudalej PS, Katsaros C. Gingival recession in orthodontic patients 10 to 15 years posttreatment: a retrospective cohort study. Am J Orthod Dentofacial Orthop. 2018;153(5):645–55. doi:10.1016/j.ajodo.2017.08.020
15. Qin Q, Guo R, Li L, Zhu K, Su X, Zhang L, et al. Alveolar bone remodelling and stability of mandibular incisors in adult patients after orthodontic treatment with premolar extractions: a prospective follow-up study. Orthod Craniofac Res. 2024;27(3):413–20. doi:10.1111/ocr.12741
16. Maspero C, Gaffuri F, Castro IO, Lanteri V, Ugolini A, Farronato M. Correlation between dental vestibular–palatal inclination and alveolar bone remodeling after orthodontic treatment: a CBCT analysis. Materials. 2019;12(24):4225. doi:10.3390/ma12244225
17. Mohamed RN, Basha S, Al-Thomali Y. Maxillary molar distalization with miniscrew-supported appliances in Class II malocclusion: a systematic review. Angle Orthod. 2018;88(4):494–502. doi:10.2319/091717-624.1
18. Duran GS, Görgülü S, Dindaroğlu F. Three-dimensional analysis of tooth movements after palatal miniscrew-supported molar distalization. Am J Orthod Dentofacial Orthop. 2016;150(1):188–97. doi:10.1016/j.ajodo.2015.12.024
19. Ravera S, Castroflorio T, Garino F, Daher S, Cugliari G, Deregibus A. Maxillary molar distalization with aligners in adult patients: a multicenter retrospective study. Prog Orthod. 2016;17:12. doi:10.1186/s40510-016-0126-0
20. Khosravi R, Cohanim B, Hujoel PP, Daher S, Neal M, Liu W, et al. Management of overbite with the Invisalign appliance. Am J Orthod Dentofacial Orthop. 2017;151(4):691–9.e2. doi:10.1016/j.ajodo.2016.09.022

21. Ke Y, Zhu Y, Zhu M. A comparison of treatment effectiveness between clear aligner and fixed appliance therapies. BMC Oral Health. 2019;19:24. doi:10.1186/s12903-018-0695-z
22. Zheng M, Liu R, Ni Z, Yu Z. Efficiency, effectiveness and treatment stability of clear aligners: a systematic review and meta-analysis. Orthod Craniofac Res. 2017;20(3):127–33. doi:10.1111/ocr.12177
23. Charavet C, Lecloux G, Bruwier A, Rompen E, Maes N, Limme M, et al. Localized piezoelectric alveolar decortication for orthodontic treatment in adults: a randomized controlled trial. J Dent Res. 2016;95(9):1003–9. doi:10.1177/0022034516645066
24. Baek ES, Hwang S, Choi YJ, Roh MR, Nguyen T, Kim KH, et al. Quantitative and perceived visual changes of the nasolabial fold following orthodontic retraction of lip protrusion. Angle Orthod. 2018;88(4):465–73. doi:10.2319/100317-665.1
25. Lu W, Zhang X, Mei L, Wang P, He J, Li Y, et al. Orthodontic incisor retraction caused changes in the soft tissue chin area: a retrospective study. BMC Oral Health. 2020;20:108. doi:10.1186/s12903-020-01099-2
26. Rongo R, Nissen L, Leroy C, Michelotti A, Cattaneo PM, Cornelis MA. Three-dimensional soft tissue changes in orthodontic extraction and non-extraction patients: a prospective study. Orthod Craniofac Res. 2021;24(Suppl 2):181–92. doi:10.1111/ocr.12506
27. Cho HN, Yoon HJ, Park JH, Park YG, Kim SJ. Effect of extraction treatment on upper airway dimensions in patients with bimaxillary skeletal protrusion relative to their vertical skeletal pattern. Korean J Orthod. 2021;51(3):166–78. doi:10.4041/kjod.2021.51.3.166
28. Papageorgiou SN, Zyli M, Papadopoulou AK. Extraction of premolars in orthodontic treatment does not negatively affect upper airway volume and minimum cross-sectional area: a systematic review with meta-analysis. Eur J Orthod. 2025;47(2):cjaf012. doi:10.1093/ejo/cjaf012
29. Dinesh A, Mutalik S, Feldman J, Tadinada A. Value-addition of lateral cephalometric radiographs in orthodontic diagnosis and treatment planning. Angle Orthod. 2020;90(5):665–71. doi:10.2319/062319-425.1
30. Baldini B, Cavagnetto D, Baselli G, Sforza C, Tartaglia GM. Cephalometric measurements performed on CBCT and reconstructed lateral cephalograms: a cross-sectional study providing a quantitative approach of differences and bias. BMC Oral Health. 2022;22(1):98. doi:10.1186/s12903-022-02131-3
31. van Bunningen RH, Dijkstra PU, Dieters A, van der Meer WJ, Kuijpers-Jagtman AM, Ren Y. Precision of orthodontic cephalometric measurements on ultra low dose–low dose CBCT reconstructed cephalograms. Clin Oral Investig. 2022;26(2):1543–50. doi:10.1007/s00784-021-04127-9
32. Maspero C, Abate A, Bellincioni F, Cavagnetto D, Lanteri V, Costa A, et al. Comparison of a tridimensional cephalometric analysis performed on 3T-MRI compared with CBCT: a pilot study in adults. Prog Orthod. 2019;20(1):40. doi:10.1186/s40510-019-0293-x
33. Caetano GFR, Soares MQS, Oliveira LB, Junqueira JLC, Nascimento MCC. Two-dimensional radiographs versus cone-beam computed tomography in planning mini-implant placement: a systematic review. J Clin Exp Dent. 2022;14(8):e669–e677. doi:10.4317/jced.59384
34. Liu J, Chen Y, Li S, Zhao Z, Wu Z. Machine learning in orthodontics: challenges and perspectives. Adv Clin Exp Med. 2021;30(10):1065–74. doi:10.17219/acem/138702
35. Liu J, Zhang C, Shan Z. Application of artificial intelligence in orthodontics: current state and future perspectives. Healthcare. 2023;11(20):2760. doi:10.3390/healthcare11202760
36. Dipalma G, Inchingolo AD, Inchingolo AM, Piras F, Carpentiere V, Garofoli G, et al. Artificial intelligence and its clinical applications in orthodontics: a systematic review. Diagnostics. 2023;13(24):3677. doi:10.3390/diagnostics13243677
37. Du W, Bi W, Liu Y, Zhu Z, Tai Y, Luo E. Machine learning-based decision support system for orthognathic diagnosis and treatment planning. BMC Oral Health. 2024;24(1):286. doi:10.1186/s12903-024-04063-6
38. Strunga M, Urban R, Surovková J, Thurzo A. Artificial intelligence systems assisting in the assessment of the course and retention of orthodontic treatment. Healthcare. 2023;11(5):683. doi:10.3390/healthcare11050683
39. Nan L, Tang M, Liang B, Mo S, Kang N, Song SH, et al. Automated sagittal skeletal classification of children based on deep learning. Diagnostics. 2023;13(10):1719. doi:10.3390/diagnostics13101719
40. Park JH, Hwang HW, Moon JH, Yu Y, Kim HS, Her SB, et al. Automated identification of cephalometric landmarks: part 1 — comparisons between the latest deep-learning methods YOLOv3 and SSD. Angle Orthod. 2019;89(6):903–9. doi:10.2319/022019-127.1