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Cephalometric Changes Associated with Clockwise and Counterclockwise Mandibular Rotation in Adult Orthodontic Patients, with an Assessment of Reuleaux Center-of-Rotation Estimation

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Abstract

The mandibular center of rotation (CoR) influences orthodontic treatment outcomes, yet most previous studies focused on counterclockwise (CCW) rotation in homogeneous populations. This study evaluated cephalometric changes associated with clockwise (CW) and CCW mandibular rotation and analyzed mandibular CoR location in a racially diverse adult population. One hundred adults who completed comprehensive orthodontic treatment (CCW, $n = 33$; CW, $n = 67$) were retrospectively analyzed. Pretreatment and posttreatment cephalograms generated from cone-beam computed tomography (CBCT) datasets were assessed for sagittal and vertical skeletal changes. Mandibular CoR was determined using the Reuleaux method after anterior cranial base superimposition. CCW rotation was associated with decreased mandibular plane angle and anterior facial height, whereas CW rotation was associated with corresponding increases. Pogonion moved posteroinferiorly in the CW group. In the CCW group, its anterior movement was not statistically significant, although the change in pogonion position differed significantly between groups. The median CoR was found to be 35.2 mm anterior and 37.8 mm inferior to condylion, but individual estimates spanned more than 2000 mm and did not stabilize when the analysis was restricted to larger rotations. The median rotation was 1.6°. CW and CCW mandibular rotations were associated with opposite changes in facial height and chin position. At rotations of this magnitude, CoR locations found by the Reuleaux method are highly uncertain and should not be interpreted as characteristic positions of the mandibular center of rotation.

Keywords: mandibular center of rotation; clockwise and counterclockwise rotation; CBCT-generated cephalograms; Reuleaux method; McNamara's cephalometric framework

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1. Introduction

Mandibular rotation is a common consequence of comprehensive orthodontic treatment and plays a critical role in determining treatment outcomes. Counterclockwise (CCW) rotation tends to decrease lower anterior facial height (LAFH) while advancing the chin, whereas clockwise (CW) rotation increases LAFH and produces a more retrusive chin

position. These rotational changes have important implications for facial esthetics, occlusal stability, and treatment planning [1]. Despite their clinical significance, the biomechanical characteristics of mandibular rotation, particularly the location of the center of rotation (CoR), remain incompletely understood across different skeletal patterns and racial populations. The CoR is not a fixed anatomical point but rather an individual point that varies among patients, the magnitude and direction of displacement, and the biomechanics of their treatment [2].

The relationship between LAFH and anteroposterior chin position has long been recognized as a fundamental principle in cephalometric diagnosis. McNamara's cephalometric analysis demonstrated that changes in LAFH can substantially influence the apparent sagittal position of the chin relative to the nasion perpendicular (Figure 1). An excessive LAFH is typically associated with a more retrusive mandibular profile, whereas shorter LAFH is associated with a more prognathic mandible [3]. These concepts are important components of contemporary orthodontic diagnosis and treatment planning, underscoring the clinical importance of understanding the mechanisms underlying mandibular rotation and positional change.

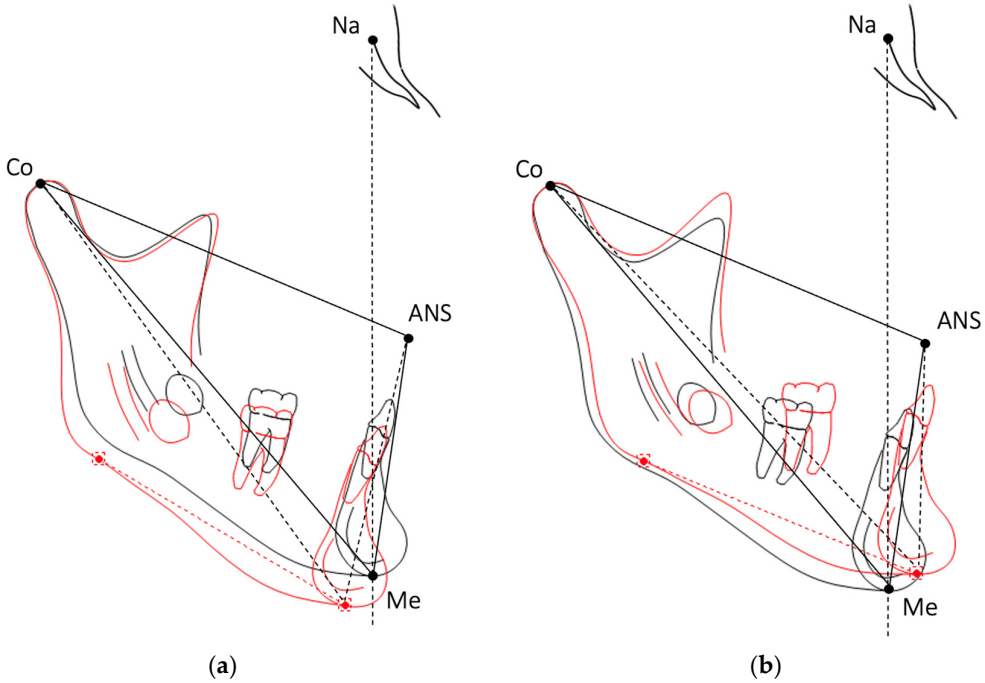

Figure 1. McNamara's principle illustrates the relationship between lower anterior facial height (LAFH) and effective mandibular length. (**a**) An excessive LAFH results in apparent mandibular retrusion. (**b**) A reduction of LAFH results in relative mandibular protrusion.

The mandibular CoR, defined as the point about which the mandible rotates between two positions [4], is a key parameter for predicting treatment outcomes. It is well established that the molar intrusion via temporary anchorage devices produce CCW mandibular rotation and reduced vertical facial height during anterior open bite correction [5], and prior investigations employing the Reuleaux kinematic method have located the resulting CoR posterior and inferior to condylion [6]. In a landmark study of a Korean population, Kim et al. reported that the average CoR was positioned 7.4 mm posterior and 16.9 mm inferior to condylion in patients undergoing CCW mandibular rotation through molar intrusion [6]. However, the precision of Reuleaux method depends heavily on the use of sufficiently separated reference landmarks and an adequate magnitude of mandibular rotation. Estimation errors of CoR increase as the rotational angle decreases, especially when

rotations are less than 6° [7]. Moreover, existing evidence is limited to CCW rotation, a single treatment method involving temporary anchorage device–assisted molar intrusion, and relatively homogeneous racial cohorts. As a result, it is unclear whether the previous findings can be generalized to other racial groups treated with different biomechanical modalities.

Several important gaps remain in the current understanding of mandibular rotational biomechanics. First, CW mandibular rotation, which occurs during many conventional orthodontic treatments involving molar extrusion, arch expansion, or Class II correction [8,9], has received little attention, despite evidence that appliance modality itself can influence posterior tooth position and vertical dimension [10]. Second, the influence of different skeletal patterns and dentoskeletal changes on CoR location has not been systematically investigated. Third, although the mandibular rotation was studied through longitudinal implant studies in Scandinavian populations [11], the only study to quantify the mandibular CoR using the Reuleaux method in a nonsurgical orthodontic sample was conducted in a Korean cohort [6]. As a result, clinical application of these findings to racially diverse populations remain uncertain. Finally, the potential influence of orthodontic tooth extraction on mandibular rotational mechanics and CoR location has been unclear. Recent evidence only suggest that extraction therapy may alter mandibular kinematics [12]. Overall, such limitations highlight the need for a broader evaluation of mandibular rotation across diverse populations, treatment modalities, and rotational patterns.

To address these uncertainties, the present study retrospectively analyzed a racially diverse cohort of adult patients who completed comprehensive orthodontic treatment in a United States postgraduate orthodontic program. The objectives include: (1) to quantify and compare changes in sagittal and vertical cephalometric parameters between CCW and CW mandibular rotation groups; (2) to characterize the location, distribution, and tendency of the mandibular CoR in each group using the Reuleaux method; and (3) to evaluate the relationship between pretreatment skeletal measurements and posttreatment changes in sagittal chin position within the context of McNamara's cephalometric framework.

2. Materials and Methods

2.1. Study Design and Ethical Approval

This retrospective cephalometric study was approved as exempt by the A.T. Still University-Arizona Institutional Review Board (Protocol No. 2025-086; approved July 2025). All patient records were fully de-identified prior to data collection. The requirement for informed consent was waived by the Institutional Review Board because of the retrospective study design and the use of fully de-identified data.

2.2. Sample Selection

Patient records were retrospectively identified from the Arizona School of Dentistry and Oral Health Postgraduate Orthodontic Program (ASDOH-POP), A.T. Still University, Mesa, AZ, USA. Eligibility criteria included: (1) age $\geq$ 18 years at the start of orthodontic treatment; (2) availability of cone-beam computed tomography (CBCT) scans obtained at both the pretreatment (T1) and posttreatment (T2) time points; (3) completion of comprehensive orthodontic treatment; and (4) evidence of overall mandibular rotation, either CW or CCW, as determined by cephalometric superimposition.

Exclusion criteria included: (1) previous comprehensive orthodontic treatment; (2) a history of orthognathic surgery; (3) craniofacial anomalies, including cleft lip and/or palate and craniofacial syndromes; (4) active temporomandibular joint disorders; (5) clinically significant discrepancies between centric relation and centric occlusion (CR-CO); and (6) systemic conditions known to affect bone metabolism. Patients were stratified into CCW and CW rotation groups according to the change in mandibular plane angle (SN-MP) from

T1 to T2. Patients with a decrease of ≥1° (ΔSN-MP ≤ −1°) were assigned to the CCW group, whereas those with an increase of ≥1° (ΔSN-MP ≥ +1°) were assigned to the CW group. The 1° threshold was chosen to exclude patients with negligible rotation while retaining an adequate sample size. The final study sample consisted of 100 patients, including 33 in the CCW group and 67 in the CW group.

Of 577 patient records reviewed, 477 were excluded, most commonly because patients were younger than 18 years at the start of treatment, the change in SN-MP was less than 1°, the pretreatment and posttreatment CBCT scans were acquired at different CBCT machines, or other exclusion criteria applied. Mean treatment duration was 25.8 months (range, 18–32 months) in the CCW group and 25.3 months (range, 12–30 months) in the CW group. Treatment mechanics were recorded from the clinical records (Table 1). Intermaxillary elastics were used in both groups but were not included because the extent of their use could not be reliably determined from the records.

Table 1. Demographic and baseline characteristics of the counterclockwise (CCW) and clockwise (CW) rotation groups.

Characteristic	CCW Group (n = 33)	CW Group (n = 67)	Total (n = 100)
Age (years), mean ± SD	34.39 ± 12.52	35.76 ± 16.99	35.31 ± 15.60
Range	19–64	18–94	18–94
Sex, *n* (%)			
Female	19 (57.6%)	49 (73.1%)	68 (68.0%)
Male	14 (42.4%)	18 (26.9%)	32 (32.0%)
Race/Ethnicity, *n* (%)			
Caucasian	19 (57.6%)	43 (64.2%)	62 (62.0%)
Hispanic	6 (18.2%)	14 (20.9%)	20 (20.0%)
Asian	4 (12.1%)	6 (9.0%)	10 (10.0%)
African American	2 (6.1%)	4 (6.0%)	6 (6.0%)
Indian American	1 (3.0%)	0 (0.0%)	1 (1.0%)
American Indian	1 (3.0%)	0 (0.0%)	1 (1.0%)
Extraction, *n* (%)	5 (15.2%)	2 (3.0%)	7 (7.0%)
Malocclusion Class, *n* (%)			
Class I	14 (42.4%)	34 (50.7%)	48 (48.0%)
Class II	15 (45.5%)	26 (38.8%)	41 (41.0%)
Class III	4 (12.1%)	7 (10.4%)	11 (11.0%)
Pre-treatment SN-MP (°), mean ± SD	37.34 ± 6.92	33.00 ± 6.94	34.43 ± 7.20
p-value (CCW vs. CW)			0.004
Pre-treatment FMA (°), mean ± SD	26.44 ± 6.47	22.93 ± 6.52	24.09 ± 6.68
p-value (CCW vs. CW)			0.013
Treatment modality, *n* (%)			
Traditional fixed appliances	25 (75.8%)	49 (73.1%)	74 (74.0%)
Clear aligners	8 (24.2%)	17 (25.4%)	25 (25.0%)
Combined (fixed + clear aligner)	0 (0.0%)	1 (1.5%)	1 (1.0%)
Treatment duration (months), mean (range)	25.8 (18–32)	25.3 (12–30)	25.5 (12–32)

Table 1. *Cont.*

Characteristic	CCW Group (n = 33)	CW Group (n = 67)	Total (n = 100)
Adjunctive mechanics, n (%)			
TADs for maxillary molar intrusion	2 (6.1%)	0 (0.0%)	2 (2.0%)
TADs for total arch intrusion	2 (6.1%)	0 (0.0%)	2 (2.0%)
Buccal shelf TADs	2 (6.1%)	0 (0.0%)	2 (2.0%)
Posterior bite turbos	15 (45.5%)	5 (7.5%)	20 (20.0%)
Maxillary expansion appliances	0 (0.0%)	4 (6.0%)	4 (4.0%)
Transpalatal arch or Nance appliance	1 (3.0%)	2 (3.0%)	3 (3.0%)
Low-hanging transpalatal arch	1 (3.0%)	0 (0.0%)	1 (1.0%)
Lower lingual holding arch	1 (3.0%)	0 (0.0%)	1 (1.0%)

2.3. Cephalometric Analysis

Standardized lateral cephalograms were generated from T1 and T2 CBCT datasets acquired using an i-CAT FLX system (Dental Imaging Technologies Corp., Hatfield, PA, USA). All scans were obtained with a standardized field of view of 23 cm × 17 cm and a voxel size of 0.3 mm. The CBCT unit was operated at 120 kVp and 5 mA using the manufacturer's standardized orthodontic imaging protocol to ensure consistency across subjects.

The digital datasets were analyzed using Dolphin 3D Imaging software (Version 11.9; Dolphin Imaging & Management Solutions, Chatsworth, CA, USA). All images were oriented with the Frankfort horizontal plane parallel to the floor before cephalometric analysis. Cephalometric tracings and landmark identification were performed by the principal investigator (C.S.), a postgraduate orthodontic resident, under the supervision of a board-certified orthodontist.

T1 CBCT scans were obtained at the pretreatment records appointment, approximately 1 month before the start of treatment, and T2 scans at debonding. The interval between scans therefore corresponded to the treatment duration plus approximately 1 month (Table 1). All scans were acquired with the patient in natural head position and the teeth in occlusion. Lateral cephalograms were generated from each CBCT volume in Dolphin 3D using orthogonal projection at a 1:1 scale, after orienting the volume with the Frankfort horizontal plane parallel to the floor; the same orientation procedure and image-generation settings were applied to the T1 and T2 volumes. For superimposition, the cephalograms were imported into Photoshop without rescaling, and the scale of each image was verified using the 100-mm ruler generated by Dolphin.

Cephalometric variables were defined according to established orthodontic conventions and included measurements derived from McNamara analysis, particularly pogonion to nasion perpendicular (Pg-Na Perp) [3]. All variables and their definitions are presented in Table 2 and Figure 2. The horizontal reference plane (HRP) was defined as the Frankfort horizontal plane (Porion-Orbitale), and the vertical reference plane (VRP) was constructed perpendicular to the HRP through nasion.

Table 2. Definition of cephalometric measurements used in this study.

Measurement	Definition
Reference Planes	
HRP	Horizontal reference plane; Frankfort horizontal plane (anatomical porion—orbitale)
VRP (Na-Perp)	Vertical reference plane; a line perpendicular to the HRP drawn from nasion

Table 2. *Cont.*

Measurement	Definition
PP	Palatal plane; line connecting the anterior nasal spine (ANS) and posterior nasal spine (PNS)
MP	Mandibular plane; line connecting constructed gonion (Go) and menton (Me)
Sagittal Parameters	
SNA (°)	Sella-nasion-A point angle
SNB (°)	Sella-nasion-B point angle
ANB (°)	A point-nasion-B point angle
OJ (mm)	Overjet; parallel distance between the incisal edges of U1 and L1 to the occlusal plane
Vertical Parameters	
FMA/MP-FH (°)	Frankfort-mandibular plane angle; the angle between the Frankfort horizontal plane (FH) and the mandibular plane (gonion–menton)
SN-MP/SN-GoMe (°)	Mandibular plane angle; the angle between the sella-nasion line (SN) and the mandibular plane (gonion–menton)
TAFH/N-Me (mm)	Total anterior facial height; linear distance from nasion to menton
OB (mm)	Overbite; parallel distance between the incisal edges of U1 and L1 to the occlusal plane perpendicular
Occlusal Plane Angles	
Palatal plane inclination (°)	Angle between the palatal plane (ANS–PNS) and the Frankfort horizontal plane (FH)
OPA (°)	Occlusal plane angle; the angle between the bisected occlusal plane and the Frankfort horizontal plane (FH)
Maxillary OPA (°)	The angle between the maxillary occlusal plane—a line connecting the mesiobuccal cusp tip of U6 and the incisal tip of U1—and the Frankfort horizontal plane (FH)
Mandibular OPA (°)	The angle between the mandibular occlusal plane—a line connecting the mesiobuccal cusp tip of L6 and the incisal tip of L1—and the Frankfort horizontal plane (FH)
Tooth Movement	
U6-PP (mm)	Perpendicular distance from the mesiobuccal cusp tip of the maxillary first molar (U6) to the palatal plane (PP)
U1-PP (mm)	Perpendicular distance from the incisal edge of the maxillary central incisor (U1) to the palatal plane (PP)
L6-MP (mm)	Perpendicular distance from the mesiobuccal cusp tip of the mandibular first molar (L6) to the mandibular plane (MP)
L1-MP (mm)	Perpendicular distance from the incisal edge of the mandibular central incisor (L1) to the mandibular plane (MP)
Mandibular and Skeletal Dimensions	
Pg to Na Perp (mm)	Perpendicular distance from pogonion to the nasion perpendicular (VRP); positive values indicate anterior positioning of the chin
Co-Pg (mm)	Linear distance from condylion to pogonion
Co-Gn (mm)	Linear distance from condylion to gnathion (effective mandibular length)
Go-Pg (mm)	Linear distance from constructed gonion to pogonion (mandibular body length)
LAFH/ANS-Me (mm)	Lower anterior facial height; linear distance from ANS to Me
Me to Na Perp (mm)	Perpendicular distance from the nasion perpendicular (VRP) to menton

HRP, horizontal reference plane; VRP, vertical reference plane; PP, palatal plane; MP, mandibular plane; U1/L1, maxillary/mandibular central incisor; U6/L6, maxillary/mandibular first molar; Go, constructed gonion; OJ, overjet; OB, overbite; OPA, occlusal plane angle; AFH, anterior facial height; Co, condylion; Pg, pogonion; Gn, gnathion; ANS, anterior nasal spine; Me, menton.

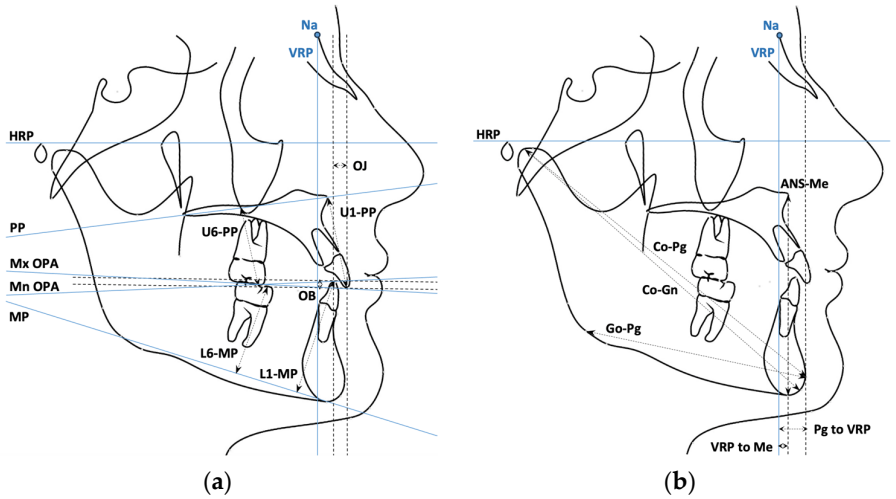

Figure 2. Cephalometric measurements. A horizontal reference plane (HRP) was established along the Frankfort horizontal plane, and a vertical reference plane (VRP) was drawn perpendicular to the HRP through nasion. PP, palatal plane; MP, mandibular plane. (**a**) Vertical, sagittal, and occlusal plane angle measurements. U1 and L1, the maxillary and mandibular central incisors, respectively; U6 and L6, the maxillary and mandibular first molars, respectively; OJ, overjet; OB, overbite; Mx OPA, maxillary occlusal plane angle; Mn OPA, mandibular occlusal plane angle, each measured relative to the HRP. (**b**) Mandibular and skeletal dimension measurements. ANS, anterior nasal spine; Co, condylion; Go, gonion; Me, menton; Gn, gnathion; Pg, pogonion.

2.4. Mandibular CoR

The mandibular CoR was determined for each patient using the Reuleaux method [13]. Lateral cephalograms at T1 and T2 were superimposed on the anterior cranial base using a best-fit registration technique in Photoshop CS6 (Adobe Systems Inc., San Jose, CA, USA). Cranial base superimposition was performed using primary landmarks at the anterior wall of the sella turcica, the greater wing of the sphenoid, the ethmoidal crests, and the cribriform plate. Secondary stable landmarks, including the anterior clinoid process, jugum sphenoidale, and the orbital portion of the frontal bone, were used to verify and refine registration accuracy.

Pre- and post-treatment cephalograms were oriented with the Frankfort horizontal plane (Porion–Orbitale) as the primary reference. Landmark identification followed standard cephalometric conventions. Pogonion (Pg) was defined as the most anterior point of the symphysis in the midsagittal plane. Menton (Me) was identified as the most inferior point of the symphyseal outline. For gonion, a constructed point was used in accordance with established methodology: the posterior border of the ramus was defined by a line from the Ramus point, the most posterior point along the ramal border, to Articulare, located at the posterior border of the condylar neck. The inferior border of the mandible was represented by the Me–Gonion line. Constructed gonion (Go) was then identified as the point on the mandibular outline at the intersection with the bisector of the angle formed by these two borders (Me–Go and Articulare–Ramus Point lines). This constructed gonion served as the posteroinferior reference landmark for the Reuleaux analysis (Figure 3).

Two mandibular landmarks, gonion (Go) and pogonion (Pg) were identified at both time points. The superimposed image was then reoriented so that the Frankfort horizontal plane was parallel to the *x*-axis, and the image was transferred to GeoGebra Classic 6 (International GeoGebra Institute, Linz, Austria). The CoR was calculated as the intersection of the perpendicular bisectors of the Go_1–Go_2 and Pg_1–Pg_2 displacement vectors (Figure 4). Condylion at T1 was designated as the origin of the coordinate system (0, 0), with positive *x*-values indicating the anterior direction and positive *y*-values indicating the superior direc-

tion. The direction of mandibular rotation (CW or CCW) was confirmed by cephalometric superimposition.

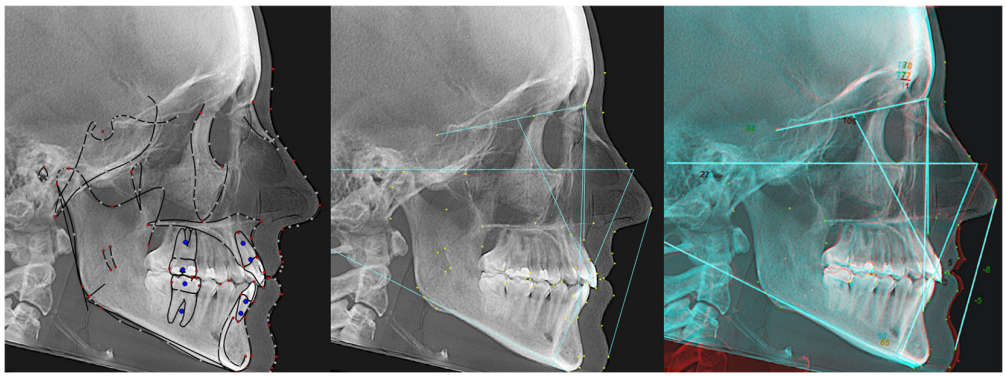

Figure 3. Representative cephalometric landmark identification and cranial base superimposition workflow. (**Left**) Full cephalometric tracing performed in Dolphin 3D Imaging software. Skeletal and dental landmark positions are indicated by red dots. Red dots in the mandibular region illustrate the constructed gonion (Go) determination: the posterior border of the ramus, defined by the Articulare–Ramus Point line, and the inferior border of the mandible, defined by the Menton–Gonion line, are traced; the bisector of the angle formed by these two borders identifies the constructed gonion at its intersection with the mandibular outline. (**Middle**) Exported landmark overlay from Dolphin, displaying identified landmark positions as yellow dots with cephalometric reference planes and analysis lines shown in blue. (**Right**) Anterior cranial base superimposition performed in Adobe Photoshop. The pretreatment (T1) cephalogram is rendered in cyan and the posttreatment (T2) cephalogram in red, with cranial base structures registered to enable identification of mandibular landmark displacement between time points.

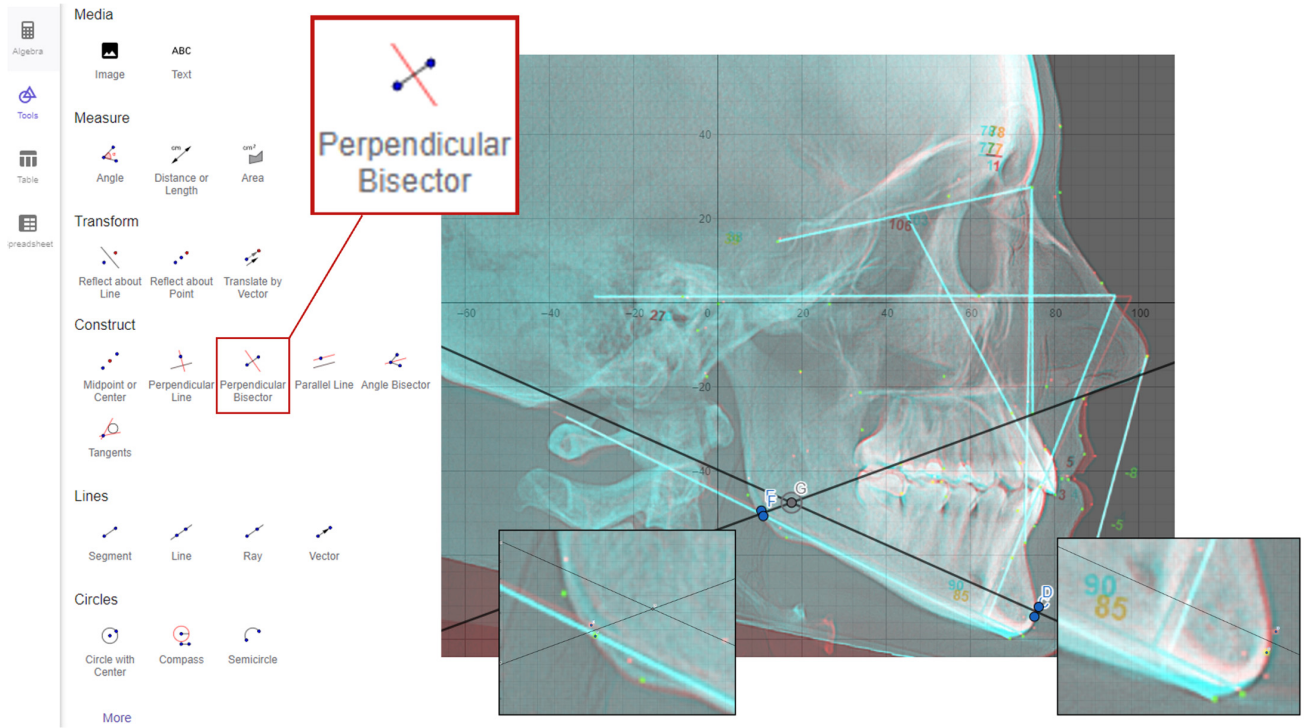

Figure 4. Identification of the mandibular center of rotation (CoR) using the Reuleaux method on superimposed lateral cephalograms. Go_1 and Go_2, gonion before and after orthodontic treatment, respectively; Pg_1 and Pg_2, pogonion before and after orthodontic treatment, respectively; R1, perpendicular bisector of the Go_1–Go_2 displacement vector; R2, perpendicular bisector of the Pg_1–Pg_2 displacement vector. The CoR is located at the intersection of R1 and R2.

Because only two time points were available, this construction yields the center of rotation for the overall displacement between T1 and T2 as a finite center of rotation rather than an instantaneous center of rotation. The term CoR is used in this sense throughout.

Because Reuleaux-based localization accuracy is influenced by rotational magnitude, summary statistics for CoR location were reported using means, medians, and ranges. Previous investigations have demonstrated that localization error increases substantially as the rotational angle decreases, particularly at rotations of less than 6°, where estimation errors may become clinically significant [7,14].

To assess whether CoR estimates became more stable with larger rotations, the distance of the CoR from condylion was compared across rotation ranges (|ΔSN-MP| 1.0–1.4°, 1.5–1.9°, 2.0–2.9°, and ≥3°), the CoR summary was repeated for patients with |ΔSN-MP| ≥ 2° and ≥3°, and the association between rotation magnitude and the distance of the CoR from condylion was examined using Spearman correlation.

Go and Pg were selected as reference landmarks because they represent anatomically distant regions of the mandible: the posteroinferior angle of the mandibular ramus and the anterior prominence of the symphysis. This configuration maximizes the angular separation between their displacement vectors relative to the estimated CoR. Such landmark selection is critical because the accuracy of the Reuleaux method improves as the angular separation between reference points increases. Rekow et al. [7] reported that landmark pairs subtending angles approaching 90° produce the lowest localization error, improving the precision of CoR estimation.

2.5. Reliability

To assess intra-examiner reliability, 18 CBCT-derived cephalograms were randomly selected, with proportional representation from both the CW and CCW rotation groups [15]. All measurements were repeated after an interval of at least two weeks. Measurement error was evaluated using Dahlberg's formula, and reliability was assessed using the intraclass correlation coefficient (ICC). A two-way mixed-effects model with absolute agreement for single measurements [ICC(3,1)] yielded a mean ICC of 0.947, with the lowest ICC value of 0.83, indicating excellent intra-examiner reliability. For the CoR, Go and Pg were re-identified at both time points in the same 18 patients, and the Reuleaux construction was repeated on the original cranial base superimpositions.

2.6. Statistical Analysis

All statistical analyses were performed using SPSS Statistics (Version 30.0; IBM Corp., Armonk, NY, USA). Descriptive statistics, including means, standard deviations, frequencies, and percentages, were calculated for all variables. Normality of cephalometric change scores was evaluated using the Kolmogorov-Smirnov test. Because several variables were not normally distributed, nonparametric statistical methods were used for all subsequent analyses.

Within-group changes between T1 and T2 measurements were assessed using the Wilcoxon signed-rank test. Between-group comparisons of cephalometric change scores, including comparisons between CW and CCW rotation groups, were performed using the Mann-Whitney U test. Categorical variables, including racial and ethnic distributions, were analyzed using cross-tabulations and chi-square tests where appropriate. Statistical significance was established at $p < 0.05$.

Changes in Pg–Na Perp, LAFH (ANS–Me), and TAFH (N–Me) were designated as the primary outcomes because they represent McNamara's framework, the central relationship examined in this study. This framework relates vertical facial height and sagittal chin position. For these outcomes, between-group differences in change scores (CW minus CCW) are reported as differences in means with 95% confidence intervals (CIs), together with

Mann–Whitney U test p values. All other variables were considered secondary outcomes. Because multiple secondary comparisons were performed without adjustment, these results are interpreted as exploratory, and p values between 0.01 and 0.05 should be interpreted with caution.

Associations between age and rotation magnitude, the primary outcomes, and CoR coordinates were examined using Spearman correlation.

3. Results

3.1. Sample Characteristics

Demographic and baseline characteristics of the study sample are presented in Table 1. The final sample consisted of 100 patients (68 females and 32 males) with a mean age of 35.3 ± 15.6 years (range, 18–94 years). No significant differences were observed between the CCW ($n = 33$) and CW ($n = 67$) rotation groups with respect to age (34.4 ± 12.5 vs. 35.8 ± 17.0 years, respectively; $p = 0.65$) or sex distribution.

Age was not associated with rotation magnitude, the primary outcomes, or CoR coordinates (Spearman $|\rho| \leq 0.10$, $p \geq 0.32$ for all), and excluding the oldest patient (94 years) did not change the between-group results for the primary outcomes.

At baseline, the CCW group exhibited significantly greater vertical skeletal dimensions than the CW group, as reflected by higher SN-MP (37.3 ± 6.9° vs. 33.0 ± 6.9°; $p = 0.004$) and FMA values (26.4 ± 6.5° vs. 22.9 ± 6.5°; $p = 0.013$), indicating a more hyperdivergent skeletal pattern prior to treatment.

The study population was racially diverse, consisting of 62% Caucasian, 20% Hispanic, 10% Asian, 6% African American, and 2% individuals of other racial backgrounds. Treatment modalities included conventional fixed appliances in 74 patients (74%), clear aligner therapy in 25 patients (25%), and a combination of both modalities in 1 patient (1%). Seven patients (7%) underwent planned tooth extraction as part of treatment, including five in the CCW group and two in the CW group. Pretreatment malocclusion classification was distributed as follows: Class I, 48 patients (48%); Class II, 41 patients (41%); and Class III, 11 patients (11%).

Posterior bite turbos were used more frequently in the CCW group (15 patients, 45.5%) than in the CW group (5 patients, 7.5%), and temporary anchorage devices (TADs) were used in 6 patients, all in the CCW group. Other adjunctive mechanics were uncommon (Table 1).

3.2. Cephalometric Changes Within Groups

T1 and T2 cephalometric values, p-values from Wilcoxon tests for the pre-post comparisons, and change scores for both groups are presented in Table 3. In the CCW group, statistically significant decreases were observed in FMA (−1.43 ± 0.98°; $p < 0.001$), SN-MP (−1.73 ± 0.78°; $p < 0.001$), TAFH (−1.62 ± 3.06 mm; $p < 0.001$), and U6-PP (−0.58 ± 1.09 mm; $p = 0.005$), alongside significant increases in SNA (+0.55 ± 1.20°; $p = 0.021$) and SNB (+0.52 ± 1.10°; $p = 0.003$). N-Perp to Me increased significantly in the CCW group (+1.17 ± 2.53 mm; $p = 0.012$), indicating anterior displacement of the chin perpendicular measurement consistent with CCW rotation. Changes in ANB, overjet, overbite, occlusal plane angles, and mandibular dimension variables (Co-Pg, Co-Gn, Go-Pg, ANS-Me) were not statistically significant in the CCW group.

Table 3. Cephalometric measurements at pretreatment (T1) and posttreatment (T2) with change scores and within-group test results for counterclockwise (CCW) and clockwise (CW) rotation groups.

Variable	CCW Pre Mean ± SD	CCW Post Mean ± SD	CCW Δ Mean ± SD	*p*-Value	CW Pre Mean ± SD	CW Post Mean ± SD	CW Δ Mean ± SD	*p*-Value
Sagittal Parameters								
SNA (°)	80.91 ± 4.26	81.45 ± 3.93	+0.55 ± 1.20	0.021 *	82.57 ± 4.06	81.50 ± 4.09	−1.07 ± 1.51	<0.001 ***
SNB (°)	77.68 ± 3.77	78.21 ± 3.51	+0.52 ± 1.10	0.003 **	79.45 ± 4.49	77.99 ± 4.35	−1.45 ± 1.54	<0.001 ***
ANB (°)	3.22 ± 2.53	3.24 ± 2.62	+0.02 ± 1.04	0.646	3.13 ± 2.51	3.36 ± 2.81	+0.22 ± 1.17	0.017 *
OJ (mm)	3.23 ± 1.72	3.64 ± 1.03	+0.41 ± 1.90	0.228	3.29 ± 2.11	3.56 ± 1.38	+0.27 ± 1.93	0.434
Pg–Na Perp (mm)	−1.35 ± 8.05	−0.61 ± 8.86	+0.75 ± 2.22	0.056	1.13 ± 8.32	−0.69 ± 8.21	−1.81 ± 2.13	<0.001 ***
Vertical Parameters								
FMA (°)	26.44 ± 6.47	25.01 ± 6.78	−1.43 ± 0.98	<0.001 ***	22.93 ± 6.52	24.67 ± 6.66	+1.74 ± 1.07	<0.001 ***
SN-MP (°)	37.34 ± 6.92	35.61 ± 7.07	−1.73 ± 0.78	<0.001 ***	33.00 ± 6.94	35.06 ± 7.07	+2.07 ± 0.94	<0.001 ***
TAFH/N-Me (mm)	122.78 ± 10.88	121.16 ± 10.38	−1.62 ± 3.06	<0.001 ***	119.00 ± 9.06	120.50 ± 8.96	+1.50 ± 1.32	<0.001 ***
OB (mm)	1.87 ± 2.22	2.23 ± 1.11	+0.36 ± 2.28	0.291	2.52 ± 2.16	1.66 ± 1.43	−0.86 ± 1.72	<0.001 ***
ANS-Me (mm)	68.55 ± 7.69	67.83 ± 7.58	−0.72 ± 2.55	0.236	65.95 ± 6.08	66.65 ± 6.00	+0.70 ± 1.93	0.007 **
Occlusal Plane Angles								
Palatal plane incl. (°)	2.62 ± 3.59	3.14 ± 3.68	+0.52 ± 2.00	0.108	2.54 ± 3.64	2.56 ± 3.55	+0.02 ± 2.45	0.936
OPA (°)	7.89 ± 4.65	7.93 ± 5.39	+0.04 ± 2.33	0.907	6.53 ± 3.98	7.57 ± 4.11	+1.04 ± 2.89	0.006 **
Maxillary OPA (°)	10.08 ± 4.78	10.22 ± 5.79	+0.14 ± 2.67	0.761	9.21 ± 4.69	9.58 ± 4.69	+0.36 ± 2.81	0.235
Mandibular OPA (°)	6.43 ± 4.45	6.09 ± 4.59	−0.34 ± 3.98	0.844	5.27 ± 3.88	5.62 ± 3.75	+0.35 ± 4.19	0.272
Tooth Movement								
U6-PP (mm)	24.54 ± 3.02	23.96 ± 3.08	−0.58 ± 1.09	0.005 **	23.96 ± 2.99	24.01 ± 2.63	+0.05 ± 1.43	0.629
U1-PP (mm)	30.87 ± 4.33	30.66 ± 4.44	−0.20 ± 1.94	0.808	29.38 ± 3.40	29.71 ± 3.28	+0.33 ± 1.90	0.167
L6-MP (mm)	33.06 ± 4.43	33.10 ± 4.38	+0.04 ± 1.71	0.433	32.07 ± 3.46	33.05 ± 3.94	+0.98 ± 1.50	<0.001 ***
L1-MP (mm)	42.08 ± 4.61	41.53 ± 4.75	−0.55 ± 1.62	0.131	40.66 ± 4.18	41.16 ± 4.30	+0.51 ± 1.32	0.002 **
Mandibular and Skeletal Dimensions								
Co-Pg (mm)	115.49 ± 9.52	115.20 ± 8.67	−0.29 ± 2.99	0.918	113.85 ± 9.62	114.29 ± 9.67	+0.44 ± 2.33	0.129
Co-Gn (mm)	118.00 ± 9.65	117.84 ± 8.76	−0.16 ± 2.74	0.520	116.44 ± 9.53	116.86 ± 9.58	+0.41 ± 1.77	0.079
Go-Pg (mm)	77.06 ± 6.55	76.52 ± 6.06	−0.54 ± 2.26	0.098	75.03 ± 6.11	75.16 ± 6.09	+0.13 ± 1.39	0.642
N-Perp to Me (mm)	−7.51 ± 8.04	−6.34 ± 9.31	+1.17 ± 2.53	0.012 *	−4.59 ± 8.46	−7.11 ± 8.58	−2.52 ± 2.30	<0.001 ***

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. p values in this table are from within-group comparisons (T1 vs. T2); between-group comparisons of the primary outcomes are presented in Table 4.

Table 4. Between-group differences in the primary outcomes (change from T1 to T2) between the counterclockwise (CCW) and clockwise (CW) rotation groups.

Primary Outcome	CCW Δ, Mean ± SD	CW Δ, Mean ± SD	Difference, CW − CCW (95% CI)	*p*-Value
Pg–Na Perp (mm)	+0.75 ± 2.22	−1.81 ± 2.13	−2.56 (−3.49 to −1.63)	<0.001
LAFH, ANS–Me (mm)	−0.72 ± 2.55	+0.70 ± 1.93	+1.42 (0.41 to 2.43)	0.014
TAFH, N–Me (mm)	−1.62 ± 3.06	+1.50 ± 1.32	+3.12 (1.99 to 4.24)	<0.001

CI, confidence interval; LAFH, lower anterior facial height; TAFH, total anterior facial height. Differences are CW minus CCW; p values are from the Mann–Whitney U test.

In the CW group, statistically significant increases were observed in FMA (+1.74 ± 1.07°; $p < 0.001$), SN-MP (+2.07 ± 0.94°; $p < 0.001$), TAFH (+1.50 ± 1.32 mm; $p < 0.001$), ANB (+0.22 ± 1.17°; $p = 0.017$), overall occlusal plane angle (+1.04 ± 2.89°; $p = 0.006$), L6-MP (+0.98 ± 1.50 mm; $p < 0.001$), L1-MP (+0.51 ± 1.32 mm; $p = 0.002$), and ANS-Me (+0.70 ± 1.93 mm; $p = 0.007$). N-Perp to Me decreased significantly in the CW group (−2.52 ± 2.30 mm; $p < 0.001$), reflecting posterior displacement of the chin. Significant decreases were found in SNA (−1.07 ± 1.51°; $p < 0.001$), SNB (−1.45 ± 1.54°; $p < 0.001$), OB (−0.86 ± 1.72 mm; $p < 0.001$), and Pg–Na Perp (−1.81 ± 2.13 mm; $p < 0.001$). Palatal plane inclination, maxillary OPA, mandibular OPA, U1-PP, Co-Pg, Co-Gn, and Go-Pg did not reach significance in either group.

Between-group differences in the three primary outcomes are presented in Table 4. Compared with the CCW group, the CW group showed greater posterior displacement of pogonion relative to the nasion perpendicular (mean difference −2.56 mm; 95% CI −3.49 to −1.63; $p < 0.001$) and greater increases in LAFH (1.42 mm; 95% CI 0.41 to 2.43; $p = 0.014$) and TAFH (3.12 mm; 95% CI 1.99 to 4.24; $p < 0.001$). Thus, although the within-group changes in Pg–Na Perp and LAFH in the CCW group were not statistically significant, the two groups differed significantly in all three primary outcomes.

3.3. Mandibular CoR

Mandibular CoR coordinates relative to the condylion at T1 are presented in Table 5. For the total sample ($n = 100$), the median CoR was located 35.17 mm anterior and 37.76 mm inferior to the condylion (mean: 34.40 ± 171.04 mm anterior and 18.51 ± 160.61 mm inferior). In the CCW group, the median CoR position was 50.54 mm anterior and 47.53 mm inferior to condylion, whereas the CW group demonstrated a median position of 28.00 mm anterior and 35.31 mm inferior to condylion. Mean CoR coordinates were 50.57 ± 96.45 mm anterior and 26.56 ± 176.59 mm inferior in the CCW group, and 26.44 ± 197.93 mm anterior and 14.54 ± 153.38 mm inferior in the CW group (Figure 5).

Table 5. Mandibular center of rotation (CoR) coordinates relative to condylion at pretreatment (T1) and comparison between clockwise (CW) and counterclockwise (CCW) groups.

Parameter	CCW Group ($n = 33$)	CW Group ($n = 67$)	Total ($n = 100$)
CoR *x*-axis (anterior = positive), mean ± SD (mm)	50.57 ± 96.45	26.44 ± 197.93	34.40 ± 171.04
Median (IQR) (mm)	50.54 (9.92 to 73.15)	28.00 (5.38 to 56.66)	35.17 (7.04 to 63.21)
Range (mm)	491.84	2023.04	2023.04
CoR *y*-axis (inferior = negative), mean ± SD (mm)	−26.56 ± 176.59	−14.54 ± 153.38	−18.51 ± 160.61
Median (IQR) (mm)	−47.53 (−83.30 to −14.65)	−35.31 (−63.20 to −5.58)	−37.76 (−68.35 to −6.29)
Range (mm)	962.78	1249.16	1418.92

Positive *x*-values indicate locations anterior to condylion, whereas negative *y*-values indicate locations inferior to condylion. IQR, interquartile range.

Substantial interindividual variability was observed in both groups, with several extreme outliers located hundreds of millimeters from the condylion. Consequently, the distributions were highly skewed, and median values likely provide a more representative measure of central tendency than means. Despite this variability, the overall tendency for the CoR to be positioned anterior and inferior to condylion was consistent across both rotational patterns.

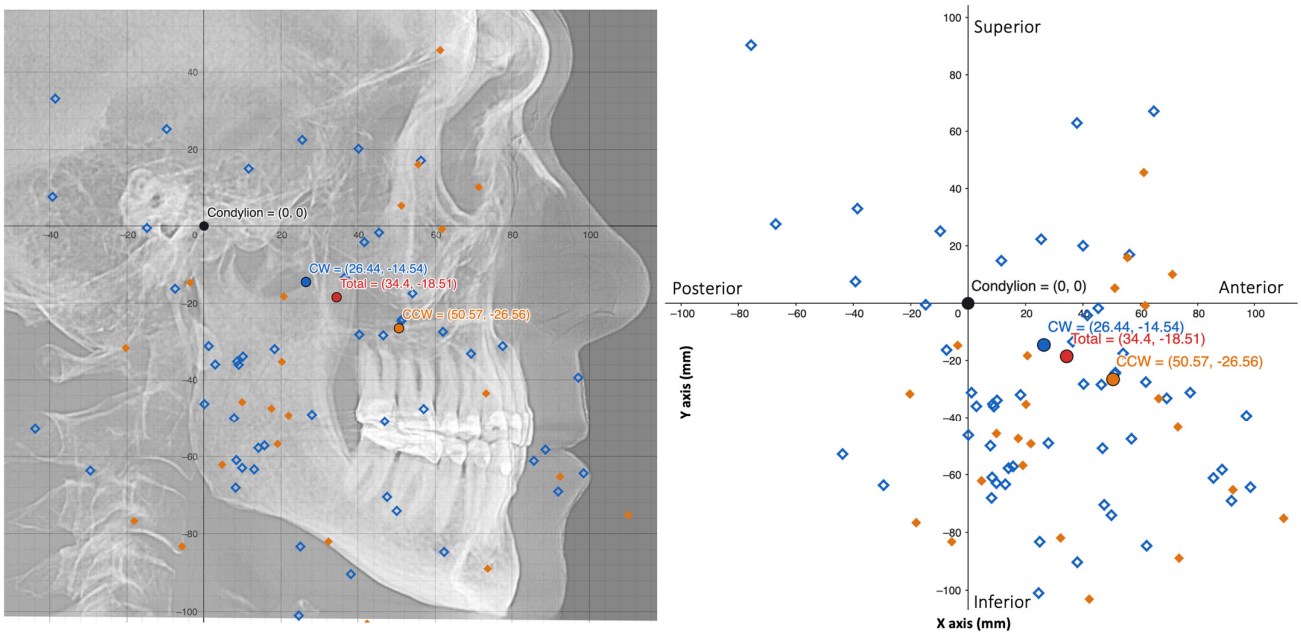

Figure 5. Centers of mandibular rotation for clockwise (CW) and counterclockwise (CCW) rotation. Blue diamond markers represent the calculated CoR for each subject with CW rotation; orange diamond markers represent the calculated CoR for each subject with CCW rotation. The blue circle indicates the mean CoR for CW rotation, and the red circle indicates the mean CoR for CCW rotation. The blue and orange circles indicate the mean CoR for the CW and CCW groups, respectively, and the red circle indicates the mean for the total sample. For legibility, the plotted area is limited to approximately ±100 mm around condylion; 24 of the 100 estimates (CCW, 11; CW, 13) lie outside this area. The full ranges are reported in Table 5. The condylion before treatment (T1) was set as the reference point (0, 0) of the coordinate system.

The median rotation (|ΔSN-MP|) was 1.6° (IQR 1.2–2.5°); 62 patients rotated less than 2°, 14 rotated 3° or more, and none rotated 6° or more. The median distance of the CoR from condylion was 61.5 mm for rotations of 1.0–1.4° ($n = 39$), 89.4 mm for 1.5–1.9° ($n = 23$), 79.6 mm for 2.0–2.9° ($n = 24$), and 64.4 mm for ≥3° ($n = 14$), and estimates more than 200 mm from condylion occurred in every range. CoR estimates therefore did not become more stable with larger rotations: the distance of the CoR from condylion was not associated with rotation magnitude (Spearman $\rho = 0.02$, $p = 0.82$), and restricting the analysis to patients with rotations of ≥2° ($n = 38$) or ≥3° ($n = 14$) yielded median CoR positions similar to those of the full sample (37.3 mm anterior and 35.3 mm inferior, and 38.3 mm anterior and 29.8 mm inferior to condylion, respectively, versus 35.2 mm anterior and 37.8 mm inferior), with extreme estimates still present. In the 18 re-measured patients, re-identifying Go and Pg on the original superimpositions shifted the CoR by a median of 1.1 mm.

No significant associations were identified between CoR coordinates and pretreatment skeletal characteristics, including SN-MP, FMA, AFH, ANB, and mandibular length (Co-Pg) (all $|r| < 0.21$, $p > 0.09$).

3.4. Sample Size Analysis

A retrospective sensitivity analysis was performed based on the final sample sizes of the CW ($n = 67$) and CCW ($n = 33$) groups. Assuming a two-tailed significance level of $\alpha = 0.05$ and 80% statistical power, the study was sufficiently powered to detect a minimum effect size of Cohen's $d = 0.63$, corresponding to a probability of superiority of 0.68 for the Mann-Whitney U test.

4. Discussion

4.1. Cephalometric Changes and McNamara's Principles

In the CCW group, the mandibular plane angle decreased (ΔSN-MP = −1.73°), whereas LAFH and Pg-Na Perp changed in the expected direction (−0.72 mm and +0.75 mm, respectively). However, these within-group changes were not statistically significant ($p = 0.236$ and $p = 0.056$). In contrast, the CW group demonstrated the opposite pattern, with increases in SN-MP (+2.07°) and LAFH (+0.70 mm), accompanied by posterior displacement of pogonion (−1.81 mm). The difference between the groups was nevertheless significant for both LAFH and Pg-Na Perp (Table 4). These findings align with the cephalometric principles described by McNamara that increased LAFH is associated with relative mandibular retrusion, whereas decreased LAFH results in a more prognathic chin position [3]. Such well-established relationship was observed in a racially diverse orthodontic population undergoing routine comprehensive treatment, rather than being limited to specific interventions such as surgical maxillary impaction or temporary anchorage device–assisted molar intrusion. However, because the groups were defined by the rotation observed after treatment, and the groups differed in baseline vertical dimensions and in treatment mechanics, these findings describe changes associated with mandibular rotation and do not establish which treatment factors caused it.

The CW group exhibited a small but statistically significant increase in ANB (+0.22°; $p = 0.017$), suggesting that CW mandibular rotation may have modestly altered the overall sagittal skeletal relationship through posterior displacement of the chin. Although the magnitude of this change is unlikely to be clinically substantial, it is consistent with the expected effects of mandibular rotation and may be relevant when planning treatment for patients with borderline sagittal discrepancies.

Additional support for the multidimensional nature of CW mandibular rotation was provided by the significant increase in occlusal plane angle (OPA; +1.04°; $p = 0.006$) and the marked posterior displacement of the chin, as reflected by changes in N-Perp to Me (−2.52 mm; $p < 0.001$). Together, these findings indicate that CW rotation involves coordinated changes in vertical, sagittal, and dentoalveolar relationships rather than isolated alterations in mandibular plane inclination alone.

The direction of these changes agrees with the relationship described by McNamara, in which an increase in LAFH is accompanied by posterior displacement of the chin and a decrease by anterior displacement [3]. Because the within-group changes in LAFH and Pg-Na Perp in the CCW group were small and not statistically significant, the magnitude of chin displacement per unit change in LAFH could not be estimated reliably; the between-group differences in Table 4 therefore provide the more appropriate summary of this relationship.

4.2. Mandibular CoR

In both the CCW and CW groups, the mandibular CoR was generally located anterior and inferior to condylion. This finding differs from previous reports, which described the CoR as being positioned posterior and inferior to the condylion following orthodontically induced mandibular rotation [6,16,17]. Moreover, the distance between the CoR and condylion in the present study was substantially greater than that reported by Kim et al. [6], who identified an average CoR location 7.4 mm posterior and 16.9 mm inferior to condylion in a Korean cohort undergoing CCW rotation.

In contrast, the median CoR positions in our sample were 50.5 mm anterior and 47.5 mm inferior to the condylion in the CCW group and 28.0 mm anterior and 35.3 mm inferior in the CW group. The distributions were characterized by considerable interindividual variability, with several extreme outliers contributing to substantially larger mean values and wide

ranges. Consequently, median values likely provide a more representative description of CoR location than means in this cohort.

Several factors may account for the discrepancy between the present findings and previous reports. First, the accuracy of Reuleaux-based CoR localization is highly dependent on the magnitude of mandibular rotation. Rekow et al. [7] demonstrated that, at only 2° of simulated mandibular rotation, mean localization errors ranged from 17.9 mm to 329.5 mm depending on landmark selection. In the same study, CoR distances from the condyle ranged from 0.48 mm to 926.47 mm among orthognathic surgery patients, a degree of variability like that observed in the present sample. Moorehead et al. [14] further showed that Reuleaux-based estimation becomes increasingly unreliable as rotational magnitude decreases, with errors rising sharply as the angle of rotation approaches zero.

Importantly, the mean SN-MP changes observed in the present study were relatively small (1.73° in the CCW group and 2.07° in the CW group), well below the rotational magnitudes generally considered optimal for accurate Reuleaux localization [7,14]. Consequently, the extreme outliers and wide coordinate ranges observed in this study are more likely attributable to mathematical limitations of the method than to true biomechanical variation in mandibular rotation. This interpretation is supported by the highly skewed distributions and the substantially smaller median values compared with the corresponding means.

Additional differences may be related to the heterogeneity of the study sample. Unlike previous investigations that focused on a single treatment modality, such as temporary anchorage device-assisted molar intrusion, the present cohort included a broad range of treatment mechanics and therefore a wider spectrum of mandibular displacement patterns. However, the present study was designed to characterize CoR location in a racially and ethnically diverse sample rather than to compare CoR location among racial or ethnic groups. Such a comparison was not feasible, because several groups included very few patients (e.g., 10 Asian and 6 African American patients), and because the uncertainty of individual CoR estimates at the small rotations observed would obscure any differences between groups. Consequently, the data cannot separate possible population differences from differences in rotation magnitude, treatment mechanics, or measurement method, and the greater dispersion of CoR estimates relative to Kim et al. [6] should not be attributed to population diversity.

An additional source of measurement error specific to the present study relates to the use of CBCT-derived lateral cephalograms rather than conventional two-dimensional radiographs. Gonion, which lies on a broad curved anatomical structure rather than a discrete bony point, has been identified as among the least reproducible cephalometric landmarks in three-dimensional analysis [16], and its localization in CBCT-derived lateral cephalograms may be further complicated by the superimposition of bilateral mandibular structures in the projected reconstruction [17]. Even small errors in gonion or pogonion placement—on the order of 0.5 to 1.0 mm, which fall within the accepted range of landmark identification variability—can produce disproportionately large displacements in the estimated CoR when actual landmark movements are small. This geometric amplification is a known property of the Reuleaux method under near-translational displacement conditions and represents a limitation specific to the present study that was not similarly operative in Kim et al. [6], whose patients underwent substantially larger and more directionally consistent mandibular displacements resulting from a controlled intervention.

The foundational implant studies of Björk demonstrated that the mandibular center of rotation is not anatomically fixed but varies considerably depending on the type and mechanism of rotation [18]. In forward mandibular rotation occurring about the condyles, the CoR approximates the joint region. When rotation occurs at the incisal edges or the premolar region, the CoR may be located anterior to condylion. These observations un-

derscore that the CoR is inherently variable per patient and cannot be expected to remain consistent across studies that differ substantially in treatment modality, rotational magnitude, and skeletal morphology. The discrepancy between the present findings and those of Kim et al. [6] most plausibly reflects the methodological constraints and design differences of this study, particularly its small rotational magnitudes, mixed treatment mechanics, and CBCT-derived landmark identification, rather than inaccuracies in the prior report. Kim et al.'s study was specifically designed to produce substantial, reproducible CCW mandibular rotation through a uniform treatment protocol, conditions inherently favorable for reliable Reuleaux-based CoR localization. The present study, in contrast, prioritized breadth of population and diversity of treatment mechanics, conditions less favorable for precise CoR estimation but more reflective of the heterogeneity encountered in routine clinical orthodontic practice.

The substantial interindividual variability in CoR location observed in both rotation groups suggests that Reuleaux-derived CoR estimates have limited precision when applied at the individual patient level. Furthermore, no significant associations were identified between CoR coordinates and pretreatment skeletal characteristics, indicating that baseline facial morphology alone does not reliably predict the location of the mandibular center of rotation.

These findings support the concept that mandibular rotation cannot be adequately represented by a single, fixed CoR across patients. Instead, CoR location appears to vary considerably among individuals and may be influenced by factors that are not captured by conventional cephalometric measurements. Consequently, clinicians should be cautious when incorporating a fixed CoR into treatment simulations or surgical prediction models. This concern has also been highlighted in the orthognathic surgery literature, where substantial variability in CoR location has been reported and patient-specific modeling has been advocated [19,20].

4.3. Clinical Implications

For patients undergoing orthodontic treatment with the potential to induce CW mandibular rotation, such as Class II correction, transverse arch expansion, or posterior tooth extrusion, clinicians should anticipate increases in LAFH, CW opening of the mandibular plane, and posterior displacement of the chin. These changes may adversely affect facial balance in patients with preexisting vertical skeletal discrepancies. Pretreatment cephalometric evaluation, including McNamara's assessment of pogonion relative to nasion perpendicular (Pg-Na Perp) and of LAFH in relation to effective midfacial length, remains useful for anticipating the esthetic impact of such changes, although the present data do not identify which patients are most susceptible to them.

For patients presenting with anterior open bite or excessive LAFH, treatment strategies aimed at inducing CCW mandibular rotation may provide meaningful improvements in both vertical facial proportions and chin projection. In the present study, reductions in FMA were accompanied by a significant decrease in TAFH, whereas the decrease in LAFH and the anterior displacement of Pg were small and not statistically significant within the CCW group. Each degree of mandibular plane closure was associated with an approximately 0.9-mm reduction in TAFH in the CCW group. Nevertheless, considerable interindividual variability was observed, and these estimates should therefore be interpreted as general guidelines rather than precise predictors of treatment outcome.

A notable strength of the present study is the racial and ethnic diversity of the study cohort. Previous investigations of mandibular rotational biomechanics have been conducted primarily in relatively homogeneous East Asian populations [6], raising questions regarding the generalizability of their findings to broader clinical populations. Extrapolating

biomechanical parameters derived from homogeneous samples to more diverse patient groups may introduce systematic bias and limit external validity [21]. However, several racial and ethnic categories in the present sample contained very few patients, and the study was not designed to compare these groups.

Despite the marked demographic heterogeneity of the present cohort, the relationships between mandibular rotation, LAFH, and sagittal chin position were consistent with established cephalometric principles. This finding is consistent with the general cephalometric effects associated with CW and CCW mandibular rotation across diverse populations. Whether CoR location differs among populations cannot be determined from the present data, because the CoR estimates were highly uncertain and were not compared across racial or ethnic groups.

4.4. Limitations

Several limitations of this study should be acknowledged. First, the retrospective design and reliance on existing clinical records precluded control over treatment mechanics. Because the groups were defined by the rotation observed after treatment, differed at baseline in SN-MP and FMA, and differed in the use of adjunctive mechanics such as posterior bite turbos, the findings describe changes associated with rotation and do not show that pretreatment characteristics or particular mechanics cause or predict it. Second, the extraction subgroup was small ($n = 7$), preventing meaningful evaluation of the potential influence of orthodontic tooth extraction on mandibular rotational patterns.

Third, the Reuleaux method assumes bodily rotation between two reference points, whereas mandibular movement in vivo is a complex three-dimensional process involving both rotational and translational components. Consequently, a two-dimensional cephalometric approach cannot fully capture the true biomechanics of mandibular displacement. Moreover, the substantial variability in CoR location observed in this study, particularly the extreme outliers associated with small rotational magnitudes, reduced the precision of group-level CoR estimates. As discussed previously, these outliers likely reflect methodological limitations of Reuleaux-based localization rather than true biological extremes.

Additionally, landmark identification on CBCT-derived lateral cephalograms introduces a source of error does not present in studies using conventional two-dimensional cephalometry. Gonion, which lies on a broad curved anatomical structure rather than a discrete bony point, has been identified as among the least reproducible cephalometric landmarks in three-dimensional analysis [16], and its localization in CBCT-derived lateral cephalograms may be further complicated by the superimposition of bilateral mandibular structures in the projected reconstruction [17]. Because the Reuleaux method geometrically amplifies even small landmark identification errors when mandibular displacements are small, this limitation may have contributed meaningfully to the wide range and extreme outlier CoR values observed. Future studies employing the Reuleaux method should consider restricting inclusion to patients with rotational changes above a minimum threshold (e.g., ≥3–4°) to ensure that Reuleaux-based localization falls within a range of acceptable precision and should consider multi-examiner landmark identification protocols to minimize the impact of placement variability.

In addition, no patient rotated 6° or more, the magnitude generally required for reliable Reuleaux localization [7,14]; the CoR coordinates reported here should therefore be regarded as uncertain estimates rather than characteristic positions of the mandibular center of rotation.

Reliability was assessed by a single examiner, and inter-examiner reproducibility was not evaluated. In addition, the 1° threshold used to define rotation is close to the measurement error of the change in SN-MP (Dahlberg error, 0.68°); on re-measurement,

3 of the 18 patients fell below 1°, although none changed direction of rotation. Some patients near the threshold may therefore have been misclassified, which would tend to reduce rather than exaggerate the differences between groups. Finally, the age range of the sample was wide (18–94 years), although age was not associated with the main outcomes.

Future investigations incorporating three-dimensional CBCT superimposition and a greater number of reference landmarks may provide more accurate and robust estimates of mandibular CoR location. In addition, studies with larger samples within each racial or ethnic group and larger rotations would be needed to test whether CoR location differs among populations. Finally, the unequal distribution of patients between the CCW ($n = 33$) and CW ($n = 67$) groups reflects the natural frequency of these treatment outcomes in clinical practice but may have reduced statistical power for subgroup analyses within the smaller CCW cohort.

5. Conclusions

This study evaluated cephalometric changes associated with CW and CCW mandibular rotation and analyzed CoR location in a racially diverse adult population.

1. At the small rotations observed (median 1.6°), Reuleaux-derived CoR estimates were highly dispersed and did not stabilize with larger rotations; their median location (35.2 mm anterior and 37.8 mm inferior to condylion) should be regarded as an uncertain estimate.
2. Pg-Na Perp decreased by 1.81 mm in the CW group; the 0.75 mm increase in the CCW group was not statistically significant, but the change differed significantly between groups (−2.56 mm; 95% CI −3.49 to −1.63).

Mandibular rotation was associated with coordinated vertical and sagittal changes in facial morphology, consistent with established cephalometric principles. At the small rotations observed, the mandibular CoR could not be located reliably with the Reuleaux method.

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Informed Consent Statement: Patient consent was waived due to the retrospective nature of the study and complete de-identification of all patient data prior to analysis.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy restrictions associated with protected health information.

Conflicts of Interest: The authors declare no conflicts of interest.

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