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Impact of Masseter and Medial Pterygoid Muscles on Skeletal Stability After Bimaxillary Orthognathic Surgery in Class III Malocclusion Patients

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(Abstract)

Background

Skeletal relapse following orthognathic surgery remains a critical concern to patients after orthognathic surgery. Although masticatory muscle function has been suggested to influence postoperative stability, the relationship between muscle morphology and skeletal relapse is not fully understood. This study aimed to evaluate the correlation between morphological characteristics (muscle volume, estimated cross-sectional area, and length) of the masseter and medial pterygoid muscles and postoperative skeletal stability of the mandible.

Results

Thirty-six patients with skeletal Class III malocclusion who underwent bimaxillary orthognathic surgery between 2020 and 2025 were included. Preoperative and postoperative computed tomography scans were analyzed to quantify muscle morphology. Significant reductions in muscle volume, estimated cross-sectional area, and length were observed postoperatively in both muscles. Preoperative muscle morphology showed no significant association with postoperative anterior drift of the mandible. In contrast, the magnitude of mandibular setback demonstrated a strong positive correlation with anterior drift. Changes in masseter muscle volume and estimated cross-sectional area were strongly associated with anterior drift and remained significant predictors after adjustment for setback magnitude. Changes in medial pterygoid muscle volume showed a similar trend but did not retain statistical significance after adjustment. Changes in muscle length were not significantly associated with skeletal relapse. No significant differences in muscle morphology changes were observed among groups stratified by setback magnitude.

Conclusions

Postoperative changes in masseter muscle morphology, particularly muscle volume, are significantly associated with skeletal relapse and may serve as a more reliable indicator than preoperative muscle size. In contrast, the contribution of the medial pterygoid muscle appears

limited. These findings suggest that postoperative muscular adaptation plays a more critical role in skeletal stability than baseline muscle characteristics, and masseter muscle adaptation plays a major role. Interventions that support muscle recovery after surgery may help reduce the risk of relapse.

Keywords

Masseter muscle; Medial pterygoid muscle; Orthognathic surgery; Skeletal relapse; Mandibular setback; Muscle morphology; Computed tomography

I. Introduction

Bimaxillary orthognathic surgery, often combining Le Fort I osteotomy and bilateral sagittal split ramus osteotomy (BSSRO), is a surgical procedure used to correct skeletal malocclusion. The aims of this treatment are to modify the occlusal plane and reposition the jaws into a more ideal anatomical relationship, thereby improving both occlusion and facial esthetics. Jędrzejewski et al. reported that various complications may occur following surgery, including nerve injury, temporomandibular joint disorders, hemorrhage, auditory tube function, infection, nonunion, skeletal relapse, bone necrosis, etc.[1]

Postoperative skeletal stability is which the planned changes in skeletal position and occlusion are consistently maintained. Long term skeletal stability after orthognathic surgery remains a major clinical concern. Skeletal relapse (SR) is commonly defined as ≥2 mm of horizontal displacement at B-point,[2,3] and its reported incidence after orthognathic surgery in Class III patients ranges widely from 14% to 46%.[4,5] A number of etiologic factors have been suggested to correlate with skeletal relapse such as condyle malposition, pterygomasseteric tension, and clockwise rotation of the proximal segment.[6,7,8] Recently, increasing attention has been directed toward the biomechanical influences of the pterygomasseteric sling before and after orthognathic surgery. The present study therefore focuses on physiological factors of the masseter muscle and medial pterygoid muscle, which constitute this sling.

Many previous literatures have addressed mean relapse, setback magnitude, or their association.[4,5,8,9,10] In addition, the rapid development of three-dimensional medical software over the past decade has enabled radiographic analyses of three-dimensional muscle morphology, including muscle volume, length, width, and cross-sectional area (CSA), as well as skeletal changes after orthognathic surgery.[11-20]

However, existing studies have not directly examined the association between SR and masticatory muscle morphology. Most studies have focused either on skeletal stability or on muscle morphology alone. For example, Lekroengsin et al. linked postoperative changes in masticatory muscle morphology with alterations in condylar shape,[21] and Beukes et al. reported significant associations between medial pterygoid detachment and skeletal stability.[22]

Nonetheless, neither study extended its analysis to the relationship between SR and muscle morphology.

Moreover, several prior studies used parameters with potential limitations in physiological interpretation. CSA is widely used as an indicator of force-generating capacity, but its accurate acquisition can be affected by the complex three-dimensional geometry of the jaw muscles and by the orientation of the imaging plane.[23] Accordingly, some studies derived CSA using skeletal reference planes[16,18] or assumed the muscle axis from overall muscle shape to construct a perpendicular measurement plane.[15,17] Thus, the reliability of CSA measurements may be influenced by the methodological approach and should be interpreted with caution.

Muscle length also lacks a standardized assessment protocol. Because of the anatomical complexity of the masticatory muscles, true muscle fiber length cannot be directly quantified.[24,25] Thus, earlier investigations have relied on three-dimensional model based estimations of muscle length.[11,12,13] These approaches provide useful approximations, but raise the possibility that the estimated muscle length may not reliably reflect true muscle fiber length.

In this study, we quantified the pre- and postoperative three-dimensional morphology of the masseter and medial pterygoid muscles to investigate the role of the pterygomasseteric sling and to evaluate their association with SR. To compensate the conventionally used CSA, we calculated the estimated cross-sectional area (eCSA) by dividing muscle volume by estimated fiber length, using this parameter as a proxy for maximal isometric force. Based on these values, we examined the relationship between muscle morphology and mandibular anterior drift, and further compared the relative contributions of the two muscles.

II. Methods and Materials

1. Patient Demographics

This study included 36 patients who were diagnosed with Class III malocclusion and underwent Le Fort I osteotomy and BSSRO. Standardized lateral cephalograms were obtained 1 month before surgery (T0), 1-2 weeks postoperatively (T1), and at the latest follow-up of at least 6 months (T2). Cone-beam computed tomography (CBCT) was taken at T0 and again at 5-6 months after surgery (T2). Patients with maxillofacial trauma or craniofacial deformities were excluded. All patients received orthodontic treatment before and after surgery. All surgical procedures were performed by a single surgeon at Dankook University Dental Hospital between 2020 and 2025, and maxillomandibular fixation was maintained for 2-3 weeks postoperatively.

2. Measurement of Muscle Morphology on CBCT (Volume, Length, and Estimated CSA)

Muscle volume was calculated by delineating the margin of each muscle. Using 3D Slicer, the masseter and medial pterygoid muscles were manually segmented on CBCT based on clear anatomical boundaries in every slice. (Fig. 1) To maintain constant contrast between muscles and surrounding tissues, an identical window/level setting was applied throughout segmentation. Bilateral muscle volumes (cm^3) were summed for analysis.

Muscle length, which was aimed to approximate fiber length, was calculated as the linear distance between the centroids of the muscle margins at the origin and insertion. First, the muscle margins at the origin and insertion were segmented in 3D Slicer, and their centroids were obtained using the Segment Statistics module (Fig. 2). The distance between the two centroids was defined as muscle length.

For the masseter muscle, the origin margin was set at the posterior two-thirds of the zygomatic arch, and the insertion margin at the pterygomasseteric sling. For the medial pterygoid, the origin was defined at the internal portion of the medial pterygoid plate, and the insertion at the pterygomasseteric sling.

eCSA was calculated by dividing muscle volume by muscle length. Bilateral muscle lengths and eCSA (cm^2) values were summed for statistical analysis.

All CBCT measurements were performed in 3D Slicer (version 5.6.2; Slicer Community, Harvard Medical School, Boston, MA, USA).

3. Measurement of Mandibular Displacement Using Cephalometric Images

Anterior drift and setback were measured on lateral cephalograms. The X-axis was defined as the Sella–Nasion (SN) plane rotated 7° clockwise, and the Y-axis as a perpendicular line through Sella (origin).[26,27,28] The anatomical landmarks used were Sella, Nasion, and B-point (Fig. 3, 4).

The horizontal position of B-point was defined as the linear distance from the origin to the perpendicular projection of B-point on the X-axis. (Fig. 5) The horizontal displacement from T0 to T1 was defined as setback, and displacement from T1 to T2 as anterior drift.

To ensure landmark reproducibility, the nasal bone and the right mandibular central incisor were used as auxiliary references for Sella and B-point. Nasion did not require additional reference due to high reproducibility. (Fig. 6)

All cephalometric tracings were performed using 3D Slicer (version 5.6.2; Slicer Community, Harvard Medical School, Boston, MA, USA).

4. Statistical Analysis

Six statistical procedures were conducted based on the acquired datasets: 1) Paired t-test; 2) Independent t-test; 3) Correlation analysis; 4) Simple regression analysis; 5) Multiple regression analysis; 6) One way ANOVA.

Statistical analysis was performed using IBM SPSS Statistics version 31.0.1.0 (IBM Corp., Armonk, NY, USA).

4-1. Comparison of pre and post operative muscle morphology (Paired T test)

Paired t-tests were performed to evaluate whether postoperative changes in muscle morphology differed significantly from preoperative values.

4-2. Comparison of muscle morphology in stable group and unstable group (Independent T test)

Independent t-tests were used to compare muscle morphology between stable and unstable groups. Grouping was based on anterior drift thresholds of 2 mm and 4 mm. No patient exceeded 4 mm of anterior drift; thus, patients were classified as stable (≤ 2 mm) or unstable (> 2 mm).

4-3. Correlation of anterior drift and independent variables (Correlation Analysis)

Correlation analyses were conducted to assess associations between muscle morphology and horizontal displacement of B-point during T1-T2 (anterior drift) using the following variables: 1. Horizontal displacement of B-point during T0-T1 (setback); 2. Change of bilateral Masseter Muscle Volume (ΔMMV); 3. Change of bilateral Medial Pterygoid Muscle Volume (ΔMPV); 4. Change of bilateral Masseter Muscle eCSA (ΔMMC); 5. Change of bilateral Medial Pterygoid Muscle eCSA (ΔMPC); 6. Change of bilateral Masseter Muscle Length (ΔMML); 7. Change of bilateral Medial Pterygoid Muscle Length (ΔMPL); 8. Bilateral Preoperative Masseter Muscle volume (pre MMV); 9. Bilateral Preoperative Medial Pterygoid Muscle volume (pre MPV); 10. Bilateral Preoperative Masseter Muscle eCSA (pre MMC); 11. Bilateral Preoperative Medial Pterygoid Muscle eCSA (pre MPC); 12. Bilateral Preoperative Masseter Muscle length (pre MML); 13. Bilateral Preoperative Medial Pterygoid Muscle length (pre MPL)

4-4. Predictability of independent variables about anterior drift (Simple Regression Analysis)

Simple regression analyses were conducted with anterior drift (T1-T2 B-point horizontal displacement) as the dependent variable. Independent variables were identical to those used in the correlation analysis.

4-5. Analysis of ΔMMV, ΔMMC, ΔMPV under adjustment of setback (Multiple Regression Analysis)

Multiple regression analyses were performed to evaluate whether muscle morphology independently influenced anterior drift after controlling for setback. The dependent variable was anterior drift, and only variables that showed significant correlations were entered into the model together with setback. The selected variables were ΔMMV, ΔMMC, and ΔMPV.

4-6. Comparison of muscle morphology change between low, medium, and high setback group (One way ANOVA)

One-way ANOVA was conducted to test whether muscle morphology differed according to setback magnitude. Patients were grouped by cutoffs of 5 mm and 10 mm into low (< 5 mm), medium (≥ 5 mm and < 10 mm), and high (≥ 10 mm) setback groups.

III. Results

1. Patient Demographics

The sample consisted of 18 males (50%) and 18 females (50%), with a mean age at surgery of 23.67 ± 4.59 years. The mean amount of postoperative anterior drift was 1.26 ± 0.94 mm, and the mean setback was 9.02 ± 3.91 mm.

For the independent t-test, cutoff values of 2 mm and 4 mm were applied to anterior drift. Twenty-nine patients (80.6%) were classified into the stable group (anterior drift < 2 mm), and 7 patients (19.4%) were classified into the unstable group (anterior drift ≥ 2 mm). No patient demonstrated anterior drift ≥ 4 mm (0%). Therefore, only two groups were included in the analysis.

For the one-way ANOVA, setback cutoffs of 5 mm and 10 mm were used. Six patients (16.7%) were classified into the low-setback group (< 5 mm), 19 (52.8%) into the medium-setback group (≥ 5 mm and < 10 mm), and 11 (30.6%) into the high-setback group (≥ 10 mm) (Table 1).

2. Comparison of pre and post operative muscle morphology (Paired T test)

Paired t-tests were performed to compare pre and postoperative muscle morphology. Volumes, eCSA, and lengths of both the masseter and medial pterygoid muscles showed significant postoperative reductions (MML and MPL, $p < 0.003$; all other parameters, $p < 0.001$).

The mean reduction in MMV was 4.48 cm^3, and MPV decreased by 2.87 cm^3. The mean reduction in MMC was 0.46 cm^2, and MPC decreased by 0.44 cm^2. MML decreased by 0.44 cm, and MPL decreased by 0.33 cm. (Table 2, Fig. 7)

3. Comparison of muscle morphology in stable group and unstable group (Independent T test)

Independent t-tests were conducted between the stable group (< 2 mm; n = 29) and the unstable group (≥ 2 mm; n = 7). The following variables showed significant differences in the unstable group: setback (mean difference = –0.56 mm, p = 0.029), ΔMMV (mean difference =

6.04%, p = 0.003), ΔMMC (mean difference = 5.57%, p = 0.022), and ΔMPV (mean difference = 4.56%, p = 0.045).

No significant differences were observed for ΔMPC, ΔMML, ΔMPL, or for any preoperative muscle morphology parameters. (Table 3, Figs. 8-1, 8-2, 8-3)

4. Correlation of anterior drift and independent variables (Correlation Analysis)

Correlation analyses were performed using anterior drift as the dependent variable. Anterior drift demonstrated significant positive correlations with the following variables: setback (Pearson r = 0.534, p < 0.001), ΔMMV (r = 0.381, p = 0.005), ΔMMC (r = 0.378, p = 0.022), and ΔMPV (r = 0.209, p = 0.023).

No significant differences were observed for ΔMPC, ΔMML, ΔMPL, or for any preoperative muscle morphology parameters. (Table 4)

5. Predictability of independent variables about anterior drift (Simple Regression Analysis)

Simple regression analyses were conducted with anterior drift as the dependent variable. Significant predictors included setback (B = 0.128, R^2 = 0.285, p < 0.001), ΔMMV (B = 0.073, R^2 = 0.212, p = 0.005), ΔMMC (B = 0.052, R^2 = 0.145, p = 0.022), and ΔMPV (B = 0.049, R^2 = 0.143, p = 0.023).

No significant differences were observed for ΔMPC, ΔMML, ΔMPL, or for any preoperative muscle morphology parameters. (Table 5, Figs. 9-1, 9-2, 9-3)

6. Analysis of ΔMMV, ΔMMC, ΔMPV under adjustment of setback (Multiple Regression Analysis)

Multiple regression analyses were performed using setback as a covariate and including ΔMMV, ΔMMC, and ΔMPV, which were significant in correlation analyses.

ΔMMV remained a significant predictor when included with setback (p = 0.016; setback p = 0.003). ΔMMC also remained significant when modeled with setback (p = 0.046; setback p = 0.002). When ΔMPV was included with setback, it showed borderline significance (p = 0.052; setback p = 0.002). ΔMPC, ΔMML, and ΔMPL were not significant predictors. (Table 6)

7. Comparison of muscle morphology change between low, medium, and high setback group (One way ANOVA)

Patients were divided into three groups according to setback magnitude (< 5 mm, ≥ 5 mm and < 10 mm, ≥ 10 mm), and postoperative changes in muscle morphology were compared.

No significant group differences were identified for any variable: ΔMMV ($F = 1.186$, $p = 0.318$), ΔMMC ($F = 1.423$, $p = 0.255$), ΔMPV ($F = 0.413$, $p = 0.665$), ΔMPC ($F = 0.080$, $p = 0.923$), ΔMML ($F = 0.162$, $p = 0.852$), and ΔMPL ($F = 0.650$, $p = 0.529$). Effect sizes were minimal for all parameters ($\eta^2 = 0.005–0.171$). (Table 7, Figs. 10-1, 10-2)

IV. Discussion

The mean postoperative SR, represented as anterior drift, was 1.26 mm in this study. This result is consistent with the previously reported range of 1.0-1.7 mm.[4,8,10] The anterior drift to setback ratio in the present article (mean 13.68%) was also comparable to earlier findings.[28] Sahoo et al. reported that the amount of setback is associated with the extent of SR,[9] and our findings support this association. Collectively, these results indicate that the present dataset aligns well with established literature and reinforces the reliability of our findings.

Preoperative muscle morphology did not show significant associations with SR in any statistical analysis. This suggests that skeletal stability after orthognathic surgery is not determined by absolute muscle morphology at a preoperative single time point.

Furthermore, our findings support the established concept that masticatory muscles undergo transient postoperative atrophy followed by long term recovery. Katsumata reported that masseter CSA in Class III patients decreases during the first 3 postoperative months and shows partial recovery by 6-12 months, although recovery was limited below baseline levels.[15]

Long term studies reinforce this pattern. Lee et al. demonstrated continuous increases in masseter muscle CSA, width, and thickness at 1 year and 4 years postoperatively.[17] Ueki et al. and Muftuoglu et al. found no significant difference in masseter muscle CSA at 1 year compared with preoperative values,[18,19] suggesting that muscular recovery is already underway at approximately 12 months.

Taken together with longer term follow up data demonstrating recovery, the 5-6 months reductions of muscle volume, eCSA, and length observed in the present study most likely represent a pre recovery or initial recovery stage within the early postoperative period described by Katsumata et al.

Preoperative muscle morphology was not associated with relapse in this study. This could suggest that skeletal stability may relate more to postoperative changes than to absolute baseline muscle size, which might be influenced by inter-individual anatomical variation rather than functional properties.

In contrast, ΔMMV, ΔMPV, and ΔMMC demonstrated significant associations with anterior drift across independent t-test, correlation analysis, and simple regression analysis. Because

these parameters represent proportional changes, they may reduce inter-individual anatomical variability, which may partly explain their predictive performance over absolute preoperative measurements. These findings also raise the possibility that postoperative muscular adaptation may contribute to SR.

Correlation and simple regression analyses showed stronger correlation and predictability for muscle volume (ΔMMV, ΔMPV) compared with muscle eCSA (ΔMMC, ΔMPC). One possible explanation is that the muscle volume reflects the total amount of contractile tissue and therefore may provide a more comprehensive representation of the structural mass available for functional recruitment. Conversely, eCSA is intended to approximate maximal isometric force, which may not represent physiological behavior during non-activation or dynamic loading. Supporting this, Gwak et al. reported that CSA correlates with maximal strength but not with muscular endurance or stability.[29] Another explanation is that because muscle length estimation is based on geometric assumptions, eCSA may incorporate methodological error and may not accurately reflect true physiological force capacity.

When comparing the masseter and medial pterygoid muscles, the masseter demonstrated stronger association and higher predictability with anterior drift. One explanation is the inherently greater force generating capacity of the masseter. Hannam et al. reported that the masseter has greater volume and CSA than the medial pterygoid and serves as a major stabilizer of occlusion,[30] consistent with our findings. Despite its smaller area of attachment to the distal mandibular segment relative to the medial pterygoid, the masseter may transmit greater mechanical loading through the pterygomasseteric sling, thereby exerting a stronger influence on anterior drift.

Another explanation relates to functional behavior. Hannam et al. reported that during oral function, the medial pterygoid muscle is selectively coactivated with the masseter muscle, rather than acting as a synergist.[31] Because medial pterygoid muscle activation tends to be dependent rather than independent, it may exert less distinguishable mechanical influence on mandibular displacement.

Finally, the medial pterygoid has less distinct anatomical boundaries from adjacent soft tissues on CBCT compared to the masseter muscle, which may increase segmentation error and contribute to the weaker associations observed for ΔMPV and ΔMPC.

In multiple regression, both ΔMMV and ΔMMC remained significant predictors even after controlling for setback, while ΔMPV demonstrated borderline significance. These findings suggest that postoperative muscle morphology change may contribute to SR independent of setback magnitude.

One way ANOVA demonstrated no significant group differences in muscle morphology according to setback magnitude, and effect sizes were uniformly small, indicating a possibility that setback exerts a limited influence on postoperative muscular changes.

Changes in muscle length (ΔMML and ΔMPL) showed no meaningful association with SR in any analysis.

Overall, our findings suggest that the atrophic change during the initial postoperative adaptation progress of masseter and medial pterygoid muscles plays an important role in skeletal stability, and the masseter showed a stronger influence. Preoperative muscle morphology alone was insufficient to predict SR. On the other hand, proportional postoperative alteration showed greater relevance, implying that the proportional atrophic change may be meaningful for skeletal stability. These results raise the possibility that the intervention for muscular weakening during postoperative rehabilitation may contribute to improved skeletal stability.

To our knowledge, this is the first study to evaluate the relationship between postoperative morphological changes in the masticatory muscles and skeletal relapse in Class III patients undergoing orthognathic surgery.

This study also attempted to refine the physiological interpretation of CSA by compensating for measurement limitations. Maughan proposed that CSA represents maximal isometric force,[32] and numerous studies have adopted CSA as a strength indicator.[15,16,17,18] However, several authors doubt the reliability of CSA. Van Spronsen et al. reported that due to the complex shapes and specific spatial orientation, perfect cross-sectional imaging with is impossible.[23] Mitsiopoulos et al. also reported that CSA is more susceptible to error than muscle volume.[33] Boom et al. pointed out that these issues may particularly enlarge medial pterygoid muscle CSA.[34]

Physiological cross-sectional area (PCSA), defined as muscle volume divided by fiber length, is considered proportional to maximal force capacity.[35] However, Lieber et al. demonstrated that muscle fiber architecture cannot be reliably identified from radiographic images because

variations in fiber length and pennation angle cannot be resolved.[25] Consequently, many studies have adopted CSA as a surrogate strength indicator[15-20] and estimation of muscle length was based on geometric assumptions.[11,12,13,15,19]

In the present study, segmentation was performed according to visible muscular boundaries on CT, and the centroid to centroid distance between the origin and insertion was used as an approximation of muscle length. The resulting eCSA was not intended to replace PCSA but rather to complement limitations of conventional CSA by incorporating three-dimensional geometry. We expect that the eCSA measurement used in the present study may reflect muscle morphology in a more quantitative manner than traditional CSA.

Nevertheless, this method also has inherent limitations. Centroid based length estimation remains only an approximation of muscle fiber length. Ounjian et al. suggested that ideal measurement can be determined only by microdissection of individual fibers,[24] which is not feasible in clinical imaging research. Mechanical line of action models may be used as alternatives, but CT-based estimates still involve geometric uncertainty.[25] Moreover, muscle attachment margins cannot always be clearly distinguished on CT, introducing uncertainty in defining origins and insertions.

This study also has limitations due to its retrospective design. Soft tissue analysis was limited to a single postoperative time point (T2), and long term (> 1 year) CT data were unavailable, preventing documentation of the recovery phase. Because CT was obtained only at T0 and T2, muscle morphology at T1 could not be analyzed, and setback and anterior drift measurements relied on cephalograms. This limitation reduced assessment of three-dimensional factors such as asymmetry or muscle vectors. Consequently, precise physiological interpretation of postoperative muscle adaptation was limited.

Future research should incorporate more accurate fiber mapping and attachment modeling, multipoint postoperative follow-up, MRI based volumetric assessments, multiple observer validation, and automated segmentation using artificial intelligence or machine learning techniques.

V. Conclusion

In this study, pre and postoperative CT images were used to measure the volume, estimated cross-sectional area (eCSA), and length of the masseter and medial pterygoid muscles. We then assessed whether setback, preoperative muscle morphology, and postoperative alteration of muscle morphology were associated with skeletal relapse after bimaxillary orthognathic surgery. Setback and anterior drift were quantified using a coordinate system rotated 7° clockwise relative to the SN plane, and various statistical analyses were performed, including paired and independent t-tests, correlation analyses, regression analyses, and one-way ANOVA. The principal findings were as follows.

1. Postoperative changes in masseter muscle volume were independently associated with skeletal relapse, even after adjusting for the magnitude of mandibular setback.
2. Postoperative changes in muscle volume and eCSA showed significant correlations with anterior drift, with volume change demonstrating greater reliability than eCSA.
3. The masseter muscle demonstrated the strongest and most consistent association with relapse, whereas the medial pterygoid muscle showed a weaker and borderline contribution.
4. The magnitude of mandibular setback was positively correlated with relapse; however, postoperative muscular changes contributed additional independent effects.
5. Preoperative muscle morphology did not predict postoperative skeletal relapse.
6. These findings suggest that postoperative muscular adaptation plays a critical role in skeletal stability, and that rehabilitation strategies—including functional training and guided masticatory exercises—may help reduce relapse risk.
7. The magnitude of setback was not associated with postoperative muscular changes.
8. Muscle length did not show significant association to skeletal relapse.

These findings suggest that skeletal stability after bimaxillary orthognathic surgery is determined more by postoperative alteration of muscle morphology of the masticatory muscles than by absolute preoperative muscle size at a single time point. The strong predictive performance of masseter muscle volume change raises the possibility that volume may reflect overall muscular capacity more comprehensively than eCSA. Furthermore, the independent

effect of muscular changes on anterior drift, irrespective of setback magnitude, indicates that postoperative muscular recovery and functional rehabilitation should be actively considered to minimize skeletal relapse.

List of Abbreviations

1. BSSRO : Bilateral sagittal split ramus osteotomy
2. SR : Skeletal relapse
3. CSA : Cross-sectional area
4. eCSA : estimated cross-sectional area
5. CBCT : Cone-beam computed tomography
6. SN plane : Sella nasion plane
7. MMV : Masseter muscle volume
8. MPV : Medial pterygoid muscle volume
9. MMC : Masseter muscle eCSA
10. MPC : Medial pterygoid muscle eCSA
11. MML : Masseter muscle length
12. MPL : Medial pterygoid muscle length
13. PCSA : Physiological cross-sectional area

Ethical Approval Statement

This study was approved by the Institutional Review Board (IRB) of Dankook University Dental Hospital (IRB No. 2026-03-005). The study was conducted in accordance with the principles of the Declaration of Helsinki.

Human Ethics and Consent to Participate declarations

As this was a retrospective study using anonymized radiographic data, the requirement for informed consent was waived by the IRB.

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Table 1. Patient Demographics

Gender	Male: 18 (50%) / Female: 18 (50%)
Age	23.67 ± 4.59
Anterior Drift (mm)	1.26 ± 0.94
Setback (mm)	9.02 ± 3.91
Anterior Drift / Setback (%)	13.68 ± 11.80
Stable Group	29 (80.6%)
Unstable Group	7 (19.4%)
Relapse Group	0 (0%)
Low Setback Group	6 (16.7%)
Medium Setback Group	19 (52.8%)
High Setback Group	11 (30.6%)

Table 2. Comparison of pre and post operative muscle morphology (Paired T Test)

	Pre OP	Post OP	Mean diff	t(34)	*P*-value	95% CI
MMV (cm³)	48.89 ± 14.71	44.40 ± 12.23	4.48	6.499	< *.001*	3.08 – 5.88
MMC (cm²)	8.08 ± 2.03	7.61 ± 1.70	0.46	4.364	< *.001*	0.25 – 0.68
MPV (cm³)	21.40 ± 5.39	18.53 ± 4.45	2.87	8.817	< *.001*	2.21 – 3.53
MPC (cm²)	4.12 ± 0.85	3.68 ± 0.65	0.44	5.873	< *.001*	0.29 – 0.59
MML (cm)	12.01 ± 0.84	11.58 ± 0.90	0.44	5.086	< *.001*	0.26 – 0.61
MPL (cm)	10.33 ± 0.81	10.00 ± 0.92	0.33	3.243	*.003*	0.12 – 0.53

Table 3. Comparison of muscle morphology in stable group and unstable group (Independent T Test)

	Mean Diff	t	*P*-Value
Setback (mm)	-0.5621296	-0.098	*0.029*
Pre MMV (cm^3)	-0.3116901	-0.394	*0.923*
Pre MMC (cm^2)	1.6580007	0.795	*0.696*
Pre MPV (cm^3)	0.2339223	0.711	*0.432*
Pre MPC (cm^2)	0.29378	0.907	*0.497*
Pre MML (cm)	0.17704	0.565	*0.371*
Pre MPL (cm)	6.5361309	3.252	*0.576*
△MMV (%)	6.0351225	2.405	*0.003*
△MMC (%)	5.5654377	2.077	*0.022*
△MPV (%)	4.5617971	1.285	*0.045*
△MPC (%)	0.74650	0.460	*0.207*
△MML (%)	0.88367	0.389	*0.649*
△MPL (%)	-0.5621296	-0.098	*0.700*

Table 4. Correlation of anterior drift and independent variables (Correlation Analysis)

	Pearson r	***P*-Value**
Setback (mm)	0.534	*< 0.001*
Pre MMV (cm³)	-0.053	*0.852*
Pre MMC (cm²)	0.150	*0.759*
Pre MPV (cm³)	0.103	*0.383*
Pre MPC (cm²)	0.275	*0.550*
Pre MML (cm)	0.195	*0.105*
Pre MPL (cm)	0.460	*0.255*
△MMV (%)	0.381	*0.005*
△MMC (%)	0.378	*0.022*
△MPV (%)	0.209	*0.023*
△MPC (%)	0.025	*0.222*
△MML (%)	0.144	*0.884*
△MPL (%)	0.032	*0.403*

Table 5. Predictive ability of muscle morphology for anterior drift (Simple Regression Analysis)

	R^2	B (Coefficient)	*P*-Value
Setback (mm)	0.285	0.128	*< 0.001*
Pre MMV (cm^3)	0.001	0.002	*0.852*
Pre MMC (cm^2)	0.003	-0.025	*0.759*
Pre MPV (cm^3)	0.022	0.026	*0.383*
Pre MPC (cm^2)	0.011	0.114	*0.550*
Pre MML (cm)	0.076	0.308	*0.105*
Pre MPL (cm)	0.038	0.227	*0.255*
△MMV (%)	0.212	0.073	*0.005*
△MMC (%)	0.145	0.052	*0.022*
△MPV (%)	0.143	0.049	*0.023*
△MPC (%)	0.043	0.021	*0.222*
△MML (%)	0.001	0.006	*0.884*
△MPL (%)	0.021	0.023	*0.403*

Table 6. Predictive ability of △MMV, △MMC, △MPV for anterior drift under adjustment of setback (Multiple Regression Analysis)

	Adjusted R^2	B (Coefficient)	*P*-Value
Setback (mm)	0.366	0.108	*0.003*
△MMV (%)		0.056	*0.016*

	Adjusted R^2	B (Coefficient)	*P*-Value
Setback (mm)	0.329	0.115	*0.002*
△MMC (%)		0.039	*0.046*

	Adjusted R^2	B (Coefficient)	*P*-Value
Setback (mm)	0.325	0.115	*0.002*
△MPV (%)		0.037	*0.052*

Table 7. Comparison of muscle morphology across setback groups (One way ANOVA)

Variable	F	η^2 (Effect size)	p-value
Pre MMV (cm^3)	1.386	0.077	*0.264*
Pre MMC (cm^2)	1.396	0.078	*0.262*
Pre MPV (cm^3)	2.075	0.112	*0.142*
Pre MPC (cm^2)	1.506	0.084	*0.237*
Pre MML (cm)	1.929	0.105	*0.161*
Pre MPL (cm)	3.405	0.171	*0.045*
ΔMMV (%)	1.186	0.067	*0.318*
ΔMMC (%)	1.423	0.079	*0.255*
ΔMPV (%)	0.413	0.024	*0.665*
ΔMPC (%)	0.080	0.005	*0.923*
ΔMML (%)	0.162	0.010	*0.852*
ΔMPL (%)	0.650	0.038	*0.529*

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Figure 7 Comparison of pre- and postoperative muscle morphology using paired t-tests for (A) MMV, (B) MPV, (C) MMC, (D) MPC, (E) MML, and (F) MPL.

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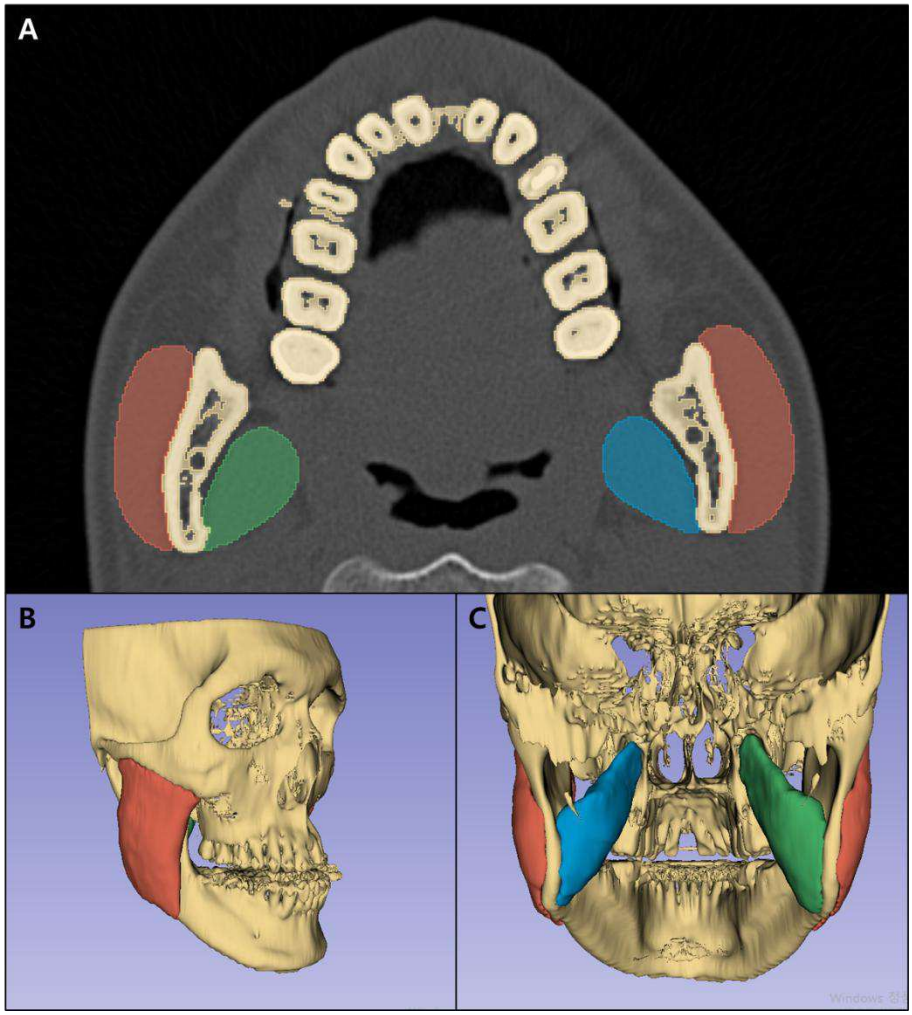


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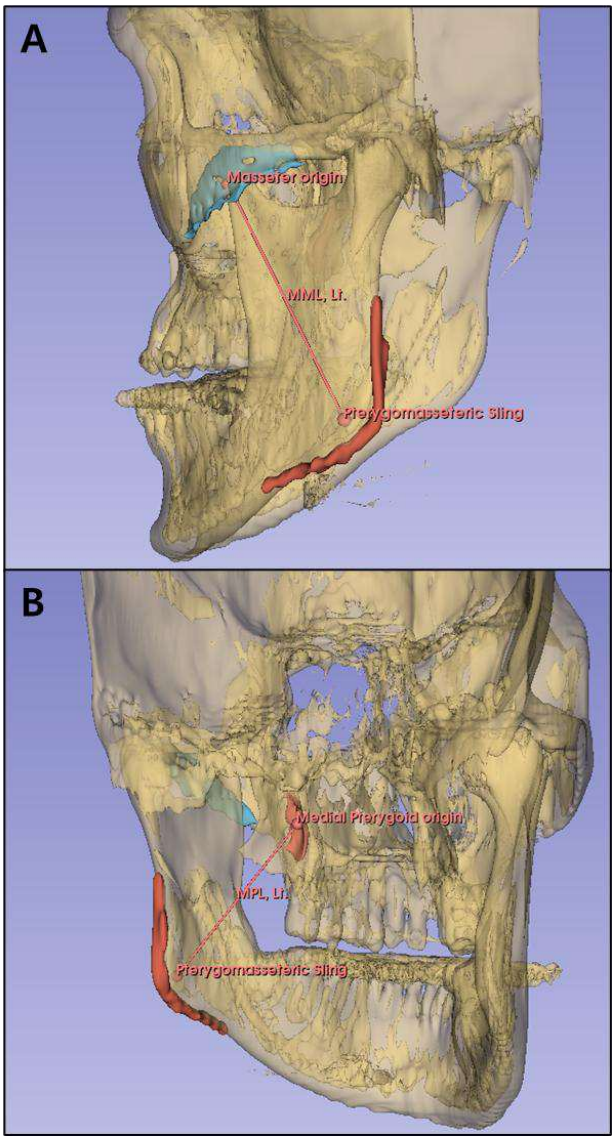


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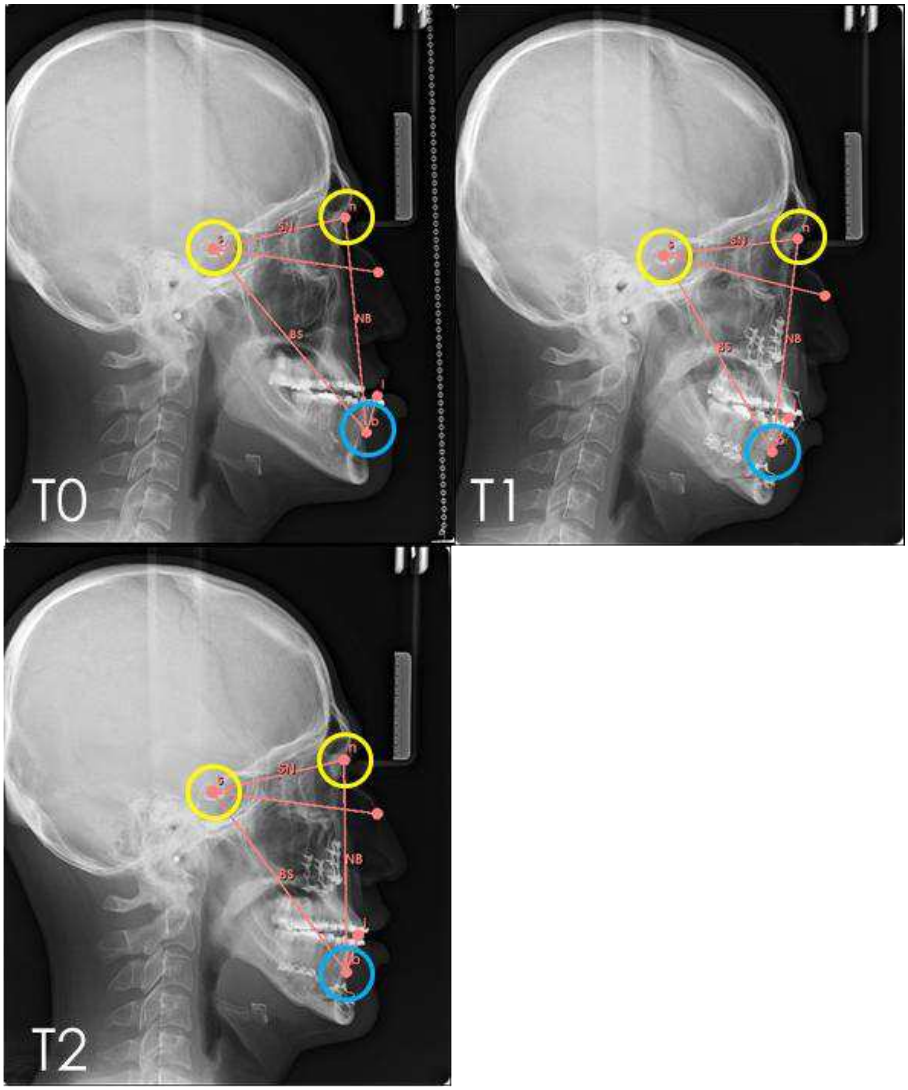


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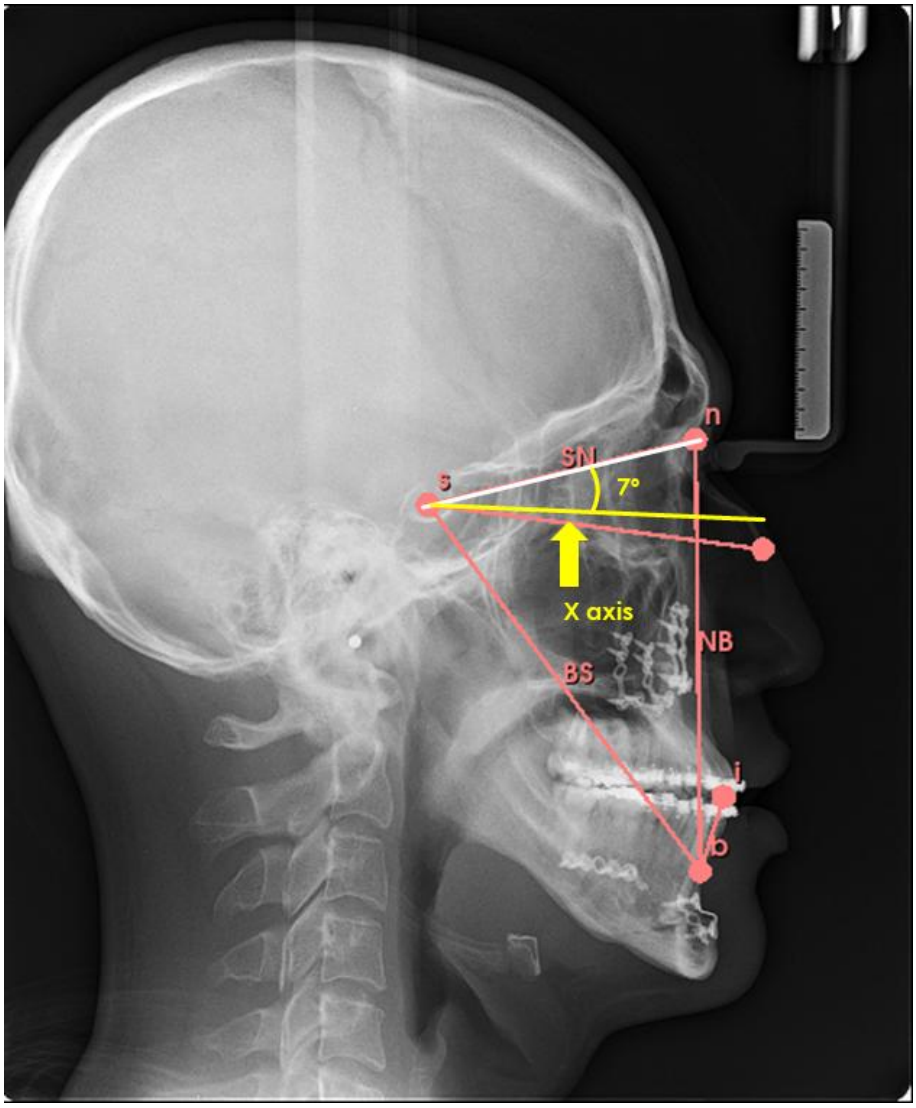


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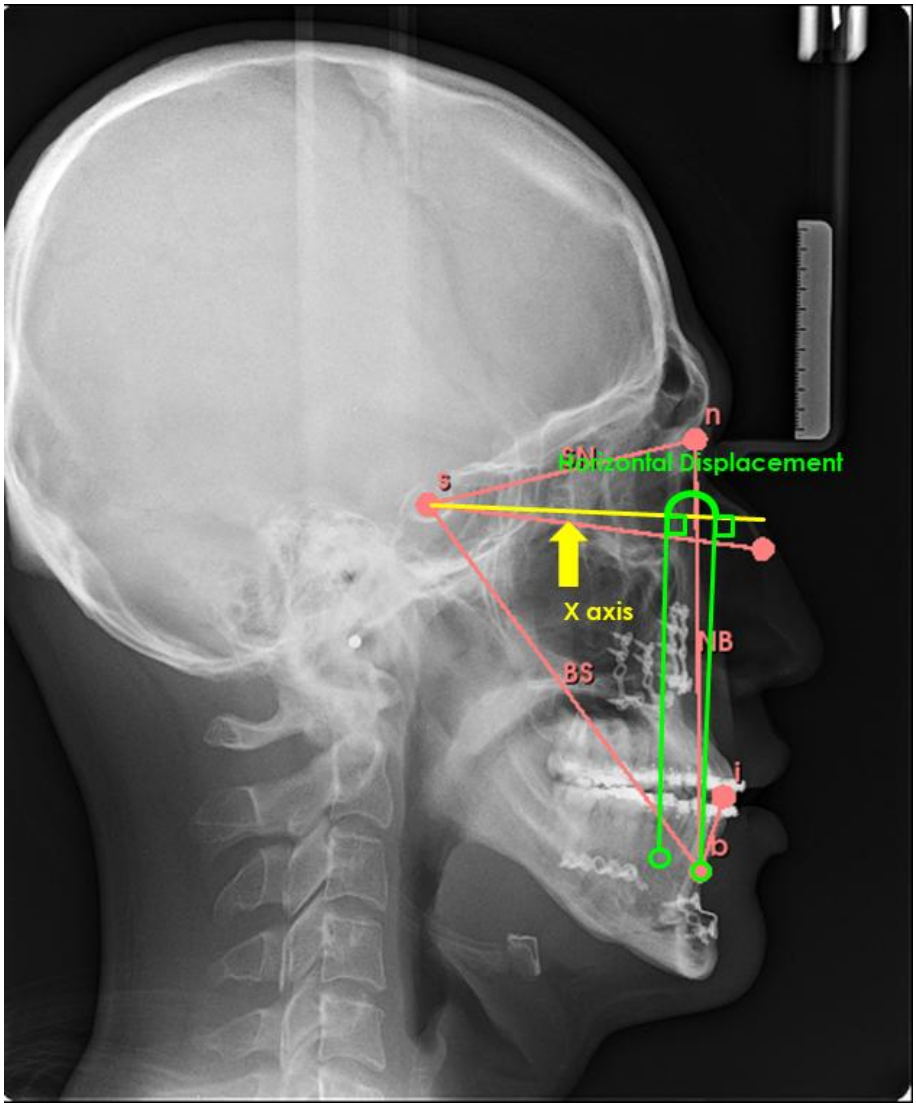


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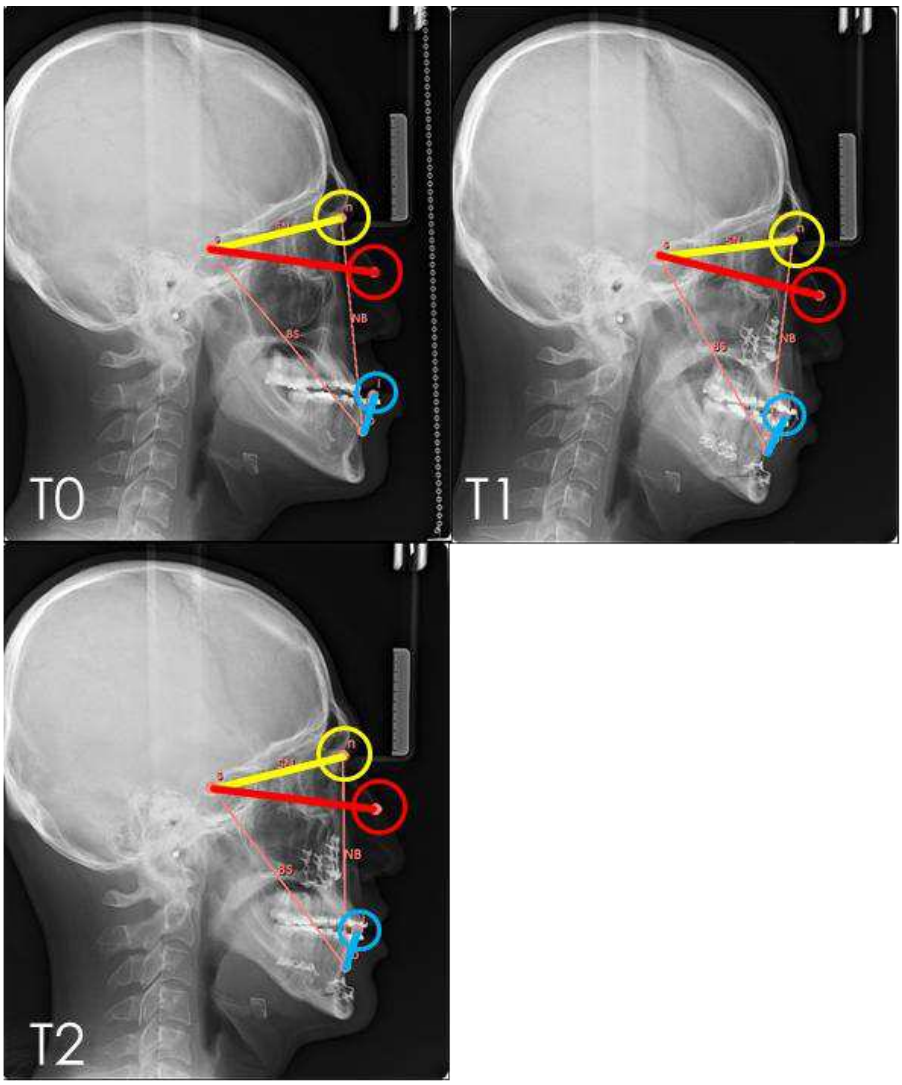


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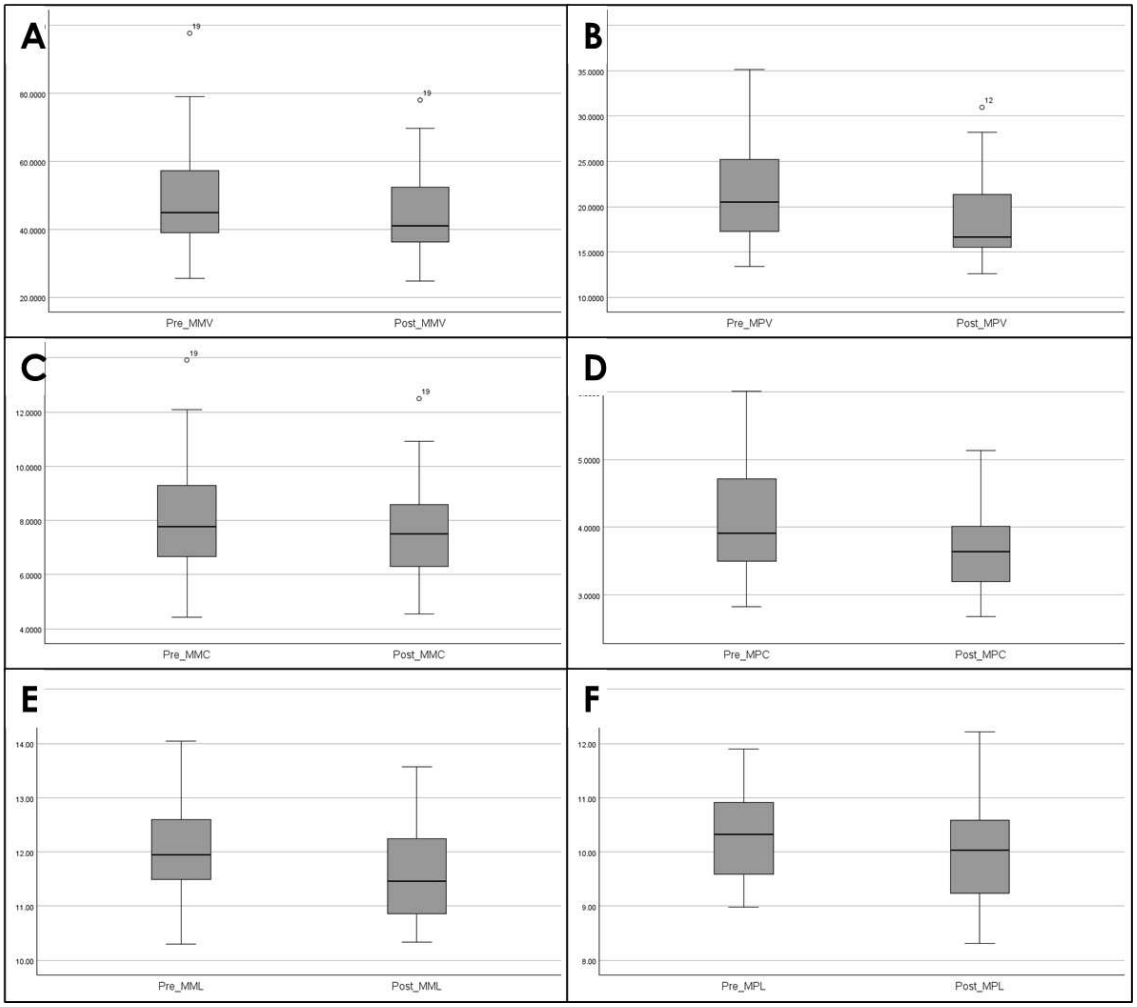


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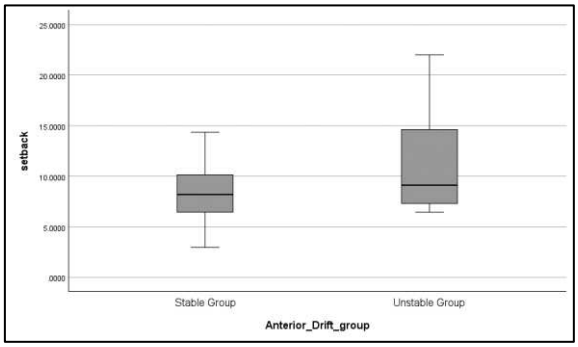


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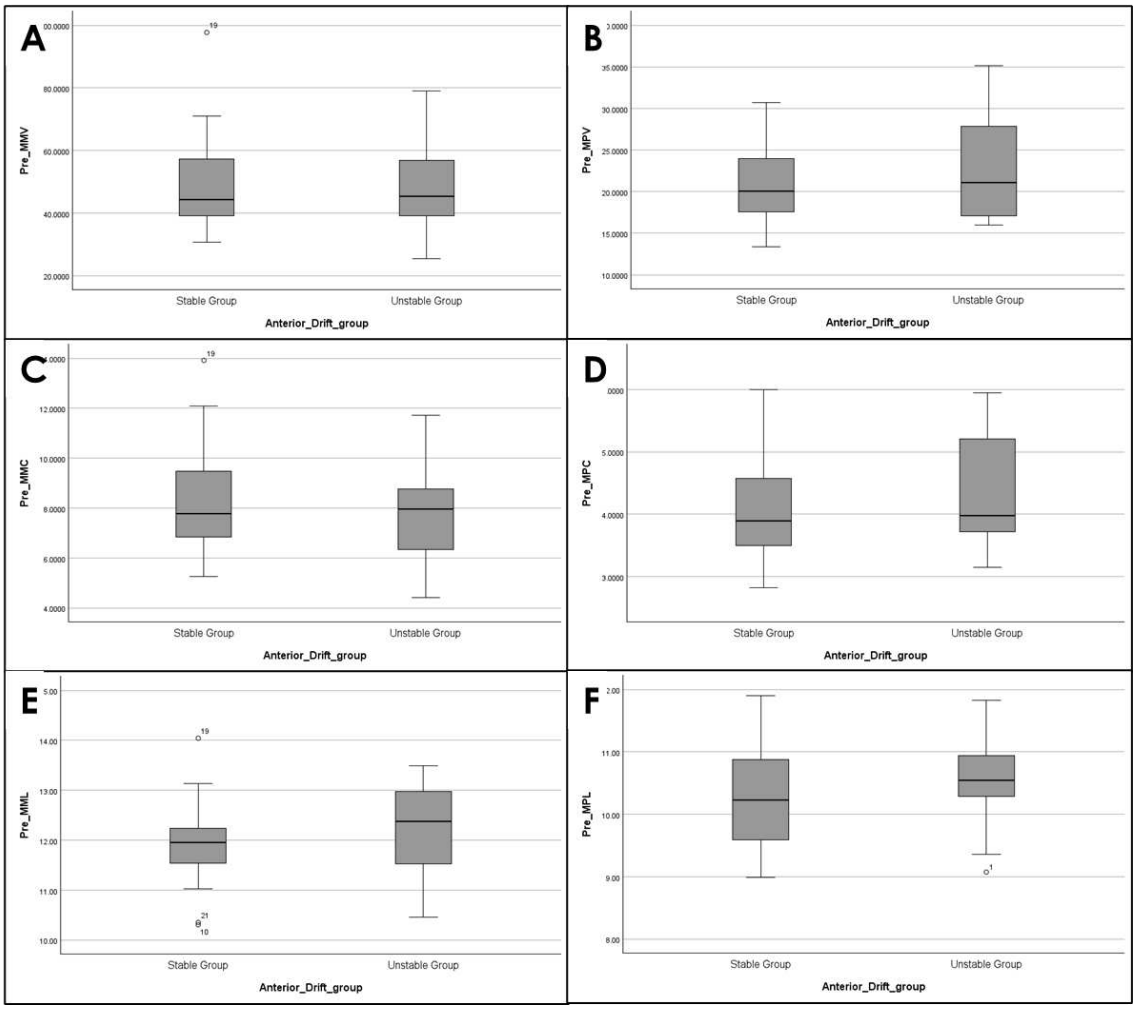


Figure 8-2. Comparison of preoperative muscle morphology between stable and unstable groups using independent t-tests for (A) pre MMV, (B) pre MPV, (C) pre MMC, (D) pre MPC, (E) pre MML, and (F) pre MPL.

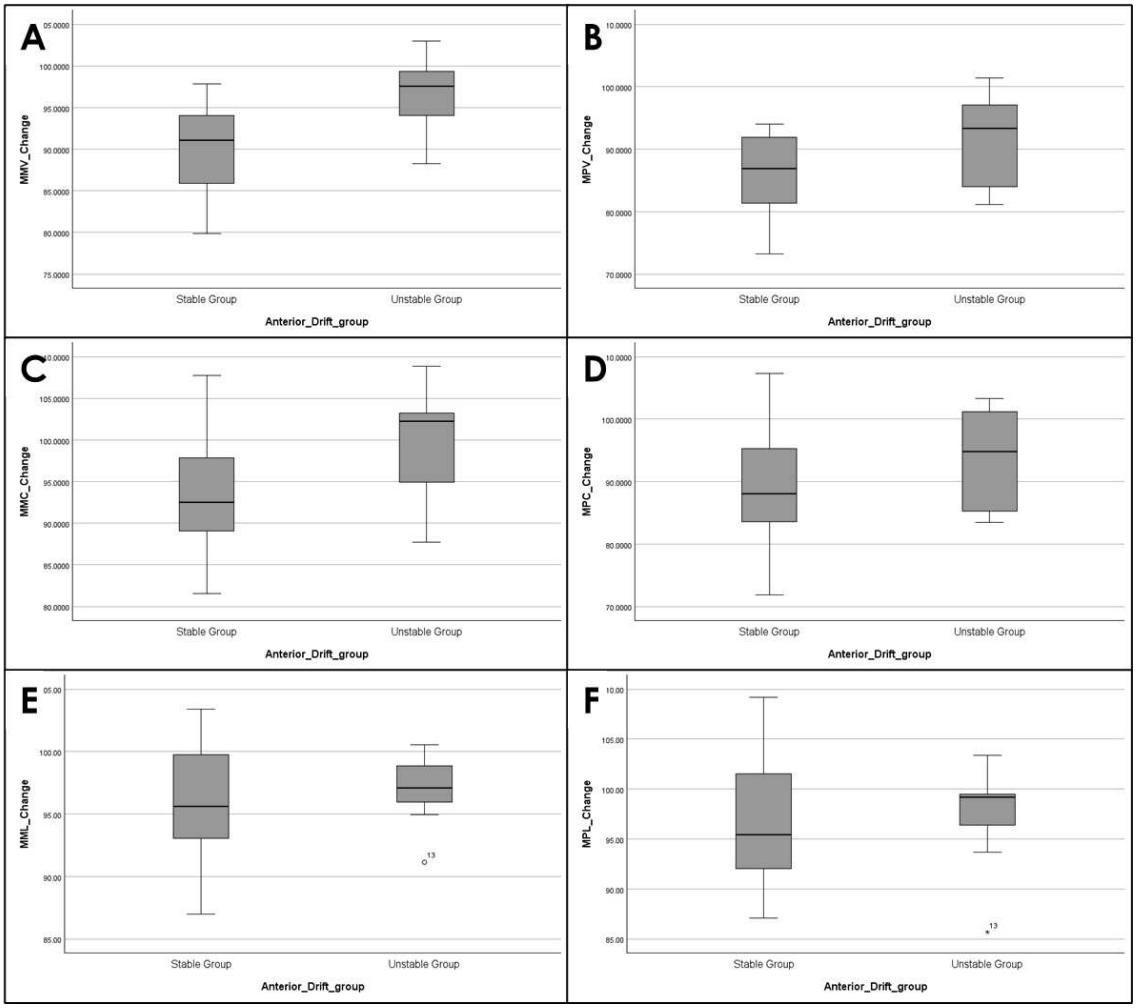


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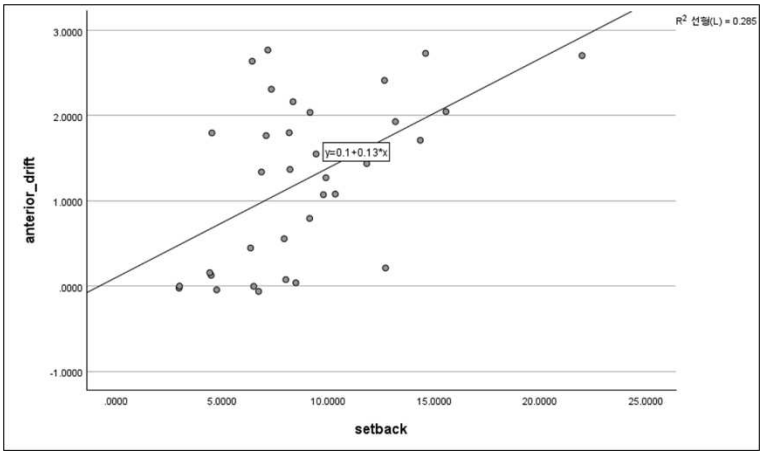


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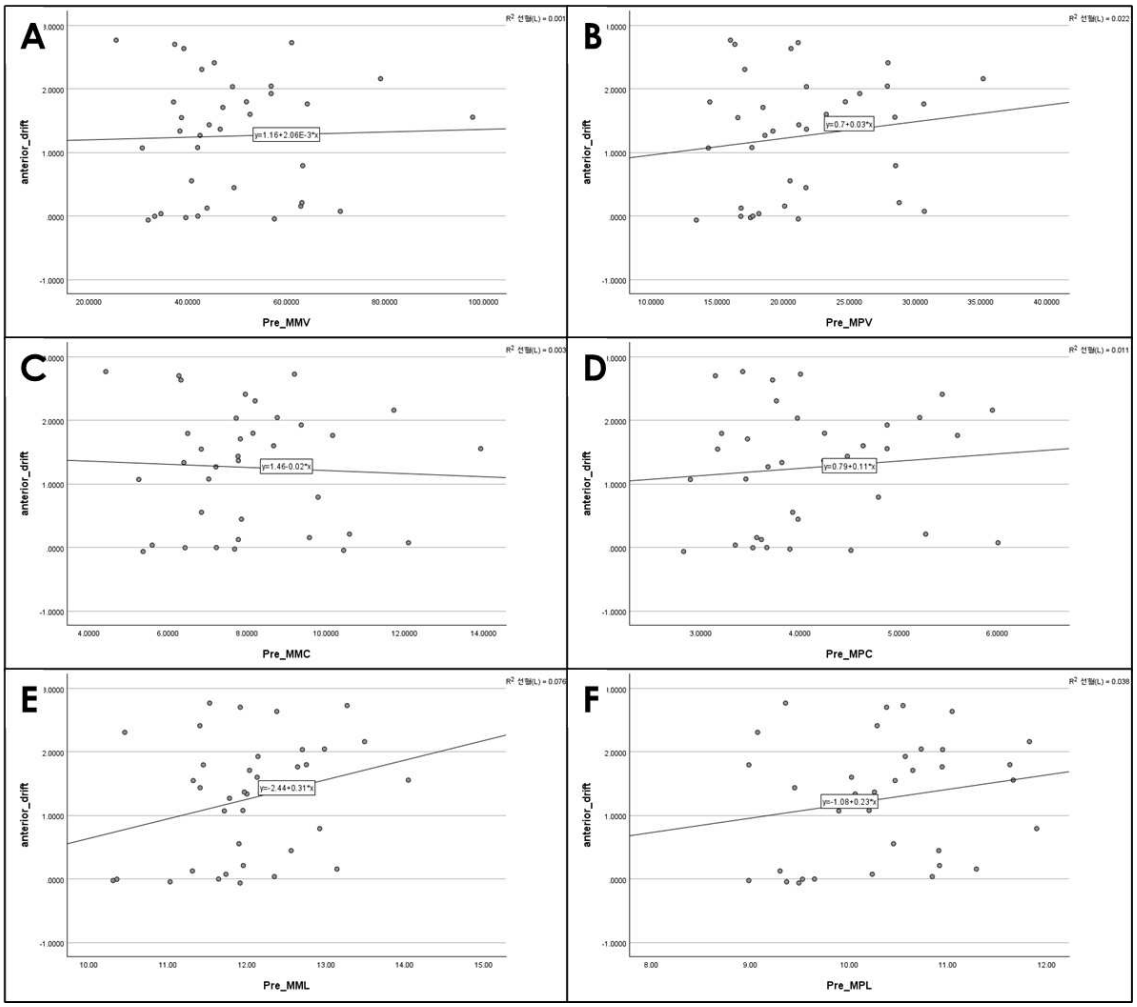


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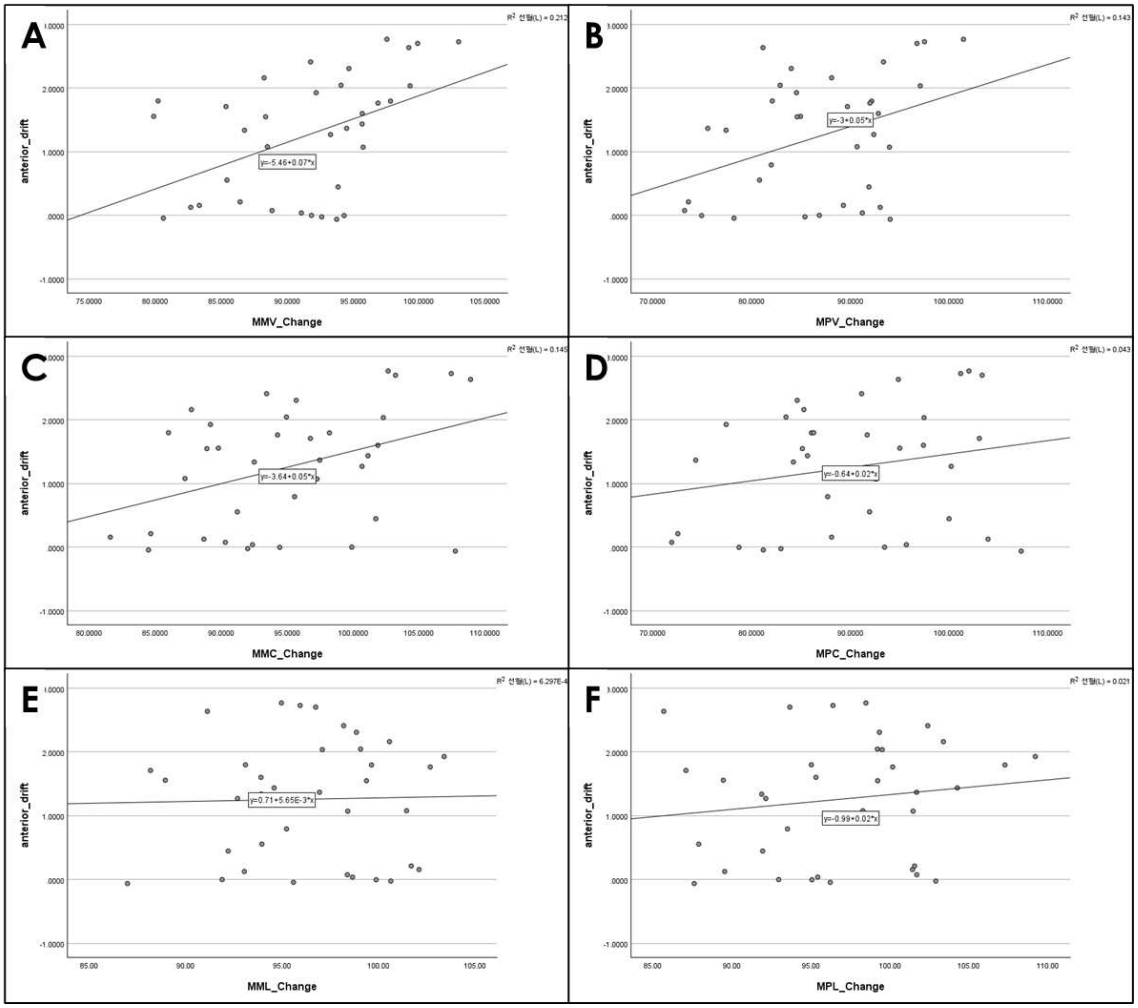


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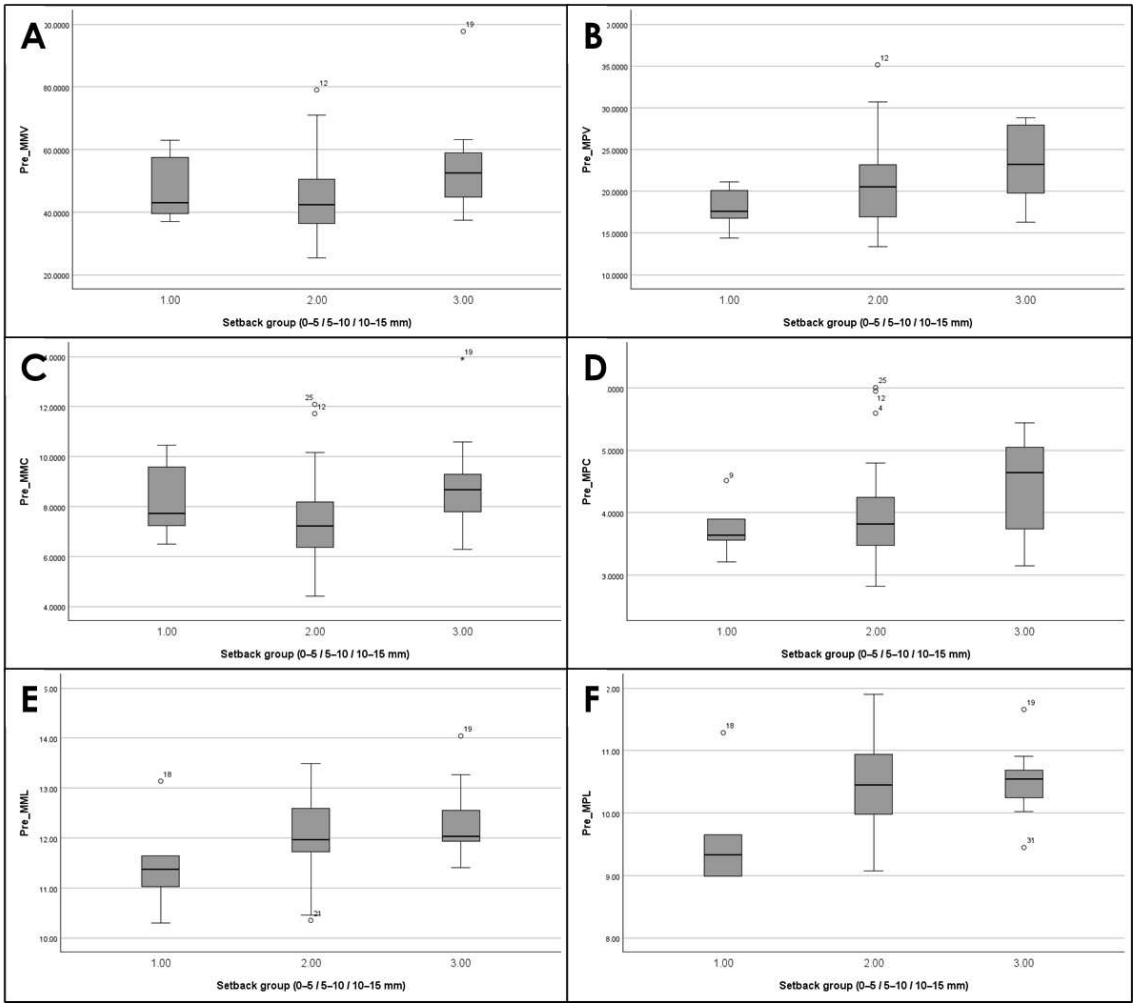


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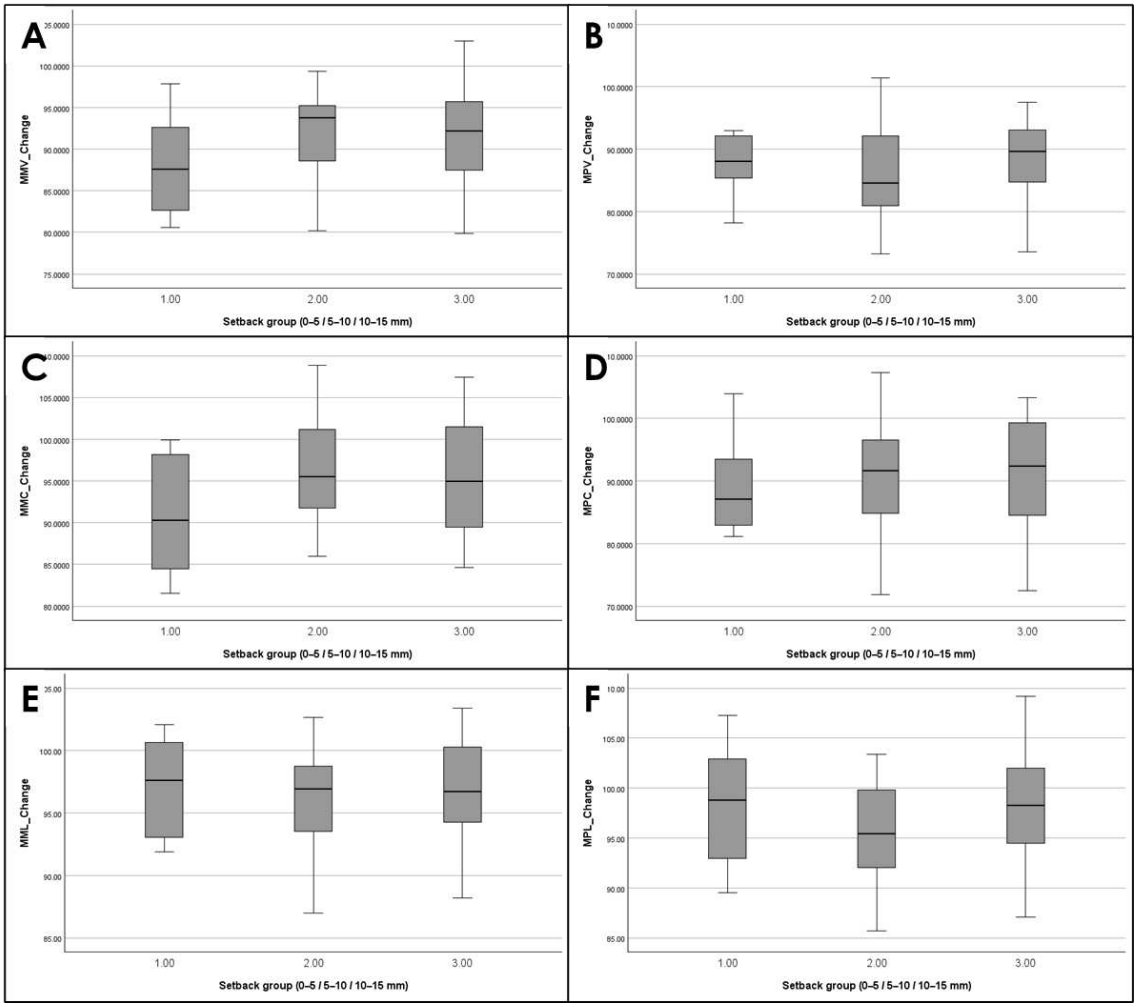


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