Relation between tongue pressure and maxillofacial morphology in Japanese children based on skeletal classification

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Short running title: Tongue pressure and maxillofacial morphology

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Summary

**Background:** During childhood, perioral muscle function is closely associated with malocclusion.

**Objective:** To clarify effects of tongue function on maxillofacial morphology in children, tongue pressure and maximum lip-closing force (LCF) were measured and the relationship between perioral muscle function and maxillofacial morphology were evaluated according to skeletal classification.

**Methods:** Maximum tongue pressure (MTP) and swallowing tongue pressure (STP) were measured on the anterior palatine rugae in 100 children (Hellman’s dental stages IIIA–IIIC) using a balloon-type tongue-pressure–measurement device. LCF was measured using an LCF-measurement device. Lateral cephalograms were examined to classify subjects into Skeletal (S)-I, -II, and -III groups. Correlations of skeletal classification with tongue pressure and LCF were examined. Correlations of lateral cephalometric measurements with palatal volume (PV), measured using a three-dimensional optical scanner, were evaluated.

**Results:** MTP was significantly lower in the S-II group than in other groups. STP was significantly lower in the S-II group than in the S-III group. LCF was significantly higher in the S-III group than in other groups. STP was positively correlated with MTP and PV.

**Conclusion:** Correlations between tongue pressure and anteroposterior skeletal classification indicated the importance of quantitative tongue function assessment.

**Keywords:** tongue pressure, lip-closing force, maxillofacial morphology

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Background

The balance between tongue and perioral muscles, including buccinators, is crucial for maintaining dental articulation.\(^1,2\) Tongue function abnormalities cause dysarthria,\(^3\) decreased chewing efficiency,\(^4\) and dysphagia,\(^5,6\) and critically influence malocclusion onset.\(^7\)

Since Rogers reported the relationship between perioral muscle function and dentition, and advocated a training method that utilized muscle function,\(^8,9\) myofunctional therapy, mainly comprising Zickefoose et al.’s method,\(^10\) has been used in orthodontic treatment. Perioral muscle function is closely associated with malocclusion onset, particularly during childhood when maxillofacial growth and development are rapid. Therefore, it is important to assess outcomes of therapies for improving perioral muscle function.

Tongue-pressure evaluations,\(^11-17\) barium swallows and palatography have been used for tongue function assessments. Barium swallows are invasive and involve radiation exposure, whereas palatography are cumbersome. However, as tongue-pressure measurements are relatively noninvasive and feasible for quantitative assessments, they are particularly useful in very young children. However, the criteria for this assessment as well as relationships of tongue pressure with malocclusion and maxillofacial morphology in children remain unclear.

We aimed to quantitatively assess tongue function in children using tongue-pressure measurements to elucidate the association between tongue function and maxillofacial morphology.

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Methods

1. Subjects and Skeletal classification

Hundred children [mean age, 9.1 ± 1.5 years; 34 boys (9.3 ± 1.2 years) and 66 girls (9.1 ± 1.5 years] in Hellman’s dental stages IIIA–IIIC examined at the Department of Orthodontics of Ohu University Dental Hospital (Fukushima, Japan) were included. Subjects with congenital diseases, nasal disorders, or abnormalities of the frenulum of tongue or in the number of teeth, and those using removable orthodontic appliances or fixed orthodontic appliances were excluded. The Rohrer index was used for growth assessment. The study protocol was approved by the Ohu University institutional review board (approval no. 110); all subjects and their legal guardians were provided with detailed study information before participation.

To assess the relation of perioral muscle function with maxillofacial morphology, subjects were divided into Skeletal (S)-I, -II, and -III groups, according to the ANB angle, which indicates the anteroposterior relation of the maxilla and mandible apical bases measured using lateral cephalograms, and were classified according to criteria described by Utsuno et al. Analysis of skeletal classification according to the Rohrer index revealed no significant difference in body type among groups (Table 1).

2. Tongue-pressure and Lip-closing force measurements

Tongue pressure was measured using a balloon-type tongue-pressure–measurement device (JMS Co., Ltd, Tokyo, Japan). Subjects were seated with the Frankfort horizontal (FH) plane parallel to the floor. The balloon was inserted into the mouth and fixed onto the anterior palatine rugae by asking the subjects...
to lightly bite the rigid device ring with the maxillary and mandibular central incisors\textsuperscript{11} (Fig. 1).

The subjects were instructed to elevate their tongues with a maximum force for 7 s for maximum tongue pressure (MTP) measurements. Swallowing tongue pressure (STP) was measured by instructing subjects to swallow water (5 ml) and fixing the balloon as described previously. Each measurement was performed three times after two practice attempts. Mean values for each measurement set were used. A 30-s rest period was allowed between measurements. With regard to the reproducibility of MTP and STP measurements, the validity of the mean of the three measurements was confirmed by a pilot study.

Lip-closing force (LCF) was measured using the LCF-measurement device Lip de Cum\textsuperscript{®} LDC-110R (Cosmo Instruments Co., Ltd., Tokyo, Japan). The subjects were seated with the FH plane parallel to the floor. A sensor was attached to the Ducklings\textsuperscript{®} lip holders; the device was placed onto the mouth and lips. LCF was measured for 5 s with the subject maintaining the intercuspal position (Fig. 2).\textsuperscript{19} After two practice attempts, three measurements were obtained 30 s apart. Mean values of the three measurements were used as LCF values. With regard to the reproducibility of LCF measurements, the validity of the mean of the three measurements was confirmed by a pilot study.

3. Palatal volume measurement

Palatal volume (PV) was measured using a maxillary dentition model, as described previously.\textsuperscript{20} Dental casts were measured using a noncontact, 3D shape-measuring device (Vivid 910; Konica Minolta, Tokyo, Japan). Rapidform 2006

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(Inus Technology Inc., Seoul, South Korea) was used to create surface models (polygonal data) according to the obtained 3D shape data.

4. Lateral cephalometric measurements

The following 12 measurements were made using lateral cephalograms obtained using a standard procedure. All procedures were performed by the same orthodontist to avoid tracing and measurement errors.

Errors in the cephalometric analyses were evaluated using Dahlberg’s formula on 20 randomly selected cephalograms, with a 2-week interval between measurements. The mean error was $0.64^\circ$ and $0.77$ mm for angular and linear measures, respectively.\textsuperscript{21}

1) SNA
2) SNB
3) ANB
4) Wits value
5) Facial angle
6) FH-MP angle
7) Gonial angle
8) Occlusal plane (Occ. P.)
9) U1-FH
10) L1-MP
11) Overbite
12) Overjet
5. Statistical analysis

Sex-based differences in tongue pressure and LCF in the skeletal classification groups were assessed using the Mann–Whitney U-test. Tongue pressure, LCF, lateral cephalometric measurements, and PVs among the groups were compared using the Kruskal–Wallis test. Measurements with significant differences were further analyzed using the Mann–Whitney U-test with Bonferroni correction. Relationships between tongue pressure/LCF and PV/lateral cephalometric measurements were assessed using the Spearman’s rank correlation coefficient. Rohrer index scores for subjects were assessed using the Kruskal–Wallis test. The standard of significance was set at 5%. Analyses were performed using SPSS 22.0J software (Japan IBM, Tokyo, Japan).

Results

1. Maximum tongue pressure and swallowing tongue pressure

There were no significant differences in MTP, STP, and LCF among the groups (Table 2); thus, statistical total measured value assessment in boys and girls was performed.

MTP was significantly lower in the S-II group than in other groups \( (p < 0.01) \), whereas there was no significant difference in MTP between S-I and S-III groups. The median MTP was the largest in the S-III group, followed by S-I and S-II groups (Table 2).

STP was significantly lower in the S-II group than the S-III group \( (p < 0.01) \), whereas there was no significant difference in STP between S-I vs. S-II and S-III groups. The median STP was the highest in the S-III group, followed by S-I and S-II groups.
2. Lip-closing force

The mean LCF was 9.6 ± 2.1, 9.1 ± 2.1, and 11.5 ± 1.9 N in the S-I, S-II, S-III groups, respectively. LCF was significantly higher in the S-III group than other groups ($p < 0.01$) and the lowest in the S-II group, with no significant difference in LCF between S-I and S-II groups. (Table 2)

3. Lateral cephalometric measurements and palatal volume

Mean ANB was 3.0° ± 0.8°, 6.2° ± 1.6°, and −0.6° ± 1.8° in S-I, S-II, and S-III groups, respectively (Table 3).

SNB ($p < 0.05$) and facial angle ($p < 0.05$) were significantly higher, whereas ANB ($p < 0.01$) and overjet ($p < 0.05$) were significantly lower in the S-I group than the S-II group. ANB, FH-MP, L1-MP, and overjet were significantly higher ($p < 0.01$), whereas SNB and facial angle were significantly lower ($p < 0.01$) in the S-II group than the S-III group. Despite a significantly lower SNB value ($p < 0.01$), ANB ($p < 0.01$), L1-MP ($p < 0.05$), and overjet ($p < 0.01$) were significantly higher in the S-I group than the S-III group. With regard to overbite, there was no statistically significant difference among the three groups, all of which showed standard values.

Statistically significant differences were found between SNB, ANB, and overjet among the groups, indicating that skeletal classification is closely associated with the mandible’s anteroposterior position. L1-MP was significantly smaller in the S-III group than other groups and showed lower central incisor linguoclination. FH-MP was significantly greater in the S-II group than the S-III group.

There was no statistically significant difference in PV among the groups (Table 3).
4. Correlation between tongue pressure and lip-closing force

A comparatively strong positive correlation was observed between MTP and STP \( (r = 0.671) \) and weak positive correlations were noted between MTP and LCF \( (r = 0.357) \) and between STP and LCF \( (r = 0.327) \) (Table 4).

5. Correlation between palatal volume and lateral cephalometric measurements

There was a weak positive correlation between PV and U1-FH \( (r = 0.281) \), but no correlation between PV and any other lateral cephalometric measurements (Table 4). There was no association between the size of the palate and the anteroposterior position of the maxilla and mandible; however, an association was observed between PV and the tooth axis of the maxillary central incisor.

6. Correlation between tongue pressure, lip-closing force, and maxillofacial morphology

MTP exhibited a strong positive correlation with SNB \( (r = 0.448) \), weak positive correlation with facial angle \( (r = 0.213) \), strong negative correlation with ANB \( (r = -0.420) \), and weak negative correlation with overjet \( (r = -0.219) \). STP demonstrated a relatively strong positive correlation with PV \( (r = 0.487) \), weak positive correlations with SNB \( (r = 0.363) \) and U1-FH \( (r = 0.209) \), and weak negative correlation with ANB \( (r = -0.315) \). This indicates that in young patients with low tongue strength, the mandible has a backward position. Furthermore, young patients with large STP have labial inclination of the maxillary central incisor and a large palate. LCF showed a relatively strong negative correlation with ANB \( (r = -0.412) \) and weak correlations with SNA \( (r = -0.254) \), U1-FH \( (r = -0.233) \), L1-MP \( (r = -0.269) \), and overjet \( (r = -0.374) \) (Table 4). This indicates that unlike STP, young patients with large LCF tend to have

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lingual inclination of the maxillary central incisor.

Discussion

1. Methods for measuring tongue pressure and lip-closing force

Several past assessments of tongue functions have utilized methods involving tongue pressure and barium swallow test and palatography. The barium swallow test evaluates swallowing and sound production and enables real-time assessment of tongue dynamics. However, the subject is exposed to radiation; in addition, the procedure requires specialized equipment and expertise to read the results. Palatography allows for the evaluation of the site where the tongue contacts the palate during sound production; nevertheless, result assessment is subjective, and it is difficult to conduct quantitative assessments. Consequently, measuring the therapeutic outcome is challenging, making it inappropriate for use in clinical orthodontics. Based on these factors, in the present study, we utilized tongue pressure for quantitative assessments because it is safe for use in children and is highly reproducible.

Oral function and pressure assessments using a JMS tongue-pressure–measurement device are highly reproducible. This device is also safe and portable, making it suitable in routine clinical situations. Subjects in our study were children aged 6.7–12.4 years. We presumed that a balloon-type tongue-pressure–measurement device would be effective for tongue-pressure measurements because the instructions are easy to understand and the measurement process is simple.
LCF was measured using Lip de Cum® LDC-110R, which is easy to use. Ducklings® lip holders are disposable and allows for safe LCF assessment. Yoshida et al.\textsuperscript{19} set a single measurement time at 5 s with 30-s rest periods because subjects experienced muscle fatigue following each repetition. Because some children were reportedly unable to successfully close their lips during the first measurement, we decided to have three attempts for each subject after two practice attempts. All subjects understood the instructions for tongue-pressure and LCF measurements; measurements were successful in all cases. Thus, it is important to allow the subjects to practice prior to the final measurement process.

2. Sex-based tongue pressure and lip-closing force differences

The mean MTP in children with malocclusion was lower than that reported in a previous study\textsuperscript{12} on Japanese adults aged 20–79 years (41.7 ± 9.7 kPa), suggesting that MTP increases with growth. MTP was significantly higher in males than in females in the 20–49-year age group. However, although no significant sex-based difference in MTP was observed among the groups in the study, differences will probably arise as these subjects approach adulthood.

In our study, no significant sex-based difference in LCF was observed among the groups, similar to that observed previously.\textsuperscript{19}

3. Correlation between tongue pressure and maxillofacial morphology

MTP and STP were the lowest in the S-II group. A study on correlations between the tongue and hyoid location and the maxillofacial morphology in 70 children with malocclusion (Hellman’s stages IIIA–IIIB) indicated that the anteroposterior
position of the tongue apex and base and hyoid are correlated to SNB and that tongues and hyoids of children with mandibular retrusion are in a relatively posterior position.\textsuperscript{22} Mandibular retrognathism or mandibular micrognathia were characteristics of the S-II group; therefore, the oral floor and tongue are retropositioned and the smaller volume of the tongue in the region of rugae palatine is not available.

Subjects with S-III deformities have significantly larger tongues than those with normal occlusion.\textsuperscript{23} The significantly higher MTP and STP in the S-III group in our study indicate that tongue size may be a factor.

No significant difference has been reported in the mean MTP between normal and malocclusion groups (32.0 ± 6.9 vs. 30.1 ± 4.3 kPa, respectively).\textsuperscript{17} In our study, mandibular plane angles were significantly larger in the S-II group than the other groups. Hyoids of subjects with an open bite and open mandibular plane angles are reportedly located in a relatively inferior position.\textsuperscript{24} In our study, MTP was significantly lower in the S-II group than the other groups. Tongues and hyoids of subjects in the S-II group are in a relatively posterior position,\textsuperscript{22} with the hyoids in a relatively inferior position,\textsuperscript{24} making tongue elevation difficult. Further assessments of tongue pressure by maxillofacial skeletal morphology using not only the anteroposterior classifications but also the vertical classifications are warranted.

4. Correlation between lip-closing force and maxillofacial morphology

In this study, LCF was significantly larger in the S-III group, with the S-II group having the lowest values. Jung et al.\textsuperscript{25} have reported that LCF was significantly smaller.

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in the Angle II group than in the Angle I group for both the upper and lower lips. In another study by Chen et al.,\textsuperscript{26} comparison of LCF using a Y meter between subjects divided into S-I and S-III groups according to mandibular protrusion revealed that lower lip LCF was significantly higher in the S-III group than the S-I group. They indicated that lower lip LCF results from orbicularis oris and mentalis muscle contractions, suggesting that involvement of these muscles is a factor for mandibular protrusion onset. The results on the associations between relative anteroposterior positional change of the maxilla and mandible and LCF are similar. However, LCF, which in this study was a comprehensive measurement of the vertical LCF of the upper and lower lips in children, showed no correlation with SNB and had a weak negative correlation with SNA. This indicates the possibility that LCF may be involved in the development of the maxilla during periods of rapid growth and development. We consider that this is one of the reasons why it is important to normalize the functions of scar tissues on the upper lip after cheiloplasty given strong pressure and growth suppression of the maxillary complex in a young cleft lip patient.

In this study, the S-II group had significantly larger FH-MP than did the S-III group. It is often observed that mouth breathing causes posterior inferior rotation of the mandible, resulting in long-face characteristics. Because dolichofacial patients tend to have inadequate lip closure, lip closure strength decreases. Sabashi \textit{et al.}\textsuperscript{27} reported on many skeletal type-II individuals with malocclusion and nasal obstruction with decreased LCFs. Thus, in addition to the anteroposterior relationship of the maxilla and mandible, breathing style may also have a major effect on the decrease in LCF. Hence, we believe that it is important to conduct a longitudinal study to evaluate the manner in which
differences in LCFs based on skeletal type affect mandibular growth and to elucidate the relationship with breathing styles.

5. Palatal volume

In our study, to assess the characteristics of the palate against which the tongue rests, PV was measured using 3D analysis of maxillary dentition models. Our results indicated no statistically significant differences in PVs of children with stages IIIA–IIIC, consistent with the finding of Primozic et al.\textsuperscript{20}

MTP reflects tongue function performed according to the operator’s instructions. Conversely, STP indicates tongue function during the normal course of daily life.

In our study, PV was positively correlated with STP and U1-FH, which were also positively correlated with each other. Hashimoto et al.\textsuperscript{15} reported that because the median STP was significantly lower, motor impairment of the tongue in the Down syndrome group was due to palatal stenosis, which may have caused difficulty in swallowing. They suggested that tongue elevation pressure during swallowing promotes hard-palate formation. Currently, myofunctional therapy comprises training involving tongue apex placement at a spot located in the anterior of the hard palate while at rest, followed by tongue elevation while swallowing.\textsuperscript{10} In our study, STP and PV were positively correlated, suggesting that an increase in tongue elevation pressure during swallowing, as part of the myofunctional therapy, increases PV. PV increases during the primary and mixed dentition periods; therefore, the promotion of maxillary growth is thought to be important for the improvement of perioral muscles in children with maxillary stenosis.

Orthodontic therapy includes rapid expansion appliance use to expand PV of children with palatal stenosis. Phoenix et al.\textsuperscript{28} and Ozbek et al.\textsuperscript{29} reported hyoid elevation
after rapid palatal expansion, indicating elevated tongue position stability at rest. Taki and Thabit\textsuperscript{30} reported that rapid expansion appliance use along with a maxillary protractive appliance use improved nasopharyngeal and oropharyngeal airways. Therefore, these studies indicate that increasing PV through orthodontic therapy improves tongue function.

Positive correlations between STP and PV in the current study indicated that oral function and maxillofacial morphology were inter-related, suggesting that maxillary morphology and oral function improvement via myofunctional therapy is important along with mandibular expansion and growth promotion by orthodontic therapy.

6. Correlation between maximum tongue pressure/swallowing tongue pressure and lip-closing force

Correlations between MTP and STP in all children with malocclusion in this study indicated a relatively strong positive correlation between the two factors. Furthermore, the strong correlations between tongue pressure and the anteroposterior position of the mandible were also confirmed.

STP was positively correlated with PV and U1-FH, whereas no correlation was observed between MTP and PV or incisor axes. This indicated that tongue elevation pressure during swallowing affects palatal formation and the mandibular incisor axes. Hence, obtaining STP and MTP measurements enables precise assessment of the effect of tongue function on the skeleton and teeth in cases where tongue-pressure measurements are used to evaluate tongue function in children during the growth and development stage.

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In our study, weak correlations were noted between MTP and LCF and between STP and LCF, similar to previous report of weak positive correlations between tongue pressure and LCF in children with normal occlusion or anterior overbite.\textsuperscript{16}

Investigations of tooth axis in the S-III group in our study indicated that mandibular central incisor axes were within standard ranges, whereas mandibular central incisor axes had linguoclination. This suggests that the tooth axis inclination of maxillary central incisors is maintained by antagonistic effects of the powerful tongue elevation pressure and LCF. Conversely, because LCF was significantly larger in the S-III group than the other groups, we assumed that mandibular central incisor axes have linguoclination because of lip pressure.

Both MTP and STP were positively correlated with SNB, but negatively correlated with ANB. Conversely, LCF was negatively correlated with SNA and ANB. Thus, tongue function may contribute to mandibular growth, whereas lip function is closely associated with maxillary growth. Good vertical balance and anteroposterior functionality of perioral muscles are essential for adequate maxillofacial growth and development in children. Thus, it is important to include vertical functional assessment of perioral muscles in functional testing while conducting orthodontic clinical examinations in children during growth and development stages. The results of this study can be clinically applied as a tongue pressure index in children with malocclusion.

**Conclusions**

- MTP, STP, and LCF were significantly lower in the S-II group than the S-III group, indicating variations according to anteroposterior skeletal classification.
Strong positive correlations were observed between MTP and STP, which indicated their usefulness in functional assessment.

Positive correlations between STP and PV suggested that tongue pressure and functions play roles in palatal formation.

In future, we aim to use information obtained from this study to assess tongue function in children requiring orthodontic treatment.

**Funding**

This study received no funding.

**Conflict of Interest**

The authors have stated explicitly that there are no conflicts of interest in connection with this article.

**References**


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### Table 1. Subjects

<table>
<thead>
<tr>
<th>Group</th>
<th>Classification criteria</th>
<th>Boys (n)</th>
<th>Girls (n)</th>
<th>Total (n)</th>
<th>Height Med (IQR)</th>
<th>Weight Med (IQR)</th>
<th>Rohrer index Med (IQR)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skeletal-I</td>
<td>$2^\circ \leq \text{ANB} \leq 4^\circ$</td>
<td>13</td>
<td>19</td>
<td>32</td>
<td>131.8 (12.3)</td>
<td>29.3 (8.4)</td>
<td>123.6 (24.0)</td>
<td></td>
</tr>
<tr>
<td>Skeletal-II</td>
<td>ANB &gt; $4^\circ$</td>
<td>10</td>
<td>26</td>
<td>36</td>
<td>134.7 (14.8)</td>
<td>28.3 (5.8)</td>
<td>116.1 (24.3)</td>
<td>NS</td>
</tr>
<tr>
<td>Skeletal-III</td>
<td>ANB &lt; $2^\circ$</td>
<td>11</td>
<td>21</td>
<td>32</td>
<td>126.4 (10.7)</td>
<td>25.9 (6.3)</td>
<td>127.7 (15.4)</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>34</td>
<td>66</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Med: median, IQR: interquartile range, NS: not significant.
Table 2. Sex-based differences among skeletal classification groups and comparison of tongue pressure and maximum lip-closing force among the skeletal classification groups

<table>
<thead>
<tr>
<th></th>
<th>Skeletal-I group</th>
<th>Skeletal-II group</th>
<th>Skeletal-III group</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Boys (n = 13)</td>
<td>Girls (n = 19)</td>
<td>Boys (n = 10)</td>
<td>Girls (n = 26)</td>
</tr>
<tr>
<td></td>
<td>Boys (n = 26)</td>
<td>Girls (n = 11)</td>
<td>Boys (n = 21)</td>
<td>Girls (n = 21)</td>
</tr>
<tr>
<td>ANB (°) (Mean ± SD)</td>
<td>±3.0 ± 0.8</td>
<td>3.1 ± 0.8</td>
<td>6.5 ± 2.0</td>
<td>6.0 ± 1.3</td>
</tr>
<tr>
<td></td>
<td>1.9</td>
<td>±0.5</td>
<td>±0.7</td>
<td>±1.7</td>
</tr>
<tr>
<td>MTP (kPa)</td>
<td>37.2 (4.3)</td>
<td>36.1 (9.8)</td>
<td>32.2 (6.3)</td>
<td>29.8 (9.6)</td>
</tr>
<tr>
<td>Med (IQR)</td>
<td>37.1 (7.1)</td>
<td>38.2 (4.0)</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>STP (kPa)</td>
<td>16.2 (5.2)</td>
<td>16.7 (10.4)</td>
<td>15.2 (10.8)</td>
<td>12.0 (8.0)</td>
</tr>
<tr>
<td>Med (IQR)</td>
<td>17.8 (7.3)</td>
<td>19.3 (4.4)</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>LCF (N)</td>
<td>9.9 (1.2)</td>
<td>9.0 (2.7)</td>
<td>8.5 (1.8)</td>
<td>9.1 (2.2)</td>
</tr>
<tr>
<td>Med (IQR)</td>
<td>11.6 (2.6)</td>
<td>11.2 (1.4)</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

For each group:
- ANB, MTP, STP, and LCF are presented as mean ± standard deviation (SD).
- Med and IQR values are provided for comparative analysis.

For comparison:
- ** indicates a significant difference (p < 0.05).
- NS indicates no significant difference.

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LCF: Lip-Closing Force, Med: median, IQR: interquartile range. **: p < 0.01, NS: not significant

Table 3. Comparison of lateral cephalometric measurements and palatal volume among the skeletal classification groups

<table>
<thead>
<tr>
<th></th>
<th>Skeletal-I group (n = 32)</th>
<th>Skeletal-II group (n = 36)</th>
<th>Skeletal-III group (n = 32)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD (IQR)</td>
<td>Med ± SD (IQR)</td>
<td>Mean ± SD (IQR)</td>
<td>I VS. II</td>
</tr>
<tr>
<td>SNA (°)</td>
<td>79.5 ± 3.0 (80.0 (4.0) 81.0 ± 3.0)</td>
<td>80.0 (4.0) 79.0 ± 2.8 (2.8) (3.5)</td>
<td>79.0 (3.5)</td>
<td>NS</td>
</tr>
<tr>
<td>SNB (°)</td>
<td>76.5 ± 3.1 (76.3 (5.0) 74.8 ± 3.1)</td>
<td>74.0 (3.0) 79.6 ± 3.1 (3.1)</td>
<td>78.8 (4.3)</td>
<td>*</td>
</tr>
<tr>
<td>ANB (°)</td>
<td>3.0 ± 0.8 (3.0 (2.0) 6.2 ± 1.6)</td>
<td>6.0 (2.0) −0.6 ± 1.8 (1.8)</td>
<td>−0.3 (3.0)</td>
<td>**</td>
</tr>
<tr>
<td>Wits value (mm)</td>
<td>−1.5 ± 1.1 (1.0) 3.0 ± 1.5</td>
<td>3.0 (2.0) −6.2 ± 3.0 (3.0)</td>
<td>−6.5 (4.5)</td>
<td>**</td>
</tr>
<tr>
<td>Facial angle (°)</td>
<td>85.1 ± 3.2 (85.0 (4.3) 83.3 ± 4.5)</td>
<td>83.0 (4.0) 87.0 ± 3.1 (3.1)</td>
<td>87.3 (2.5)</td>
<td>*</td>
</tr>
<tr>
<td>FH-MP (°)</td>
<td>28.8 ± 5.1 (29.0 (6.9) 30.5 ± 5.9)</td>
<td>31.0 (4.3) 26.8 ± 3.5 (3.5)</td>
<td>27.3 (5.0)</td>
<td>NS</td>
</tr>
<tr>
<td>Gonial angle (°)</td>
<td>124.7 ± 7.7 (11.8) 125.5</td>
<td>122.6 ± 11.3 (7.5) 123.5</td>
<td>123.2 ± 5.0 (7.0)</td>
<td>NS</td>
</tr>
<tr>
<td>Occ. P. (°)</td>
<td>13.0 ± 4.3 (13.5 (6.0) 14.7 ± 3.4)</td>
<td>15.0 (3.3) 13.0 ± 4.1 (4.1)</td>
<td>13.0 (3.8)</td>
<td>NS</td>
</tr>
<tr>
<td>U1-FH (°)</td>
<td>116.1 ± 5.5 (117.0 (6.3) 114.1 ± 7.1 (7.1) 112.5 (10.0)</td>
<td>113.1 ± 6.1 (6.1)</td>
<td>113.8 (8.3)</td>
<td>NS</td>
</tr>
<tr>
<td>L1-MP (°)</td>
<td>93.6 ± 6.6 (92.0 (7.7) 95.8 ± 6.1)</td>
<td>95.5 (7.3) 88.8 ± 5.3 (5.3)</td>
<td>88.5 (3.4)</td>
<td>NS</td>
</tr>
</tbody>
</table>
Table 4. Correlation coefficients of palatal volume and lateral cephalometric measurements in all subjects with malocclusion as well as correlation coefficients of tongue pressure and maximum lip-closing force in all subjects with malocclusion.

<table>
<thead>
<tr>
<th></th>
<th>MTP (n = 100)</th>
<th>STP (n = 100)</th>
<th>LCF (n = 100)</th>
<th>PV (n = 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNA</td>
<td>0.165</td>
<td>0.177</td>
<td>−0.254*</td>
<td>0.082</td>
</tr>
<tr>
<td>SNB</td>
<td>0.448**</td>
<td>0.363**</td>
<td>0.141</td>
<td>0.04</td>
</tr>
<tr>
<td>ANB</td>
<td>−0.420**</td>
<td>−0.315**</td>
<td>−0.412**</td>
<td>−0.001</td>
</tr>
<tr>
<td>Wits value</td>
<td>−0.395**</td>
<td>−0.316**</td>
<td>−0.376**</td>
<td>−0.029</td>
</tr>
<tr>
<td>Facial angle</td>
<td>0.213*</td>
<td>0.181</td>
<td>0.099</td>
<td>0.043</td>
</tr>
<tr>
<td>FH-MP</td>
<td>−0.162</td>
<td>−0.092</td>
<td>−0.060</td>
<td>0.031</td>
</tr>
<tr>
<td>Gonial angle</td>
<td>−0.072</td>
<td>−0.039</td>
<td>0.051</td>
<td>−0.013</td>
</tr>
<tr>
<td>Occ. P.</td>
<td>−0.140</td>
<td>−0.096</td>
<td>−0.021</td>
<td>−0.141</td>
</tr>
<tr>
<td>U1-FH</td>
<td>0.174</td>
<td>0.209*</td>
<td>−0.233*</td>
<td>0.281**</td>
</tr>
<tr>
<td>L1-MP</td>
<td>−0.072</td>
<td>−0.048</td>
<td>−0.269**</td>
<td>0.02</td>
</tr>
<tr>
<td>Overbite</td>
<td>−0.096</td>
<td>−0.035</td>
<td>−0.086</td>
<td>−0.012</td>
</tr>
<tr>
<td>Overjet</td>
<td>−0.219*</td>
<td>−0.141</td>
<td>−0.374**</td>
<td>0.085</td>
</tr>
<tr>
<td>MTP</td>
<td>0.671**</td>
<td>0.357**</td>
<td>0.177</td>
<td></td>
</tr>
</tbody>
</table>
STP  0.327**  0.487**
LCF  –0.003

MTP, maximum tongue pressure; STP, swallowing tongue pressure; PV, palatal volume;
LCF, lip-closing force

**Figure legends**

**Figure 1. Tongue-Pressure Measurement**

Maximum tongue pressure and swallowing tongue pressure were measured using a balloon-type tongue-pressure–measurement device (JMS tongue-pressure–measurement device). Subjects were seated with the FH plane parallel to the floor. The balloon was inserted into the oral cavity, and the patient was instructed to lightly bite down the rigid ring with the upper and lower central incisors to fix the balloon onto the rugae palatinae.

**Figure 2. Lip-Closing Force Measurement**

Lip-closing force was measured using a lip-closing force measuring device (Lip de Cum® LDC-110R). Subjects were seated with the FH plane parallel to the floor. Ducklings® lip holders were placed between the lips; the maximum lip-closing force was measured in the intercuspal position.
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