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A preliminary and exploratory investigation of velopharyngeal structural MRI following a modified Z-plasty approach in patients with cleft palate

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To validate and refine the existing understanding of the effectiveness of modified Z-plasty in cleft palate patients by comparing postoperative velopharyngeal function with that of healthy non-cleft individuals using MRI. The study involved six adults one year after modified Z-plasty and fourteen adults with healthy palates. MRI was used to assess the levator veli palatini (LVP) muscle and velopharyngeal structures during rest and phonation, including measurements of soft palate length and thickness. Patients post-modified Z-plasty demonstrated restored LVP muscle trajectory and contractility, yet differences in velopharyngeal dimensions persisted compared to the control group. MRI is a valuable tool for assessing velopharyngeal function. Modified Z-plasty can improve, but not fully normalize, velopharyngeal structures and function in cleft palate patients. These findings provide a reference for future optimization of surgical techniques and rehabilitation strategies in cleft palate repair.

Keywords Cleft palate, Magnetic resonance imaging, Modified Z-Plasty, Levator veli palatini muscle, 3D reconstruction

Cleft lip and palate are among the most common congenital craniofacial anomalies, affecting a significant number of individuals worldwide. Surgical repair remains the primary and most effective treatment for cleft palate, with the primary goals of closing the gap between the oral and nasal cavities, restoring velopharyngeal closure, and enabling normal speech function. Despite the widespread use of surgical interventions, a substantial proportion of patients (7% to 30%) continue to experience velopharyngeal insufficiency (VPI) postoperatively, highlighting the ongoing challenges in achieving optimal functional outcomes[1].

To address these challenges, our research team has developed a modified Z-plasty technique for cleft palate repair. This technique has shown promising results in previous studies, demonstrating improved velopharyngeal closure rates, reduced nasal air leakage, and enhanced speech spectrum analysis compared to traditional methods such as the reverse double Z-palatoplasty and Sommerlad's levator veli palatini reconstruction[2]. However, a comprehensive understanding of the anatomical and functional changes in the soft palate structures following this modified technique remains limited.

Magnetic resonance imaging (MRI) has emerged as a powerful tool in the assessment of craniofacial anomalies, including cleft palate. It has demonstrated high sensitivity and specificity in diagnosing cleft palate in fetuses and has been increasingly applied to the evaluation of velopharyngeal function in recent years[3,4]. MRI offers several advantages for this application: it is non-invasive, avoids ionizing radiation, and provides high-resolution images that can capture detailed anatomical structures and subtle functional changes[5,6]. Dynamic MRI, in particular, allows for the visualization of velopharyngeal structures during phonation, providing valuable insights into the functional mechanisms underlying speech production.

Building upon the existing body of literature[7–12], the current study aims to utilize MRI to evaluate the anatomical and functional outcomes of the modified Z-plasty technique in cleft palate patients. By comparing the

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velopharyngeal structures and muscle morphology in both resting and phonation states between post-operative patients and healthy controls, this preliminary and exploratory study aims to enhance the current understanding of the modified Z-plasty technique. Our objective is to provide an initial assessment of its potential to improve velopharyngeal function in patients with cleft palate and to lay the groundwork for future optimization of surgical protocols and rehabilitation strategies.

Clinical data and testing methods

Participants

A total of 20 adults with normal palatal development and no speech disorders were recruited for this study, including 8 males and 6 females. Additionally, the cleft palate repair group consisted of 6 individuals, with 3 males and 3 females. The average age of the non-cleft group was 25.64 years, and the average body mass index (BMI) was 22.09, while the average age of the cleft palate group was 24.67 years, with an average BMI of 22.59. Individuals with claustrophobia, excessive obesity (BMI > 28)[13,14], metal implants, or neurological/psychiatric disorders were excluded from the trial.

All participants in the cleft palate repair group had their first cleft palate repair surgery in adulthood. This approach was chosen to minimize confounding factors such as growth development, multiple repair surgeries, and speech therapy, which could influence the outcomes. Specifically, these individuals had not undergone any prior palatal surgery in early childhood. The modified Z-plasty was their first surgical intervention for the cleft. This decision was influenced by various factors, including economic constraints and the availability of specialized surgical expertise. The selection criteria ensured that the study focused on the initial surgical outcomes of the modified Z-plasty technique in adult patients with unrepaired cleft palate.

This prospective cohort study included two groups: a cleft palate group and Non-cleft Group group. The cleft palate group consisted of patients who had undergone modified Z-plasty at the Department of Oral and Maxillofacial Surgery, Affiliated Stomatological Hospital of Zunyi Medical University, between January 2017 and September 2018. The Non-cleft group included healthy individuals with non-cleft palatal development and no history of speech disorders.

Inclusion and exclusion criteria

(1) Cleft Palate Group

Inclusion Criteria: Patients with non-syndromic cleft lip and palate. Patients aged ≥ 18 years at the time of their first cleft palate surgery. Patients with incomplete cleft palate. Patients who could attend follow-up appointments regularly within 3 months post-surgery and had not undergone speech therapy. Patients who, after speech training, could sustain vowel sounds for > 10 s (to meet the requirements for MRI scanning during phonation). Patients without claustrophobia or fear of darkness (to ensure successful completion of MRI examinations). Patients without palatal fistula post-surgery. Patients without symptoms such as adenoid hypertrophy or tonsillitis (to avoid interference with the assessment of velopharyngeal structures).

Exclusion Criteria: Patients with syndromic cleft lip and palate. Patients with intellectual or hearing disabilities. Patients with neurological or psychiatric disorders. Patients with poor compliance, unable to cooperate with special examinations (MRI). Patients who were excessively obese (BMI > 28) (as obesity may affect MRI image quality and anatomical measurements). Patients with metal implants such as metallic valves, pacemakers, or metal restorations (contraindications for MRI).

(2) Non-cleft Group

Inclusion Criteria: Healthy individuals with no history of cleft palate or other craniofacial anomalies. Individuals aged ≥ 18 years. Individuals with no history of speech disorders, hearing loss, or neurological diseases. Individuals who could sustain vowel sounds for > 10 s during MRI scanning.

Exclusion Criteria: Presence of any craniofacial anomalies, including occult cleft palate. History of speech disorders, hearing loss, or neurological diseases. Claustrophobia or fear of darkness that would interfere with MRI scanning. Presence of metal implants or other contraindications for MRI.

(3) Recruitment and screening

Participants in the cleft palate group were recruited from the Department of Oral and Maxillofacial Surgery at the Affiliated Stomatological Hospital of Zunyi Medical University. All patients who underwent modified Z-plasty during the specified period were screened for eligibility. A total of 6 patients met the inclusion criteria and agreed to participate in the study.

non-cleft participants were recruited from the local community and underwent a similar screening process. A total of 14 healthy individuals were enrolled as controls. All participants provided written informed consent prior to participation.

This study was approved by the ethics committee (Zunyi Medical University Institutional Review Board) and informed consent was obtained from all participants prior to the trial. All methods were performed in accordance with the relevant guidelines and regulations. This includes adherence to the principles outlined in the Declaration of Helsinki for research involving human subjects. All participants provided informed consent prior to their involvement in the study.

During the recruitment period, a total of 6 adult postoperative cleft palate patients who met all the inclusion criteria and none of the exclusion criteria agreed to participate in this study, forming the final cleft palate group. Therefore, the cleft palate group was a cohort rigorously selected based on predefined scientific criteria from a specific population of adult patients who underwent a particular surgery within a defined time frame and hospital setting, rather than a randomly chosen convenience sample. We acknowledge that the sample size ($n = 6$) is relatively small, reflecting the actual challenges of recruiting participants who meet all the strict criteria among adult cleft palate patients. This limitation has been mentioned in the revised manuscript. Despite this, all included patients provided high-quality, analyzable MRI data, enabling us to conduct a meaningful preliminary assessment and comparison of the surgical outcomes.

MRI scanning parameters and data definition of the velopharyngeal region

MRI scans were performed using a GE Signa HDx 3.0T MRI scanner provided by Zunyi Medical University Affiliated Hospital. The scanning procedures were carried out by the same experienced MRI technician. Participants were placed in a supine position, and scans were conducted both at rest and during phonation. To prevent motion artifacts and head movement from affecting the image quality, a head restraint was used to stabilize the head, and participants were instructed to breathe through their nose and avoid swallowing during the scan. The static and phonation-state scans of the velopharyngeal region and levator veli palatini muscle (LVP) were performed with the scan parameters shown in Supplementary Table 1.

Velopharyngeal scanning

Resting State Scanning Method: The head was first scanned in axial, coronal, and sagittal planes to identify the midline structures of the study subject and to select the soft palate region for scanning. T2-weighted fast spin echo (T2-FSE) sequences were used to perform mid-sagittal plane scans of the velopharyngeal region, obtaining 13-layer image sequences. The image showing the corpus callosum, pituitary gland, and the soft palate at maximum length was selected as the mid-sagittal plane[15], as shown in Supplementary Fig. 1A. The parameters and their definitions are presented in Supplementary Table 2.

Phonation State Scanning Method: Prior to scanning, participants were trained to practice producing the/a/ and/i/sounds[13], sustaining each sound for more than 10 s with a 5-second interval for breath adjustment between syllables. T2-weighted fast spin echo sequences (T2-FSE) were used to scan the velopharyngeal region, starting with a 10-second resting state scan, followed by a 5-second interval and 10 s of sustained/a/sound production, another 5-second interval, and then 10 s of sustained/i/sound production. This scanning process generated 15 images, with 5 images for each syllable. The image clearly displaying soft palate movement for each syllable was selected, as shown in Supplementary Fig. 1B-D.

The diagram illustrating the relative positional changes of the soft palate in different states of rest and phonation is shown in Supplementary Fig. 2A. The measurements of soft palate length changes and soft palate elongation ratios are detailed in Supplementary Table 2.

Levator veli palatini muscle (LVP) scanning and data definition

The LVP runs at an angle of approximately 58° with the cribriform plate[14]. The cribriform plate was used as the standard reference plane, and images displaying the complete course of the LVP were selected for measurement, as illustrated in Supplementary Fig. 2B. Supplementary Fig. 2 C shows the image that best presents the entire course of the LVP after scanning.

Measurement of Resting State Data: Parameters including LVP length, vertical segment length, horizontal segment length, origin distance, origin angle, and insertion distance were measured in the resting state. The definitions and parameters are presented in Supplementary Table 3.

Phonation State Data: The scanning method for the LVP during phonation was similar to the scanning of the velopharyngeal region during phonation. A 10-second resting state scan was first performed, followed by a 5-second interval, 10 s of sustained/a/sound, another 5-second interval, and 10 s of sustained/i/sound. Images clearly showing LVP contraction after each syllable were selected. Supplementary Fig. 3A-C presents images of LVP stretching and contraction during the resting state and under different syllable conditions. LVP stretching length and contraction rate were measured, and the parameters are presented in Supplementary Table 3.

Three-Dimensional Sequence Scanning of the Levator Veli Palatini Muscle: In the resting state, a T2-weighted cube three-dimensional sequence (T2-CUBE) was obtained within 5 min using the GE Signa HDx 3.0T MRI. The 3D sequence MRI scan provided sufficient signal-to-noise ratio, high contrast between tissues, and high-resolution images while significantly shortening imaging time[16–18]. Supplementary Fig. 3D clearly shows the origin of the LVP, the course of the muscle bundles, and the sling structure formed at the midline of the soft palate.

Image measurement and analysis

The null hypothesis for this study is that there are no significant differences between the non-cleft group and the cleft group in the anatomical continuity and trajectory of the LVP muscle and velopharyngeal function after modified Z-plasty, based on MRI assessment.

Measurement of the velopharyngeal region and LVP

The original MRI files in DICOM format were imported into Mimics Research Version 20.0 software for measurement. Parameters such as length, thickness, and stretch length of the velopharyngeal region and LVP in both resting and phonation states were measured directly using the Distance tool.

Image segmentation and 3D reconstruction of the levator veli palatini muscle

Prior to 3D reconstruction of the LVP, the region of interest was accurately identified. Masks were created, and the lasso tool in the Edit Mask function was used to manually segment the LVP along the boundaries in each image slice, with fine adjustments made using the Draw and Erase commands, as illustrated in Supplementary Fig. 3E, showing the segmented LVP in green.

For 3D modeling, the rough and irregular initial 3D model shown in Supplementary Fig. 3 F was smoothed using the smooth tool (iterations: 10, smooth factor: 0.6), yielding the final result shown in Supplementary Fig. 3G. The muscle volume was assessed in the 3D attributes. The engineering file was imported into 3-Matic Research Version 12.0 software from Materialise, and the circumference of six points between the origin and the point of cross-over between bilateral LVP muscles was measured using the Length tool (Supplementary Fig. 3G and Supplementary Fig. 4). Measurement points included: S1, the origin of the muscle; S2, the midpoint between the origin and insertion; S3, the midpoint between S2 and S4; S4, the muscle insertion point into the soft palate; S5, the midpoint between S4 and S6; and S6, the cross-over point of the bilateral LVP muscles at the midline. Due to the anatomical constraints of the LVP origin, muscle bundles were measured along the plane at the base of the skull at the starting point. Other measurement points' circumferences were obtained by following the arc generated around the muscle bundles perpendicular to the long axis. Previous studies[16,19] indicated that the LVP muscles on both sides are nearly symmetrical, with no statistically significant differences in muscle length, thickness, origin angle, or origin distance. Therefore, this experiment measured the muscle circumference only on the right muscle bundle of the subject.

Surgical approach

The modified Z-plasty technique employed in this study is designed to address the anatomical and functional deficits associated with cleft palate by improving the continuity and function of the levator veli palatini muscle (LVP) and enhancing velopharyngeal closure. The surgical procedure begins with the creation of a nasal mucosal muscle flap. An oblique incision is made at a 60° angle along the direction of the muscle fiber of the levator palatine muscle on one side. On the other side, a corresponding oblique incision is made to form a pair of Z-shaped flaps. The side incision is a free end muscle bundle that has cut off a little palatine levator muscle. On the lateral side of the oblique incision, the levator palatine muscle is positioned outside the line of the levator palatine and then crosses the line along the direction of the muscle fiber, making the whole incision resemble a zigzag letter Z. After the flap is rotated and sutured, the direction of the fibers of the levator palatine turns into the normal transverse direction, and the broken end is positioned opposite. A few muscle bundles that have been cut off are used to fill the junction of the hard and soft palate, and the mucous membrane of the nasal cavity and oral mucosa are sutured. The Sommerlad levator muscle of the palatine velum reconstruction is performed according to the method of Sommerlad et al.

Compared with Furlow's Modified Z-plasty, the modified Z-plasty technique used in this study has several distinct differences. Furlow's method involves dissection between the oral mucosa and the soft palate muscle on one side, and between the nasal mucosa and the soft palate muscle on the other side. This can lead to significant muscle damage and scar formation, which may affect the function of the soft palate. In contrast, our modified Z-plasty technique involves dissection only between the oral mucosa and the soft palate muscle. This approach minimizes muscle damage and scar formation, preserving more of the muscle function. Additionally, Furlow's method results in overlapping muscle flaps, which can alter the normal thickness of the levator veli palatini muscle. Our modified Z-plasty technique involves end-to-end muscle suture, which maintains the normal fiber direction and thickness of the muscle, closely resembling the anatomy of a non-cleft palate. These modifications aim to improve the functional outcomes of cleft palate repair by enhancing muscle continuity and reducing postoperative scarring.

Result

Velopharyngeal measurement results

As shown in Table 1, there were significant differences in soft palate length, effective soft palate length, hard palate length, and velopharyngeal ratio (VP ratio) between the two groups, with $P < 0.05$, indicating statistical significance. However, there were no significant differences between the groups in soft palate thickness and pharyngeal depth, with $P > 0.05$.

LVP measurement results

Table 2 shows that there were no statistically significant differences in the LVP parameters between the cleft palate and non-cleft groups at rest ($P > 0.05$).

Variable	Cleft Palate Group	Non-cleft Group	t-value	*p*-value
Soft Palate Length (mm)	36.20 ± 3.10	40.19 ± 3.49	−2.414	0.027
Effective Soft Palate Length (mm)	18.48 ± 1.79	24.53 ± 3.35	−4.13	0.001
Soft Palate Thickness (mm)	8.90 ± 1.42	7.79 ± 0.99	2.003	0.06
Hard Palate Length (mm)	33.45 ± 1.46	42.81 ± 3.25	−6.681	< 0.001
Pharyngeal Depth (mm)	35.67 ± 3.52	33.39 ± 2.70	1.588	0.13
VP Ratio	1.00 ± 0.06	1.17 ± 0.11	−3.394	0.003

Table 1. Comparison of velopharyngeal parameters between the cleft palate group and the non-cleft group at rest.

Variable	Cleft Palate Group	Non-cleft Group	t-value	*p*-value
LVP Average Length (mm)	46.85 ± 3.13	46.59 ± 3.96	0.141	0.89
LVP Average Vertical Distance (mm)	28.83 ± 2.74	28.20 ± 2.05	0.57	0.576
LVP Average Horizontal Distance (mm)	20.30 ± 4.00	18.08 ± 2.62	1.482	0.156
Origin Distance (mm)	58.29 ± 2.61	61.37 ± 4.01	−1.711	0.104
Insertion Distance (mm)	32.81 ± 1.50	30.91 ± 2.59	1.657	0.115
Origin Angle (°)	59.08 ± 4.24	56.80 ± 2.25	1.587	0.13

Table 2. Comparison of LVP between the cleft palate group and the non-cleft group at rest.

Variable	Cleft Palate Group	Non-cleft Group	t-value	*p*-value
S1 (mm)	15.26 ± 1.01	17.40 ± 2.45	−3.15	0.006
S2 (mm)	22.66 ± 0.59	27.76 ± 4.97	−3.786	0.002
S3 (mm)	24.97 ± 1.20	30.50 ± 4.79	−4.039	0.001
S4 (mm)	26.55 ± 1.23	32.39 ± 4.01	−4.942	< 0.001
S5 (mm)	26.31 ± 1.23	33.11 ± 3.57	−6.308	< 0.001
S6 (mm)	25.79 ± 2.00	32.79 ± 2.83	−5.463	< 0.001
Volume (mm^3)	2420.68 ± 142.06	3509.78 ± 656.97	−5.89	< 0.001

Table 3. Comparison of parameters between the cleft palate group and the non-cleft group.

Variable	Cleft Palate Group	Non-cleft Group	t-value	*p*-value
At Rest	18.48 ± 1.79	24.53 ± 3.35	−4.13	0.001
/a/Sound	21.32 ± 2.42	27.92 ± 2.25	−5.88	< 0.001
/i/Sound	22.12 ± 1.77	29.76 ± 2.19	−7.53	< 0.001

Table 4. Comparison of effective soft palate length between the cleft palate group and the non-cleft group under different pronunciation states (mm).

Variable	Cleft Palate Group	Non-cleft Group	t-value	*p*-value
/a/Sound	1.16 ± 0.09	1.15 ± 0.08	0.209	0.837
/i/Sound	1.21 ± 0.07	1.23 ± 0.13	−0.363	0.721

Table 5. The expansion ratio of the soft palate in different pronunciation states.

LVP three-dimensional reconstruction results
As shown in Table 3, the volume and circumference of LVP muscles at various measuring points were significantly greater in the non-cleft group compared to the cleft palate group ($P < 0.01$).

Pronunciation state
Soft palate in pronunciation state

The effective length of the soft palate in the non-cleft group was significantly longer than that in the cleft palate group at rest and during pronunciation ($P < 0.01$), as shown in Table 4. Table 5 presents the changes in the effective soft palate length during pronunciation, with no statistically significant differences between the two groups ($P > 0.05$).

LVP in pronunciation state

There were no statistically significant differences in LVP length changes between the non-cleft and cleft palate groups during pronunciation (Table 6).

Discussion
Analysis of results in the resting state
In this study, we compared the anatomical and functional outcomes of the modified Z-plasty technique in cleft palate patients with those of healthy controls using MRI. Our results showed that, compared to the non-cleft group, adults in the cleft palate group exhibited smaller soft palate length[20], effective soft palate length, hard palate length, and velopharyngeal (VP) ratio. Specifically, the average VP ratio in healthy adults was 1.17, which was significantly higher than that in adults after cleft palate repair (1.00, $P < 0.01$). This finding is consistent with

Variable	Cleft Palate Group	Non-cleft Group	t-value	*p*-value
At Rest	46.85 ± 3.13	46.59 ± 3.96	0.141	0.89
/a/Sound	43.52 ± 2.69	43.25 ± 2.94	0.188	0.853
/i/Sound	43.44 ± 2.40	43.14 ± 2.31	0.262	0.797

Table 6. Changes of LVP length in different pronunciation states (mm).

previous studies, such as those by Tian[21,22], who reported a healthy adult VP ratio ranging from 1.37 to 1.32, and by Nyswonger[23], who reported a VP ratio of 1.28 for healthy adults compared to 0.85 for cleft palate patients. Perry[24] also found a VP ratio of 1.7 for healthy adults compared to 0.9 for patients. A lower VP ratio is associated with an increased likelihood of palatopharyngeal closure insufficiency, which may explain the persistent speech problems in some patients despite surgical repair.

Although the pharyngeal cavity depth and soft palate thickness were higher in the cleft palate group, the differences were not statistically significant. This suggests that while the soft palate is shorter in cleft palate patients, the pharyngeal cavity depth is not necessarily deeper compared to healthy individuals. If the soft palate contraction function is normal, patients undergoing this surgical method may achieve complete palatopharyngeal closure. However, the variability in hard palate length among participants in the cleft palate group may be due to disruptions in hard palate fusion during embryonic development. The surgical goal is to connect the midline mucoperiosteal tissue and promote further development of the hard palate tissue, but the results are often unsatisfactory. Compared to normal anatomy, adults after cleft palate repair have significantly shorter hard palates, which is often accompanied by relative or absolute shortening of the soft palate[25,26].

Previous reports indicate a normal anatomical adult hard palate length ranging from 48.4 mm to 60.6 mm[21–23,27,28]. In this study, the average hard palate length in the non-cleft group was 42.81 mm, compared to 33.45 mm in the cleft palate group, showing a significant difference ($P < 0.001$). This discrepancy may be due to the specific surgical techniques used and the individual variations in palate development. Kollara[27] found significant differences in soft palate length and thickness across different races and genders. Although the soft palate thickness in cleft palate patients appears slightly thicker compared to healthy individuals, there is no significant statistical difference between the groups in this study. This may be because the cleft palate patients underwent surgery as adults when palatal development was nearly complete. Thus, muscle and soft tissue thickness did not show defects, and MRI imaging may not distinguish muscle, mucosa, and local scar tissue accurately. Future studies should include larger sample sizes to better understand the anatomical differences between non-cleft individuals and cleft palate patients.

Measurement of the levator veli palatini (LVP) muscle

In the resting state, there were no statistically significant differences in LVP measurements between repaired cleft palate patients and non-cleft individuals ($P > 0.05$). This finding is somewhat surprising given the known anatomical differences in cleft palate patients. However, some studies have reported differences in LVP and other palatopharyngeal structures between males and females[28], but Ettema[29] previously reported no significant differences in LVP length between genders, possibly due to the small sample size. In this study, the average LVP length in non-cleft adults was 46.59 mm, compared to 46.85 mm in the cleft palate group, with no statistically significant difference. Nyswonger[23] reported a healthy LVP length of 45.3 mm and 44.4 mm for cleft palate patients. Perry[24] reported an LVP length of 46.2 mm for non-cleft individuals and 41.2 mm for cleft palate patients. Other researchers[16,21] also reported a healthy adult LVP length ranging from 32.6 mm to 47.5 mm, which is consistent with the findings of this study.

Additionally, there were no significant differences in the average vertical segment length, horizontal segment length, origin distance, insertion distance, and origin angle of the LVP between non-cleft individuals and cleft palate patients. Although the soft palate and effective soft palate lengths in cleft palate patients are shorter than in non-cleft individuals, the study confirms that the primary muscle responsible for extending the soft palate is the LVP. The LVP in cleft palate patients exhibits similar shape and function to that of non-cleft individuals, suggesting that the surgical method can partially restore the length and continuity of the LVP, thus enhancing the possibility of achieving palatopharyngeal closure.

However, there were noticeable differences in LVP morphology between cleft palate patients and non-cleft individuals. The muscle shape in cleft palate patients sometimes appeared "U"-shaped, whereas it typically appears "V"-shaped in non-cleft individuals. In adults with cleft palate repair, the LVP muscle does not curve gradually into the soft palate as observed in non-cleft individuals; instead, it protrudes inward at a sharp angle before extending downward[30]. It is currently unclear how these morphological differences affect speech function. Variability in the LVP horizontal segment muscle shape, such as irregularities, sparse or discontinuous appearance, was not observed in the non-cleft anatomical group. The vertical segment of the LVP muscle, located on the outside of the soft palate, may be more critical for normal palatopharyngeal function. Therefore, surgical reconstruction of the vertical segment may produce more favorable muscle positioning and function[31]. However, further imaging studies are needed to understand the impact of surgery on muscle function.

Perry[16] measured significant circumference differences between origin points S1 (18.90 mm) and S2 (22.40 mm) in non-cleft individuals, with little to no variation at remaining points. Kotlarek[18] compared LVPs in five cleft palate patients and ten non-cleft individuals, finding that the LVP volume in cleft palate patients (1247.50 mm^3) was significantly smaller than in non-cleft individuals (1855.90 mm^3). They also noted the largest diameter and circumference differences at the cleft midline and found LVP sling separation at the soft palate midline in cleft palate patients, possibly related to incomplete reconstruction of LVP continuity in early surgeries. In this study, the LVP volume in non-cleft individuals (3509.78 mm^3) was significantly larger than in cleft palate patients (2420.68 mm^3), and the circumference of the LVP in non-cleft individuals was also notably larger than in cleft palate patients. Possible reasons for these differences include: first, the cleft palate repair was performed in adulthood, and prolonged abnormal LVP function may lead to muscle atrophy; second, the modified Z-plasty surgical design may cut part of the LVP to extend the soft palate, possibly missing some muscle tissue during reconstruction; third, different cleft types may lead to greater postoperative damage and scarring. The modified Z-plasty technique is suitable for incomplete cleft palates, and previous studies did not screen for cleft types, leading to discrepancies with this study's results. In this study, no LVP separation was observed at the soft palate midline in cleft palate patients, indicating that the surgery can restore LVP continuity.

Clinical significance of MRI in cleft palate patients

MRI plays a significant role in diagnosing fetal cleft palates, assessing palatopharyngeal function, and evaluating speech disorders. Functional MRI studies have shown that the abnormal cortical development patterns in CLP patients are directly related to their speech disorders, and conversely, speech rehabilitation training mediates cortical plasticity in adult non-syndromic cleft palate subjects[32,33]. During fetal cleft palate screening, the diagnostic reliability of fetal MRI as an adjunct to ultrasound has been significantly improved[34]. Research on the muscles and soft tissue structures involved in palatopharyngeal closure can enhance our understanding of the mechanisms in non-cleft and cleft palate patients, provide theoretical guidance for clinical surgical plans, and support ongoing assessment of both short-term and long-term postoperative effects. This will contribute to a better understanding of the impact of various cleft palate repair surgeries on the structure and function of the palatopharyngeal muscles.

With advancements in technology, MRI can combine dynamic imaging with acoustic correlations to obtain high-quality images, which will benefit future research in the field of cleft palate phonetics[27,35–37]. Advanced imaging techniques, such as 3D MRI, can quantify and visualize tissue changes and identify patient-specific factors that may affect postoperative tissue migration and scar contraction[38]. In this study, we utilized MRI to provide a comprehensive assessment of the anatomical and functional outcomes of the modified Z-plasty technique. Our findings highlight the potential of MRI as a valuable tool in evaluating surgical outcomes and guiding clinical decision-making.

Limitations and future directions

This study has several limitations. First, the sample size is relatively small, which may limit the statistical power and generalizability of the findings. Future studies should include larger sample sizes to better understand the anatomical and functional differences between cleft palate patients and non-cleft individuals. Second, the study focused on adult patients who underwent cleft palate repair in adulthood. It remains unclear whether the findings would be similar for patients who underwent surgery in childhood. Future studies should consider including patients of different age groups to assess the impact of age at surgery on postoperative outcomes. Additionally, while MRI provides detailed anatomical information, it does not directly assess speech function. Future studies should include speech evaluations to determine whether anatomical improvements translate into functional benefits. Finally, the study did not account for variability in cleft severity or speech therapy history, which may influence the results. Future research should consider these factors to provide a more comprehensive understanding of the impact of modified Z-plasty on cleft palate patients.

In conclusion, this study provides valuable insights into the anatomical and functional outcomes of the modified Z-plasty technique in cleft palate patients. Our findings suggest that while the technique can improve velopharyngeal structures and function, it does not fully normalize these parameters. MRI is a powerful tool for assessing surgical outcomes and guiding clinical decision-making. Future studies should aim to address the limitations identified in this study and further explore the potential of MRI in optimizing cleft palate repair techniques.

Data availability

Data is provided within the manuscript or supplementary information files.

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Author contributions
Liu Mi: Dr. Liu Mi conceptualized the study, participated in data collection and analysis, and was a major contributor in writing the manuscript. He also supervised the overall project and provided critical revisions for important intellectual content. Ding Fugen: Mr. Ding Fugen was responsible for the experimental design, conducted the laboratory experiments, and contributed to the acquisition of data. He also assisted in drafting the initial manuscript and provided technical support throughout the research process. He Wei: Ms. He Wei played a key role in data analysis and interpretation. She was involved in the statistical analysis of the results and contributed to the drafting and revision of the manuscript. Additionally, she provided administrative support and ensured the accuracy of the data presented. Qinggao Song, DDS, MD: Dr. Qinggao Song was the principal investigator of the study. He secured the funding, provided overall supervision, and ensured the integrity of the research. He also contributed to the critical revision of the manuscript for important intellectual content and approved the final version to be published. All authors have read and approved the final manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

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