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Three-dimensional attachment morphometry and volumetric changes of masticatory muscles after free fibular flap reconstruction of the mandibular condyle

Shuang Bai, Yao Yu, Wen-Bo Zhang, Ya-Qing Mao, Yang Wang, Chi Mao, Xin Peng*

Department of Oral and Maxillofacial Surgery, Peking University School and Hospital of Stomatology, Beijing, 100081, China

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ABSTRACT

This retrospective case-series study aimed to elucidate the three-dimensional attachment morphometric features and to quantify the volumetric changes of the masticatory muscles following free fibular flap reconstruction of the mandibular condyle. Navigation software (iPlan, version 3.0; Brainlab) was used to perform delineation and volumetric measurement of the masticatory muscles using DICOM data.

In total, 30 patients were included in this retrospective case series. In 25 cases (83.33%), the lateral pterygoid muscle achieved reattachment within 6 months postoperatively. The medial pterygoid muscles on the affected side achieved ectopic attachment in all cases. However, masseter reattachment on the affected side was achieved in only three cases. On the normal side, the volumes of lateral pterygoid muscle, medial pterygoid muscle, and masseter had recovered to almost preoperative levels at 1 year postoperatively. On the affected side, the volume of medial pterygoid muscle had decreased significantly ($p = 2.4\text{e-}04$) at 3 months postoperatively. The volumes of lateral pterygoid muscle and masseter showed mild decreases at 3 months postoperatively, but these were not significant ($p = 0.52$ and $p = 0.05$ for the pterygoid muscle and masseter, respectively). At 6 months after surgery, with the exception of the volume of the lateral pterygoid muscle ($p = 0.06$), the total volume of the masticatory muscles decreased significantly on the affected side. The volumes of lateral pterygoid muscle, medial pterygoid muscle, and masseter showed significant decreases at 1 year postoperatively ($p = 0.03$, $p = 4.7\text{e-}08$, and $p = 1.1\text{e-}05$, respectively) on the affected side. The postoperative volumes of the masseter, medial pterygoid, and lateral pterygoid muscles showed significant decreases due to the loss of reattachment.

The results of this study may not help to ascertain whether reattachment of masticatory muscles will lead to better function. As a consequence, clinical trials of higher quality are needed.

1. Introduction

Since vascularized fibular flaps for mandibular reconstruction were introduced in 1989 (Hidalgo, 1989), the free fibular flap has been considered the gold standard for the reconstruction of segmental defects in the mandible. Moreover, the free fibular flap has been advocated as the best option for reconstructing lateral and anterolateral mandibular defects (Papadopulos et al., 2008). In addition, the popularity of free fibular flap reconstruction has benefited from advances in computer-assisted techniques, such as virtual planning and surgical navigation (Yu et al., 2016a,b).

Mandibular defects involving the condyle are less common and account for only 6% of mandibulectomy procedures (Brown et al., 2016). Reconstruction of these defects is challenging with regard to achieving complete functional and aesthetic rehabilitation. For example, malocclusion may occur because of inadequate positioning of the neocondyle, loss of attachment of masticatory muscles and fibers around the temporomandibular joint, or subsequent fracture of the miniplate. Based on clinical observation, the end of the reconstructed fibular flap — the neocondyle — tends to shift from its initial position postoperatively (Yu et al., 2020). This shift is probably caused by an imbalance in the forces around the

* Corresponding author. Department of Oral and Maxillofacial Surgery, Peking University School and Hospital of Stomatology, No. 22 Zhongguancun South Avenue, Haidian District, Beijing, 100081, China.
E-mail address: pxpengxin@263.net (X. Peng).

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neocondyle, which results from attachment loss and morphological atrophy of the masticatory muscles.

Data obtained from CT scans have been used to measure the volume of masticatory muscles in cases of distraction osteogenesis of the mandible, resection of mandibular angles, and bimaxillary surgery (Kane et al., 1997; Huisinga-Fischer et al., 2001; Mackool et al., 2003; Takashima et al., 2003; Takayama et al., 2019). The significant decrease reported in the volume of masticatory muscles is likely to be the result of extensive detachment, but the causative mechanisms are unclear. Furthermore, although loss of masseter muscle volume (Lo et al., 2005) and masseter atrophy (Yang et al., 1995) have been reported in patients following mandibular angle resection, such volume loss has not been supported by sufficient objective and quantitative evaluations in mandibular reconstruction. Long-term follow-up studies on volumetric changes and the attachment patterns of masticatory muscles have been inadequate in the literature published so far.

Our study aimed to elucidate the three-dimensional attachment morphometric features and quantify the volumetric changes of the masticatory muscles following free fibular flap reconstruction of the mandibular condyle.

2. Materials and methods

This retrospective study was performed in accordance with the tenets of the Declaration of Helsinki. Informed consent was obtained from all the patients, and approval was obtained from the Ethics Review Board of Peking University School and Hospital of Stomatology (approval No. PKUSSIRB-202055073).

2.1. Study population

All patients who underwent mandibulectomy involving the condyle for benign tumors and mandibular reconstruction with free fibular flap at Peking University School and Hospital of Stomatology between August 2013 and September 2016 were reviewed. According to the HCL classification described by Jewer et al. (1989), mandible defect type H was included in this study. Lesions involving the masticatory muscles and osteoradionecrosis were excluded. Furthermore, only patients with preoperative and long-term follow-up CT scans were included in this study. In all cases, muscular morphometry conducted during follow-up did not include the artificial attachment.

2.2. Surgical procedure

The computer-aided design and intraoperative navigation system used have been described in a previous study (Yu et al., 2016b). Our technique involved rounding and shaping the distal end of the reconstructed fibula to form a neocondyle. The temporomandibular joint disc was carefully preserved in all cases. All tumor resections and mandibular reconstructions were performed by the same chief surgeon (Peng X.). Typically, guiding elastics were used 2–4 weeks postoperatively to obtain a stable occlusion.

2.3. Data management and analysis

Delineation and volumetric measurement of the masticatory muscles was performed with the software Analyze (iPlan, version 3.0; Brainlab, Feldkirchen, Germany) using DICOM data. The CT range was set from −165 HU to 235 HU so that the CT densities could be adjusted to clearly view the muscles, and distinguish them from the surrounding structures. The temporalis inserts mainly into the coronoid process of the mandible, which exerts a minor influence on temporomandibular joint function. The muscle bundle originates from part of the pterygoid fovea of the condylar process (Sakaguchi-Kuma et al., 2016), which makes it difficult to distinguish the border between the temporalis and lateral pterygoid muscle on CT images. The midmedial muscle bundle of the temporalis is attached to the bony ridge on the condylar process. During mandibulectomy including the condyle, a very small amount of the temporalis is detached. Thus, the temporalis was excluded from evaluation. The masseter, medial pterygoid, and lateral pterygoid muscles were defined as separate objects based on axial slices on both the affected side and the normal side. Manual outlining tools were used to delineate the contours of the muscles from the origins to the insertions (Fig. 1). Segmentation was performed in the axial view, and refinements were made in the coronal view. The masticatory muscular objects were displayed in the three-dimensional view (Fig. 2) and properties window for evaluation and volumetric measurement (Fig. 3). The reattachment status of the lateral pterygoid muscle, medial pterygoid muscle, and masseter was confirmed from the three-dimensional view and defined as ‘reattachment’ or ‘ectopic attachment’. Muscle attachment status was evaluated by two raters (Bai S. and Mao Y.Q.). Disagreements were resolved by another rater (Yu Y.). Muscular object definitions and volumetric measurements were performed twice by the same observer (Bai S.). Inter-rater and intra-rater reliability were evaluated according to intraclass correlation (ICC) values.

The volume of masticatory muscle was analyzed statistically at different follow-up visits. The data were checked for normality of distribution and homogeneity of variance using the Shapiro-Wilk test and Bartlett’s test, respectively. Within-subject volumetric changes over time were analyzed using repeated-measures analysis of variance with the following design: masticatory muscle (normal side, affected side) $\times$ time (preoperative, and 3 months, 6 months, and 1 year postoperative). R version 4.0.0 was used to analyze the data. The level of statistical significance was set at 0.05.

3. Results

3.1. Demographic characteristics and surgical outcomes

In total, 30 patients were included in this retrospective case series (mean age 30.10 ± 17.17 years). The primary tumor type identified in the majority of the patients was ameloblastoma ($n = 17$; 56.67%). All the free fibular flaps survived after surgery without any complications. All patients achieved normal mouth opening and masticatory function with solid diet at least 6 months after the operation. In most cases, the lateral pterygoid muscle achieved reattachment within 6 months postoperatively ($n = 25$, 83.33%). All the medial pterygoid muscles on the affected side exhibited ectopic attachment. Masseter reattachment on the affected side was achieved in only three cases postoperatively.

The follow-up period for postoperative imaging evaluation ranged from 12 to 48 months. Eight patients achieved dental rehabilitation, which was defined as receiving an implant-retained lower denture or removable partial denture. The demographic characteristics of the patients and types of muscle reattachment are summarized in Table 1.

3.2. Postoperative volumetric changes

The volumetric changes of the lateral pterygoid muscle, medial pterygoid muscle, and masseter on the normal side and affected side are shown in Figs. 4 and 5, respectively. On the normal side, the volume of masticatory muscle showed a slight decrease 3 months postoperatively and a slight increase 6 months postoperatively. One year after the procedure, the volumes of lateral pterygoid muscle,

Fig. 1. Delineation of the lateral pterygoid muscle, medial pterygoid muscle, and masseter on the CT axial slice.

medial pterygoid muscle, and masseter recovered to almost pre-operative levels on the normal side. However, the volumetric changes on the normal side were not significant. On the affected side, the volume of medial pterygoid muscle had decreased significantly ($p = 2.4e\text{-}04$) at 3 months postoperatively. The volumes of lateral pterygoid muscle and masseter showed slight decreases at 3 months postoperatively, but these were not significant ($p = 0.52$ and $p = 0.05$ for the pterygoid muscle and the masseter, respectively). At 6 months after surgery, with the exception of the volume of lateral pterygoid muscle ($p = 0.06$), the total volume of the masticatory muscles had decreased significantly on the affected side. The volumes of lateral pterygoid muscle, medial pterygoid muscle, and masseter showed significant decreases at 1 year after surgery on the affected side ($p = 0.03$, $p = 4.7e\text{-}08$, and $p = 1.1e\text{-}05$). The mean times for stable volumetric changes on the affected side were 8.40 ± 2.99 months (lateral pterygoid muscle), 7.80 ± 3.21 months (medial pterygoid muscle), and 8.60 ± 3.02 months (masseter). The ICC values for inter-rater reliability and intra-rater reliability were 0.80 and 0.95, respectively. This indicated good agreement with regard to repeated-object volumetric measurements.

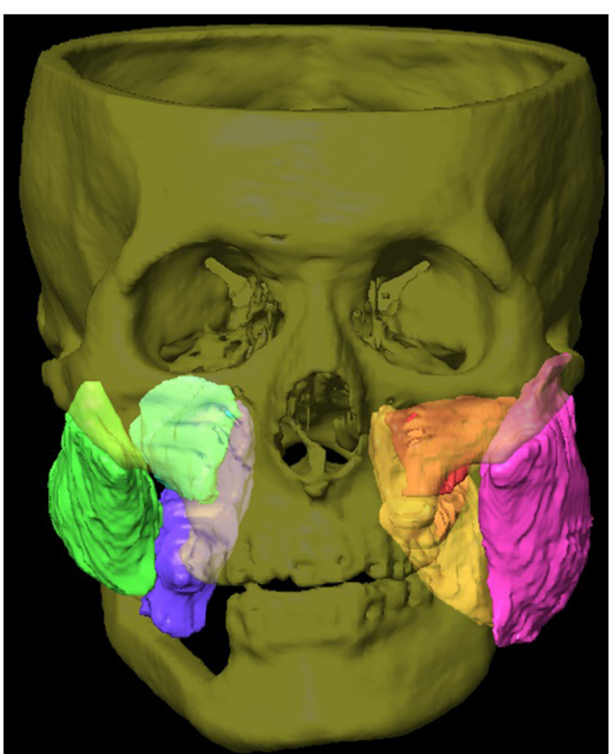

Fig. 2. Three-dimensional view of the masticatory muscular objects.

3.3. Follow-up findings

The long-term follow-up CT scans of the eight patients who achieved dental rehabilitation showed that the degree of muscular atrophy was lower than in the other patients, with increases in the volumes of lateral pterygoid muscle, medial pterygoid muscle, or masseter 1 year after the operation.

Of the 30 patients in this study, 16 showed neocondyle regeneration at follow-up. Neocondyle regeneration was significantly associated with age at the time of the procedure, with the rate significantly higher in patients aged 18 years or younger (10 out of 16) compared with those older than 18 years (6 out of 16) ($p = 0.006$). It is worth noting that in all the neocondyle regeneration cases, reattachment of the lateral pterygoid muscles was achieved postoperatively.

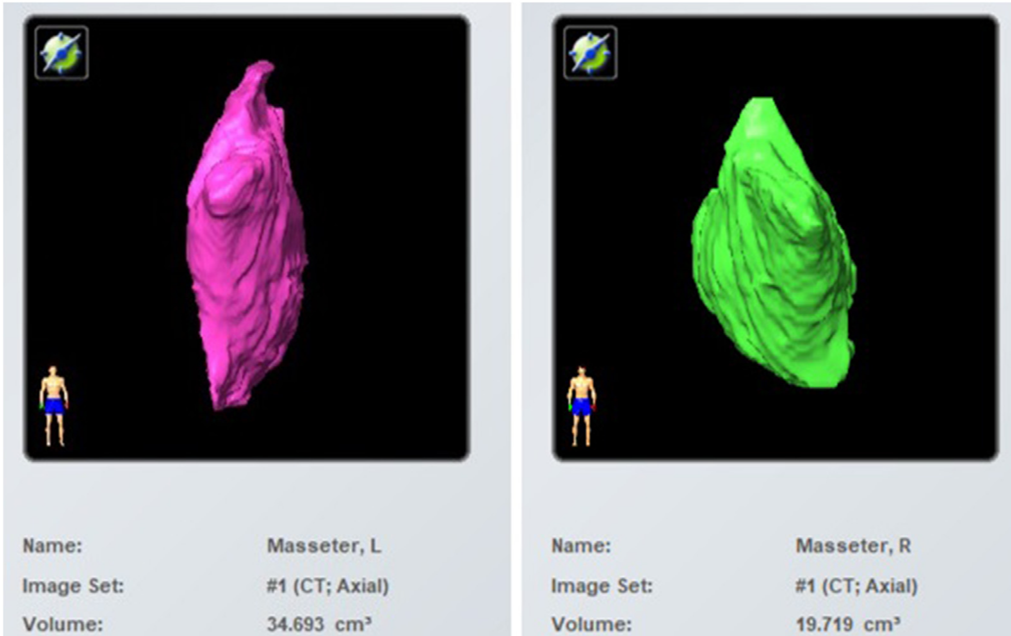

Fig. 3. Identification of muscular objects and volumetric measurements in the plan content window.

Table 1
Demographic characteristics of the study cohort.

Patient	Age	Sex	Diagnosis	Extent of resection	Muscle reattachment status on the affected side			Dental rehabilitation
					Lateral pterygoid muscle	Medial pterygoid muscle	Masseter	
1	53	Female	Ossifying fibroma	46-RC[a]	RA[b]	EA[c]	EA	No
2	18	Male	Ameloblastoma	46-RC	RA	EA	EA	No
3	16	Male	Ameloblastoma	45-RC	RA	EA	EA	No
4	33	Male	Ameloblastoma recurrence	36-LC[d]	RA	EA	EA	Prosthesis
5	15	Male	Ameloblastoma	45-RC	RA	EA	EA	No
6	35	Male	Ameloblastoma	36-LC	RA	EA	EA	No
7	19	Male	Ameloblastoma	44-RC	RA	EA	EA	Prosthesis
8	51	Male	Odontogenic keratocyst	36-LC	EA	EA	EA	No
9	48	Female	Ameloblastoma recurrence	34-LC	EA	EA	EA	No
10	58	Female	Solitary fibrous tumor	47-RC	RA	EA	EA	No
11	13	Female	Ameloblastoma	43-RC	RA	EA	RA	Prosthesis
12	26	Female	Ameloblastoma	35-LC	RA	EA	RA	Implants
13	26	Female	Odontogenic keratocyst	47-RC	RA	EA	EA	Implants
14	21	Male	Aneurysmal bone cyst	47-RC	RA	EA	EA	No
15	35	Female	Ameloblastoma recurrence	46-RC	RA	EA	EA	No
16	68	Male	Odontogenic keratocyst	45-RC	RA	EA	EA	No
17	7	Male	Ossifying fibroma	45-RC	RA	EA	EA	No
18	64	Male	Odontogenic keratocyst	44-RC	EA	EA	EA	No
19	32	Male	Schwannoma	36-LC	RA	EA	EA	No
20	16	Female	Fibroma	46-RC	EA	EA	EA	No
21	30	Female	Ameloblastoma	45-RC	RA	EA	EA	Prosthesis
22	52	Female	Odontogenic ghost cell tumor	34-LC	RA	EA	EA	No
23	35	Female	Ameloblastoma	45-RC	EA	EA	RA	Prosthesis
24	15	Male	Ameloblastoma	45-RC	RA	EA	EA	No
25	13	Male	Ameloblastoma	43-RC	RA	EA	EA	Prosthesis
26	17	Female	Ameloblastoma	35-LC	RA	EA	EA	No
27	14	Female	Ameloblastoma	34-LC	RA	EA	EA	No
28	39	Female	Ameloblastoma	34-LC	RA	EA	EA	No
29	25	Female	Odontogenic keratocyst	47-RC	RA	EA	EA	No
30	9	Male	Fibrous dysplasia	45-RC	RA	EA	EA	No

[a] RC, right condyle.
[b] RA, reattachment.
[c] EA, ectopic attachment.
[d] LC, left condyle.

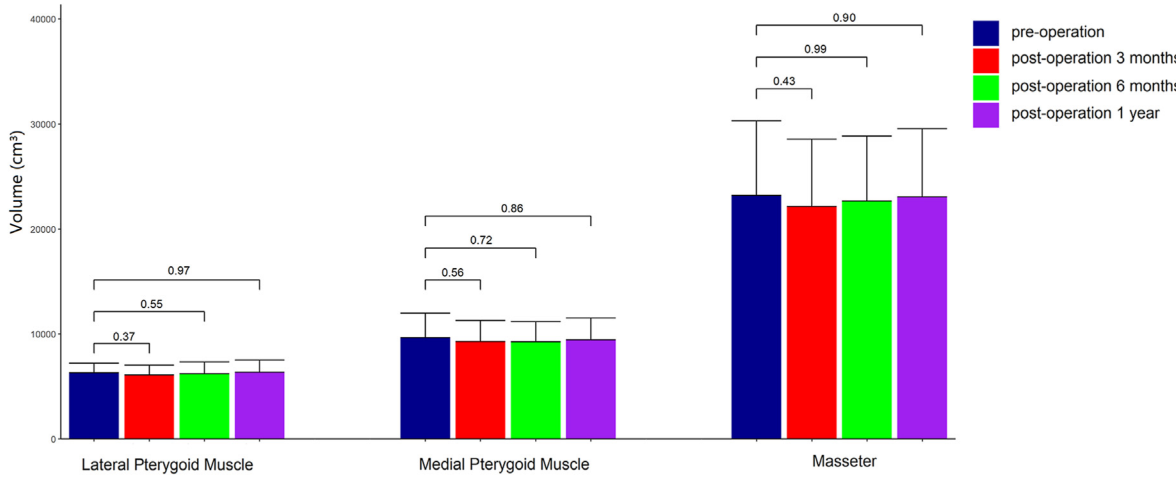

Fig. 4. Volumetric changes of the lateral pterygoid muscle, medial pterygoid muscle, and masseter on the normal side. The columns show the means of each set of data, and the error bars show the standard deviations. Arabic numerals represent the *p*-values.

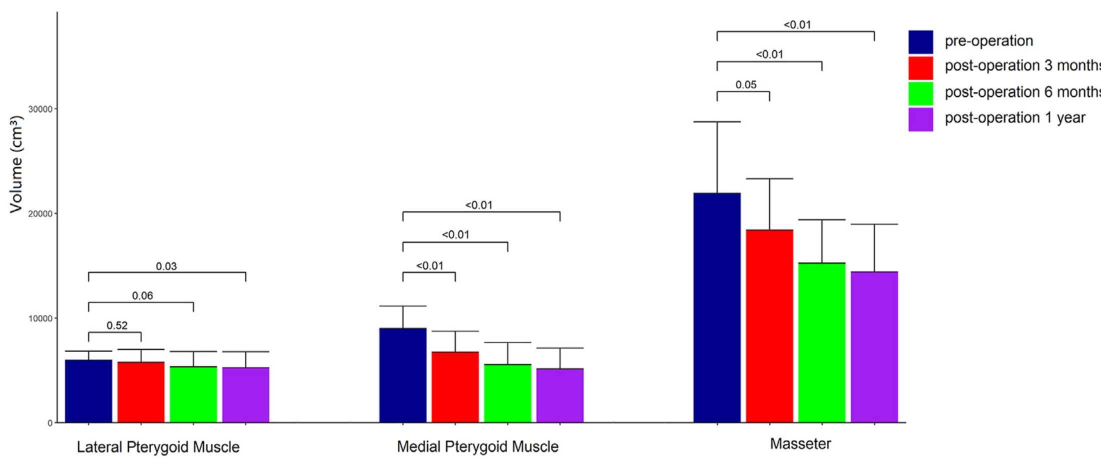

Fig. 5. Volumetric changes of the lateral pterygoid muscle, medial pterygoid muscle, and masseter on the affected side. The columns show the means of each set of data, and the error bars show the standard deviations. Arabic numerals represent the *p*-values.

4. Discussion

Our study evaluated the long-term outcomes of free fibular flap reconstruction of the mandibular condyle in terms of masticatory muscle reattachment and volume changes. According to our previous publication (Yu et al., 2020), the neocondyle is stable for 2.5–10.5 months after surgery. Soft tissues generally exhibit various degrees of swelling 1 month after surgery. Hence, cases with CT scans for at least 3 months postoperatively were considered to be eligible for muscle measurement.

The lateral pterygoid muscle is thought to play an important role in mandibular movement. The fibers of the lateral pterygoid muscle are attached to the temporomandibular disc and condyle (Imanimoghaddam et al., 2013). In our mandibular condyle reconstruction technique, the temporomandibular disc was preserved in all cases. That part of the lateral pterygoid muscle attachment was preserved in order to increase the chances of reattachment of the lateral pterygoid muscle postoperatively. Using a technique similar to ours, Thor et al. (2008) reported functional reconstruction of the temporomandibular joint with a free fibular flap by preserving the temporomandibular disc, correctly securing the vascularized fibular end in the fossa, and reattaching the lateral pterygoid muscle to the end of the vascularized fibular flap. The radiological findings for neocondyle remodeling indicated rapid functional adaptation. Wax et al. (2000) also reported satisfactory functional results by preserving the temporomandibular disc, which was attached with a permanent suture to the neocondyle, and suturing the fibular periosteum over the neocondyle. De Meurechy et al. (De Meurechy et al., 2021) conducted an animal experiment to evaluate the lateral pterygoid muscle's enthesis, which involved implanting sheep with a temporomandibular joint replacement. In addition, Mommaerts (2019) reported a technique in which the lateral pterygoid muscle was reattached to the scaffold of the temporomandibular joint prothesis using a 3-0 poly-p-dioxanone tendon suture as part of total temporomandibular joint replacement surgery. Their findings showed that reattachment of the lateral pterygoid muscle could provide the patient with greater interincisal opening and improve lateral and protrusive movement of the mandible. In accordance with these findings, the majority of cases in our cohort (83.33%) achieved lateral pterygoid muscle reattachment within 6 months postoperatively. Thus, preservation of the temporomandibular disc and attachment of the lateral pterygoid muscle fibers to the flap seem to be effective strategies for ensuring postoperative reattachment of the lateral pterygoid muscle after free fibular flap reconstruction of the mandible.

The insertion of the medial pterygoid muscle is observed to be oval in shape and widely attached to the mandibular angle. In a long-term follow-up study by Lo et al. (2005), resection of the mandibular angle resulted in a varied amount of muscle reduction, with an average decrease of 14.4% in the volume of the medial pterygoid muscle. In our study, the medial pterygoid muscle showed a more significant postoperative volume decrease when compared with the lateral pterygoid muscle and masseter. This muscle atrophy appears to be related to total loss of osseous attachment as a result of mandibular angle resection. However, it is difficult to reconstruct the reattachment of the medial pterygoid muscle on account of the vessel pedicle being located on the lingual side of the reconstructed mandible.

Mandibulectomy requires exposure of the inferior border of the mandible, with concomitant elevation of the masseter insertion and the pterygomasseteric sling. Contraction of the superior part of the masseter might result in the mandible moving forward and causing a protrusion postoperatively. The deep fibers of the masseter radiate into the anterior capsule and the temporomandibular disc. This may indicate that the masseter helps to stabilize the tension in the articular capsule of the temporomandibular joint. Gravvanis et al. attempted to suture the deep portion of the masseter to the angle of the reconstruction plate and to the periosteum of the fibula (Gravvanis et al., 2017). This artificial reattachment of the masseter in the reconstructed mandible caused the neocondyle to actively fit into the glenoid fossa. Engroff et al. also suggested suturing the masseter directly to the osteosynthesis plate in the mandibular angle, in order to secure the neocondyle actively in the glenoid fossa. However, without reconstruction, reattachment of the masseter may result in loss of soft-tissue volume over the neo-angle of the reconstructed mandible, and an asymmetric appearance. This deformity is dynamically influenced by the contraction of the masseter postoperatively, and can be corrected by reattachment of the muscle to the inferior border of the mandible. Thomas et al. (2009) reconstructed the masseter insertion by using drill holes placed at the inferior border of the mandible, which were used to reattach the inferior edge of the masseter with a nonabsorbable suture during mandibular angle surgery.

In our case series, 16 patients showed neocondyle regeneration, and all of them achieved reattachment of the lateral pterygoid muscles postoperatively. The osseous regeneration was likely to be associated with the reattachment of the muscles and its effect on the recovery of masticatory function. These findings imply that masticatory muscular attachment, suspensory capsular ligaments, and limitations placed by the joint capsule on the condylar head and neck permitted condylar movement within a certain range. This might have created a favorable environment for neocondyle osseous regeneration, and the regenerated condyle in the fossa might have guided the distal end of fibula to move towards the fossa.

The major limitation of our study was the lack of functional assessment of masticatory muscles with regard to the clinical significance of muscular reattachment. This caused difficulty with stratification based on interventions, as well as a lack of comparison. Moreover, this study was a retrospective study with a relatively small sample size.

Conclusion

In conclusion, the postoperative volume of the masseter, medial pterygoid, and lateral pterygoid muscles showed a significant decrease due to the loss of reattachment. The results of this study may not help to ascertain whether the reattachment of masticatory muscles will lead to better function. Consequently, clinical trials of higher quality are needed.

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Author contributions

Conceptualization — Xin Peng; data curation — Yao Yu, Wen-Bo Zhang; formal analysis — Shuang Bai, Ya-Qing Mao; methodology — Shuang Bai, Ya-Qing Mao, Yao Yu, Wen-Bo Zhang; resources — Yang Wang, Chi Mao, Xin Peng; supervision — Xin Peng; writing (original draft) — Shuang Bai; writing (review and editing) — Xin Peng.

Ethical approval

Ethical approval was obtained from the Ethics Review Board of Peking University School and Hospital of Stomatology (PKUSSIRB-202055073).

Patient consent

Informed consent was obtained from all the patients.

Declaration of competing interest

None.

Acknowledgements

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