Int. J. Oral Maxillofac. Surg. 2019; xxx: xxx–xxx
https://doi.org/10.1016/j.ijom.2021.02.033, available online at https://www.sciencedirect.com

International Journal of Oral & Maxillofacial Surgery

Research Paper
Reconstructive Surgery

Spatial deviations of the temporomandibular joint after oncological mandibular reconstruction☆

W.-F. Yang[1], W. S. Choi[1], W.-Y. Zhu[1], C.-Y. Zhang[2], D. T. S. Li[1], J.K.-H. Tsoi[3], A.W.-L. Tang[4], K.-W. Kwok[4], Y.-X. Su[1]

[1]Division of Oral and Maxillofacial Surgery, Faculty of Dentistry, The University of Hong Kong, Hong Kong SAR, China; [2]Guangzhou Janus Biotechnology Co., Ltd, Guangzhou, China; [3]Dental Materials Science, Division of Applied Oral Sciences and Community Dental Care, Faculty of Dentistry, The University of Hong Kong, Hong Kong SAR, China; [4]Department of Mechanical Engineering, The University of Hong Kong, Hong Kong SAR, China

W. -F. Yang, W. S. Choi, W. -Y. Zhu, C. -Y. Zhang, D. T. S. Li, J. K. -H. Tsoi, A. W. -L. Tang, K. -W. Kwok, Y. -X. Su: Spatial deviations of the temporomandibular joint after oncological mandibular reconstruction. Int. J. Oral Maxillofac. Surg. 2019; xxx: xxx–xxx.

Abstract. Spatial deviations of the temporomandibular joint (TMJ) after oncological mandibular reconstruction are important to the aesthetic and functional rehabilitation. The aim of this study was to clarify whether and how three dimensionally (3D) printed patient-specific surgical plates, and the preservation of the condyle or ramus, affect spatial deviations of the TMJ. A total of 33 patients who underwent mandibular reconstruction via computer-assisted surgery were included. Regarding absolute deviations, patients in the 3D-printed plate group showed smaller TMJ deviations compared to those in the conventional plate group. There was no difference in absolute deviations of the TMJ regardless of whether the condyle or ramus was preserved. Regarding physiological deviations, the impact on the contralateral TMJ was smaller in the 3D-printed plate group. Patients with both the condyle and ramus removed had significantly higher deviations of the condyle and joint space. In summary, 3D-printed patient-specific surgical plates improved the spatial accuracy of the TMJ. Under physiological conditions, TMJ deviations on the operated side were mainly affected by the preservation of the condyle. Removal of both the condyle and ramus caused more severe spatial interference to the TMJ; this should be further confirmed.

Key words: three-dimensional printing; computer-assisted surgery; mandibular reconstruction; temporomandibular joint; head and neck cancer.

Accepted for publication 17 February 2021

Mandibular defects after oncological resection impair the mandibular continuity and cause spatial deviations of the joint structures[1–3]. Spatial deviation denotes the three-dimensional (3D) change in joint position and morphology. To rehabilitate aesthetics and function, it is important to restore a normal fossa–condyle relationship, especially in the case of ramus defects[1,3–5]. The fossa–condyle is important for the attachment of muscles and ligaments of the temporomandibular joint (TMJ)[3]. An abnormal TMJ can lead to aberrant occlusion, difficulty chewing, asymmetric facial contours, and even pain[6,7]. However, due to limited research in this field, little is known about the

☆ This study was presented at the 2020 American Association of Oral and Maxillofacial Surgeons Annual Meeting.

0901-5027/000001+010

spatial deviations of the TMJ after mandibular reconstruction[1,3,5,8].

The TMJ position is assumed to be mainly affected by the extent of the posterior mandibular resections[2,9]. For instance, anterior mandibular defects cause less interference to the TMJ, whilst lateral defects show more severe impacts. If the condyle is removed, transplanted bone grafts are passively placed in the glenoid fossa without an anatomical anchor[3,9], thereby increasing mobility of the neomandible and inducing severe TMJ deviations[1,9,10]. In the case that the condyle is preserved, the intact joint capsule and the encapsulated fossa–disc–condyle help to stabilize the free end of the transplanted bone graft and contribute to initial stability of the fossa–condyle[3,9]. However, the initial stability may be distracted by the neomandible, leading to a deviation from the normal position. Only when the condyle and posterior ramus are preserved can TMJ stability be enhanced by major mandibular elevator muscles. Anyhow, the normal fossa–condyle is easily compromised after oncological mandibular reconstruction, and thus TMJ deviations should be studied in different settings to gain a better understanding and to guide reconstruction and rehabilitation of the mandible intentionally[1,8].

Computer-assisted surgery (CAS) facilitates the accurate harvest of transplanted bone grafts by preoperative virtual surgery and 3D-printed cutting guides[6,11–13]. More recently, the advent of 3D-printed patient-specific surgical plates has further enhanced the precise alignment and fixation of bone grafts[14,15]. In previous studies conducted by the present authors, patient-specific surgical plates have been demonstrated to enhance the overall accuracy of oncological mandibular reconstruction[14,16–19]. However, spatial deviations of the TMJ are rarely evaluated, and whether CAS and patient-specific surgical plates contribute to the normal fossa–condyle relationship remains to be elucidated.

Superimposition of the CAS postoperative skull with the preoperative model facilitates the evaluation of the spatial deviations of the TMJ[6,19,20]. Conventionally, the algorithm for superimposition is based on the non-operated side of the mandible[19–21]; this has been adopted in many previous studies assessing the accuracy of CAS. The algorithm deposits reconstruction discrepancy on the operated side for assessing spatial accuracy; therefore, this was termed ‘absolute deviation’. However, under physiological conditions, the mandible is distracted by muscles and adapts to occlusal contacts[6,10]. In order to investigate spatial deviations of the TMJ physiologically, the postoperative and preoperative models were superimposed based on the maxilla so that the mandibles could be compared in the physiological state. This method of superimposition and accuracy analysis was termed ‘physiological deviation’ in the present study. As such, both the absolute and physiological deviations of the TMJ after oncological mandibular reconstruction can be investigated, as well as how the spatial accuracy of the reconstruction may affect the physiological deviations of the TMJ.

Patients who had undergone oncological mandibular reconstruction by CAS were recruited into this clinical study. The aims were to determine (1) whether patient-specific surgical plates increased the spatial accuracy, i.e., decreased the absolute deviations of the TMJ when compared to conventional surgical plates; (2) whether the preservation of the condyle or ramus contributed to the spatial accuracy of the TMJ; and (3) how physiological deviations of the condyle and the fossa–condyle relationship are affected by mandibular reconstruction in different settings.

Materials and methods

Study design and participants

This study was designed to evaluate spatial deviations of the TMJ after oncological mandibular reconstruction. Patients were eligible if they had undergone mandibular reconstruction by CAS. Patients were excluded if defects only involved the anterior mandible (class III defects according to the Brown classification), or extensive mandible including bilateral rami (cliaa IV/IVc defects)[2].

Two grouping strategies were used. In the first strategy, patients were allocated to the study group receiving 3D-printed patient-specific surgical plates or to the control group with conventional plates (Fig. 1, Strategy 1). 3D-printed patient-specific surgical plates were designed and applied in a novel ‘surgeon-dominated’ approach, which has been detailed in previous articles[16,17]. The study group has been registered at ClinicalTrials.gov (3DJP16, NCT03057223)[14,19]. Patients in the control group underwent CAS performed by the same chief surgeon in the same unit. Patients in the control group received conventional commercial surgical plates (DePuy Synthes, Raynham, MA, USA).

In the second grouping strategy, patients were allocated to three groups based on the extent of the posterior resections (Fig. 1, Strategy 2). Patients were assigned to group A if both the condyle and posterior ramus were preserved, group B if only the condyle was preserved, or group C if neither the condyle nor ramus was preserved.

Ethical approval for this study was granted by the Institutional Review Board of the University of Hong Kong/Hospital Authority Hong Kong West Cluster (UW 16-315). Patient written consent was obtained routinely. All procedures were executed strictly according to the tenets of the Declaration of Helsinki.

Procedures

CAS was performed on all patients, including preoperative virtual surgery, real surgery, and postoperative accuracy analysis[16,17,19]. In the preoperative virtual surgery, the oncological mandibular resection and reconstruction were conducted in ProPlan CMF 3.0 (Materialise, Leuven, Belgium). Patient-specific cutting guides and surgical plates were designed in 3-matic 13.0 (Materialise). Patient-specific surgical plates were fabricated by selective laser melting (SLM) using pure titanium powders[15,16]. Cutting guides were manufactured by 3D-printing using ISO-certified MED610 or ULTEM 1010 (Stratasys, Rehovot, Israel)[14,16,17].

Surgery was performed in the Department of Oral and Maxillofacial Surgery, Queen Mary Hospital in Hong Kong. Major procedures included tumour resection, bone flap harvest, and mandibular reconstruction, which were facilitated by CAS. In the control group, tumour resection and bone flap harvest were aided by cutting guides. In the study group, in addition to cutting guides, patient-specific surgical plates were applied to facilitate the alignment and screw fixation of the bone grafts.

In the postoperative accuracy analysis, the patient's computed tomography (CT) data were used. CT scans were taken routinely before surgery and at around 1 month after surgery. Patients were instructed to bite their teeth together and stabilize their occlusion while the CT scans were taken. The CT data were used to construct virtual models in ProPlan CMF 3.0 and 3-matic 13.0 for accuracy analysis.

Two superimposition algorithms were developed, one to study absolute deviations of the TMJ and the other to study physiological deviations of the TMJ. In algorithm 1 for absolute deviations, the

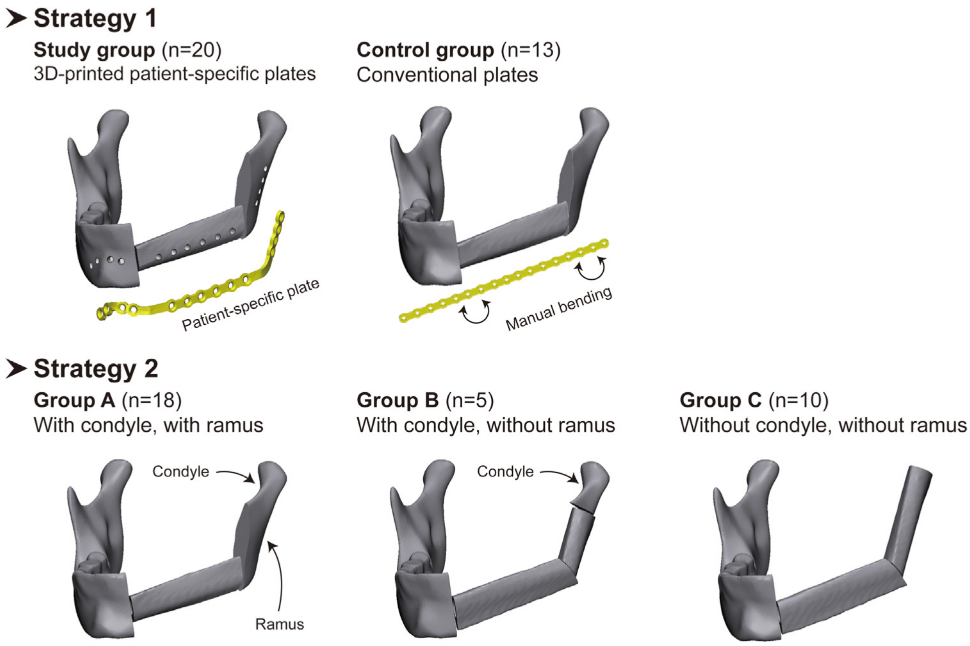

Fig. 1. Study design—strategies and groupings. In strategy 1, patients were allocated to the study group (3D-printed patient-specific plates) or the control group (conventional surgical plates). In strategy 2, patients were allocated according to the preservation of the condyle or ramus: in group A, both the condyle and posterior ramus were preserved; in group B, only the condyle was preserved; in group C, neither the condyle nor the ramus was preserved.

postoperative reconstructed mandible was superimposed onto the preoperative virtually planned mandible based on the non-operated side[14,19]. Thereafter, absolute TMJ deviations on the operated side were visualized and measured (Fig. 2A). In algorithm 2 for physiological deviations, considering that the TMJ was affected bilaterally due to muscular attachment and occlusal adaptation in the physiological state, the mandibles were superimposed based on the maxilla. Through the maxillary superimposition, the mandibles could be registered in the physiological state, thereby facilitating the assessment of physiological deviations of the fossa–condyle bilaterally (Fig. 2B).

Outcomes and measurement

Various outcome parameters were established to evaluate spatial deviations of the TMJ[14]. Initially, the sagittal, coronal, and transverse planes of skull models were verified and updated to the world coordinate system, which was taken as the reference for all measurements (Fig. 3A, B). First, to assess overall deviations of the bilateral condyles, the most superior points of the bilateral condylar heads were connected by the intercondylar line. The intercondylar distance and angulation deviations were calculated based on the difference in length and the angle between the preoperative and postoperative intercondylar lines (Fig. 4A). Second, to assess the distance shifts of the condyle, the most superior point of the condyle was traced in three dimensions, namely superior-inferiorly, anterior-posteriorly, and medial-laterally (Fig. 4B). Thirdly, the condylar axis was delineated by connecting the most medial and lateral points of the condylar head, and rotational displacement of the condyle was determined by the angles

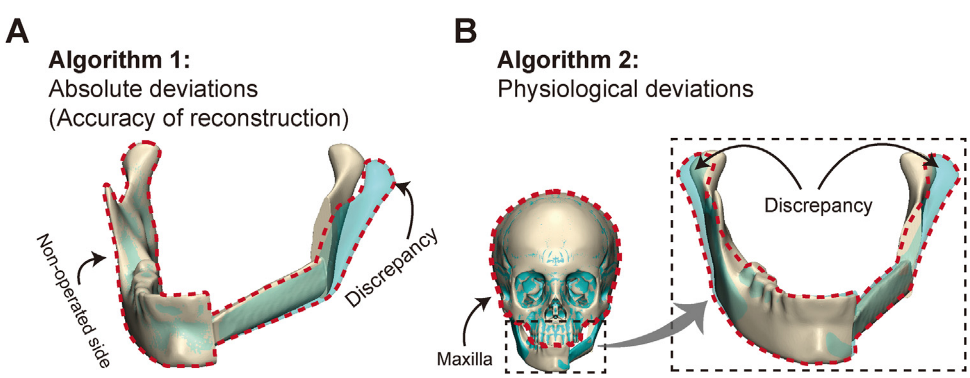

Fig. 2. Superimposition algorithms for spatial deviations. (A) In algorithm 1, the preoperative and postoperative mandible models were superimposed based on the non-operated side of the mandible to assess the spatial accuracy, or absolute deviations, of the TMJ. Discrepancy was deposited on the operated side of the mandible. (B) In algorithm 2, the models were superimposed based on the maxilla to assess the physiological deviations of the TMJ in the physiological state, in which the discrepancy was distributed on both sides.

Please cite this article in press as: Yang WF, et al. Spatial deviations of the temporomandibular joint after oncological mandibular reconstruction, *Int J Oral Maxillofac Surg* (2021), https://doi.org/10.1016/j.ijom.2021.02.033

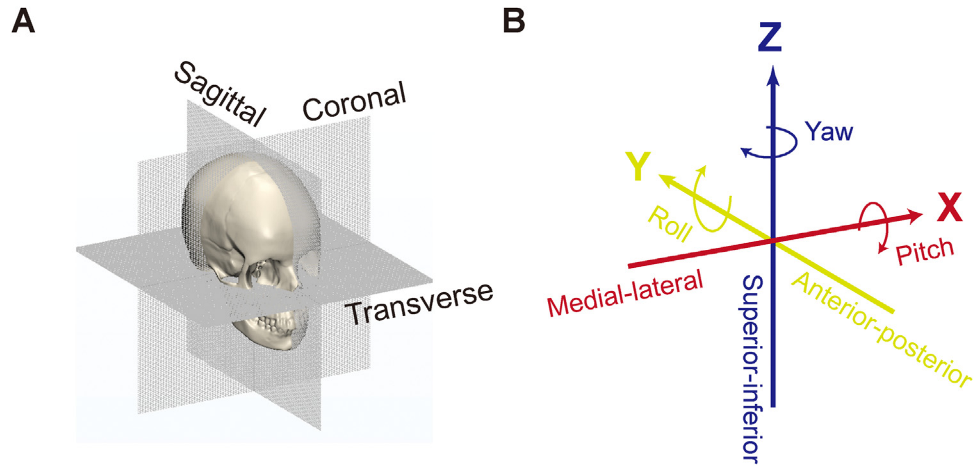

Fig. 3. The coordinate system for spatial deviations. (A) The sagittal, coronal, and transverse planes of the skull model were determined. (B) The established coordinate system served to study the deviations in angulation of the condyle, including yaw, pitch, and roll.

between the preoperative and postoperative condylar axes in three dimensions, representing roll, pitch, and yaw of the condyle (Fig. 4C). Fourthly, to evaluate overall spatial deviations of the condyle, the condyle was dissected by a plane running from the sigmoid notch and perpendicular to the posterior border of the mandible. Absolute distance deviation of the condyle was calculated from the mean distance between each point on the postoperative condyle and its corresponding point on the preoperative condyle (Fig. 4D). Lastly, to assess the impact on the fossa–condyle relationship, the joint space of the TMJ was visualized using the colour map and the average joint space was calculated by the mean distance between the fossa and condyle (Fig. 4E).

Statistical analysis

Continuous data were recorded as the mean with standard deviation (SD); comparisons were made using the two-sample *t*-test or one-way analysis of variance (ANOVA). Categorical data were recorded as the count with percentage; comparisons were made using the χ^2 test or Fisher's exact test. All statistical tests were two-sided, and significance was defined as a *P*-value <0.05. All statistical analyses were done using IBM SPSS Statistics version 22.0 (IBM Corp., Armonk, NY, USA) and GraphPad Prism 5 (GraphPad Software Inc., San Diego, CA, USA).

Results

Demographics and baseline characteristics

The demographics and baseline characteristics are summarized in Table 1. A total of 33 patients were included: 13 in the control group who received conventional plates and 20 in the study group who received 3D-printed plates. There was no difference between the two groups concerning age, sex, lesion type, pT3/T4 cancer, Brown classification of the defects, extent of the posterior resection, donor bone graft, or use of postoperative radiotherapy/chemoradiotherapy.

Algorithm 1—absolute deviations

The spatial accuracy of the TMJ on the operated side after oncological mandibular reconstruction is shown in Fig. 5.

The first grouping strategy (Fig. 5A–D) investigated patients according to their allocation to either the control group or study group. One case in the study group of 3D-printed plates was excluded from the analysis due to a severe data bias. The absolute deviations of the TMJ were generally more obvious in the control group with conventional surgical plates. In the analysis of the 3D distance shifts of the uppermost points (Fig. 5A), there was no significant difference between the two groups. A significantly higher deviation in the medial–lateral dimension was detected in the control group (mean difference 2.9 ± 1.0 mm; $P = 0.007$). No significant difference was detected in the superior–inferior or anterior–posterior dimensions. Regarding the 3D angulation shifts of the condyle (Fig. 5B), a greater angulation deviation was detected in the control group (mean difference $9.4 \pm 3.1°$; $P = 0.004$). The difference was statistically significant in the coronal plane (mean difference $7.1 \pm 2.2°$; $P = 0.003$) and transverse plane (mean difference $6.1 \pm 2.9°$; $P = 0.04$), but not in the sagittal plane. The intercondylar deviations reflect the overall deviation of the bilateral TMJ. As shown in Fig. 5C, the distance deviations were more obvious in the control group (mean difference 2.0 ± 1.0 mm; $P = 0.041$). However, there was no significant difference in the angulation deviations. Finally, a significant difference was found in the absolute distance deviation of the condylar head (mean difference 4.4 ± 1.6 mm; $P = 0.009$) (Fig. 5D), indicating more severe absolute deviations of the condylar head in the control group with conventional plates.

In the second grouping strategy (Fig. 5E–H), patients were divided into three groups in order to determine the impact of preserving the condyle or ramus. There was no significant difference between the groups for the great majority of parameters investigated, which might be due in part to the small sample size in group B and group C. However, the data heterogeneity was more obvious in group C, suggesting that heterogeneous TMJ reconstruction outcomes might occur when both the condyle and ramus are sacrificed. Furthermore, it was observed that the absolute deviations of the TMJ were lowest in group B, which should be investigated further.

Algorithm 2—physiological deviations

The physiological deviations of the TMJ are shown in Fig. 6.

In the first grouping strategy, as depicted in Fig. 6A, absolute distance deviations of the condyle on the operated side were decreased in the physiological state, especially in the control group patients. In contrast, deviations on the non-operated contralateral side were slightly increased. This indicates that TMJ deviations on the operated side could

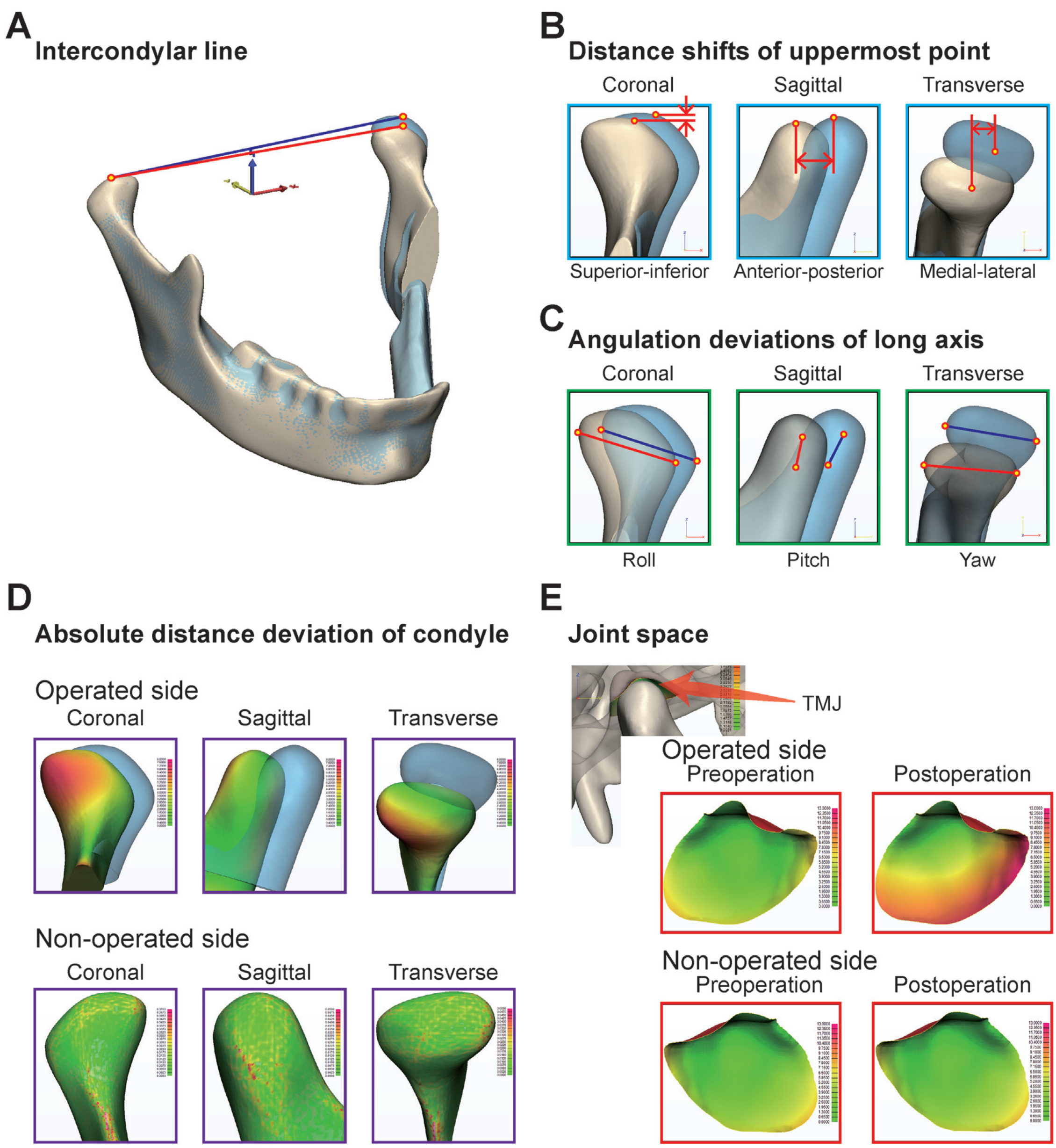

Fig. 4. Outcome parameters for the spatial deviations. (A) The bilateral uppermost points were located and connected through the intercondylar line, by which the intercondylar distance and angulation deviations were measured. (B) The uppermost point of the condyle was located to measure the shifts in distance in three dimensions. (C) The condylar axis was defined by connecting the most medial and lateral points of the condyle, and the angulation deviations of the condylar head were measured in three dimensions. (D) The absolute distance deviation of the condylar head on the operated and non-operated sides. (E) The joint space of the TMJ was visualized and measured on the operated and non-operated sides.

actually be transferred to the contralateral side after adaptation. The contralateral TMJ was physiologically affected after oncological mandibular reconstruction, although to a relatively small degree. Hence, after physiological adaptation, there was no difference on the operated side (Fig. 6B). The impact on the contralateral condyle was smaller in the study group of 3D-printed plates (mean difference 0.4 ± 0.2 mm; $P = 0.015$). Changes in the TMJ joint spaces were observed to follow the same trend (Fig. 6C). No significant difference in TMJ joint space deviations was detected between the two groups (Fig. 6D), suggesting that even though 3D-printed plates contributed to an enhanced spatial accuracy, the fossa–condyle relationship could be maintained in a physiological range.

In the second grouping strategy, when dividing the patients according to the preservation of the condyle or ramus, while spatial deviations of the condyle or joint space could be alleviated on the operated side (Fig. 6E, G), significantly higher deviations of the condyle and joint space were identified in group C (neither the condyle nor the ramus was preserved). In group A, group B, and group C, the absolute distance deviations of the condylar head on the operated side were 1.5 mm, 1.1 mm, and 3.6 mm, respectively (Fig. 6F); the corresponding physiological deviations of the joint space were 0.8 mm, 0.8 mm, and 4.2 mm, respectively

Table 1. Demographics and baseline characteristics of the patients.

Characteristic	Conventional plates ($n = 13$), n (%)	3D-printed plates ($n = 20$), n (%)	P-value
Age (years), mean ± SD	56.0 ± 17.4	59.7 ± 15.2	0.52[d]
Sex			0.84[f]
Female	8 (61.5%)	13 (65%)	
Male	5 (38.5%)	7 (35%)	
Lesion type			0.55[e]
Benign	4 (30.8%)	4 (20%)	
Malignant	8 (61.5%)	13 (65%)	
Other[a]	1 (7.7%)	3 (15%)	
pT3/T4 cancer[b]	5 (38.5%)	7 (35%)	0.86[f]
Brown classification			0.95[e]
I	4 (30.8%)	7 (35%)	
Ic	2 (15.4%)	5 (25%)	
II	5 (38.5%)	7 (35%)	
IIc	2 (15.4%)	1 (5%)	
Condylar resection			1.00[e]
Group A	7 (53.8%)	11 (55%)	
Group B	2 (15.4%)	3 (15%)	
Group C	4 (30.8%)	6 (30%)	
Donor bone graft[c]			1.00[e]
Fibula	12 (92.3%)	18 (90%)	
Iliac crest	1 (7.7%)	2 (10%)	
Postoperative RT/CRT	2 (15.4%)	9 (45%)	0.08[e]
Adverse events			
Wound infection	1 (7.7%)	3 (15%)	
Plate breakage	0	1 (5%)	
Bone malunion/non-union	0	0	

3D, three-dimensional; CRT, chemoradiotherapy; RT, radiotherapy; SD, standard deviation.
[a] 'Other' includes secondary reconstruction and osteoradionecrosis.
[b] Pathological tumour category according to the American Joint Committee on Cancer Staging for Head and Neck Cancer, eighth edition.
[c] All defects were repaired using a vascularized bone flap.
[d] P-value calculated by means of the independent-samples t-test.
[e] P-value calculated by means of Fisher's exact test.
[f] P-value calculated by means of the χ^2 test.

(Fig. 6H). The results suggest that patients who had both the condyle and ramus removed had significantly higher deviations of the condyle and joint space.

Discussion

This comprehensive study investigated TMJ spatial deviations after oncological mandibular reconstruction in different clinical settings. It was found that 3D-printed patient-specific surgical plates increased the spatial accuracy, i.e. they decreased absolute deviations of the TMJ when compared to conventional plates. No difference in absolute deviations of the TMJ was found regardless of whether the condyle or ramus was preserved. In the physiological state, 3D-printed plates did not produce different TMJ deviations on the operated side, however the impact on the contralateral condyle was smaller in the 3D-printed plates group. Patients with both the condyle and ramus removed had significantly higher deviations in terms of the condyle and joint space.

Previous studies have confirmed the benefits of CAS in improving the accuracy of mandibular reconstruction[6,13,22]. However, the results of the present study are novel in showing that 3D-printed surgical plates improved the spatial accuracy of the TMJ. Although a few previous studies stated that patient-specific surgical plates might act as a link to more accurate reconstruction[10,14], they did not provide compelling evidence. The present study adds convincing clinical evidence towards revealing the benefits of 3D-printed patient-specific surgical plates.

Regarding the major role of the TMJ, this study focused on spatial deviations of the TMJ and employed multiple outcome parameters to comprehensively confirm the benefits of 3D-printed surgical plates in the new era of CAS[7,19,20]. Distance and angulation deviations of the condyle were evaluated, and the overall deviations of the condyle and joint space were assessed. The strategies established in this study could potentially facilitate more similar studies in the future[8].

The mandible provides attachment to muscles and ligaments that contract during masticatory function and maintain the mandible in equilibrium. Generally, mandibular defects in different regions cause varying deviations of the TMJ[2,3,10]. In the present study, patients with anterior defects were excluded in order to reduce this possible bias[2]. Similarly, patients with extensive mandibular defects affecting the bilateral rami were also excluded. The predesigned exclusion criteria ensured the consistency of the patient group and this should be taken into consideration when interpreting the results. However, whether and how anterior or extensive defects affect spatial deviations of the TMJ should be explored further.

Conventionally, when evaluating the accuracy of reconstruction, the preoperative and postoperative mandibles are superimposed based on the non-operated side[14,19]. However, this algorithm does not reproduce the maxillary-mandibular relationship under physiological conditions and does not support the study of fossa–condyle interactions[23]. In the current study, a new algorithm was defined in which the mandible is registered based on the maxilla, which facilitated the assessment of physiological deviations of the TMJ. Since patients were instructed to bite their teeth together during CT scans, and no occlusal interference was detected when the maxillae were overlaid, the postoperative mandible was superimposed on the preoperative mandible in the physiological state. As revealed in this

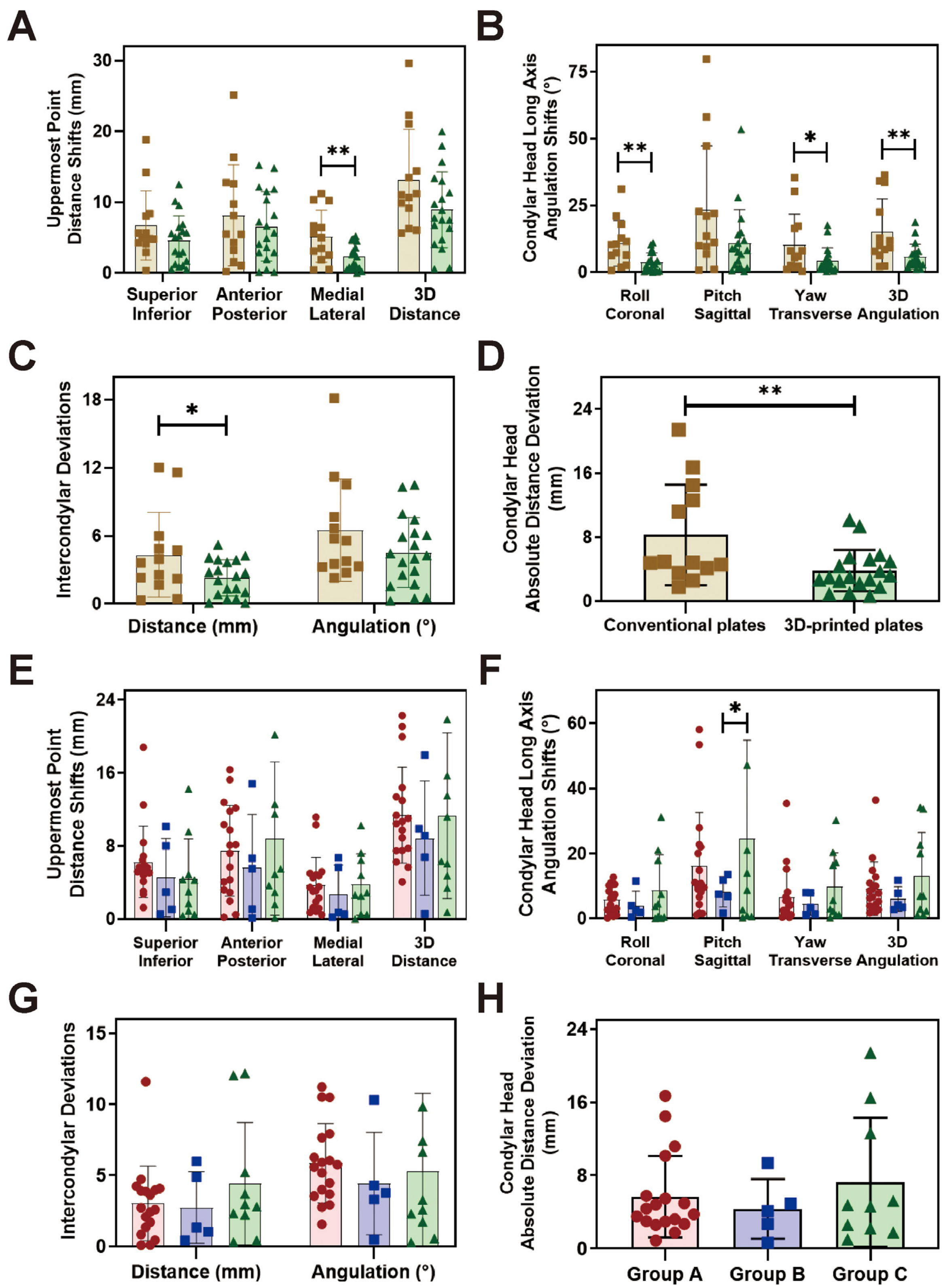

Fig. 5. Spatial accuracy, or absolute deviations of the TMJ after oncological mandibular reconstruction. Images (A) to (D) show the absolute deviations of the TMJ between the study group and control group: control group (brown squares), conventional surgical plates; study group (green triangles), 3D-printed patient-specific surgical plates. Images (E) to (H) show the absolute deviations of the TMJ according to the preservation or removal of the condyle and ramus: group A (red circles), with condyle, with ramus; group B (blue squares), with condyle, without ramus; group C (green triangles), without condyle, without ramus. Significant differences: $^{*}P < 0.05$, $^{**}P < 0.01$ (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Please cite this article in press as: Yang WF, et al. Spatial deviations of the temporomandibular joint after oncological mandibular reconstruction, *Int J Oral Maxillofac Surg* (2021), https://doi.org/10.1016/j.ijom.2021.02.033

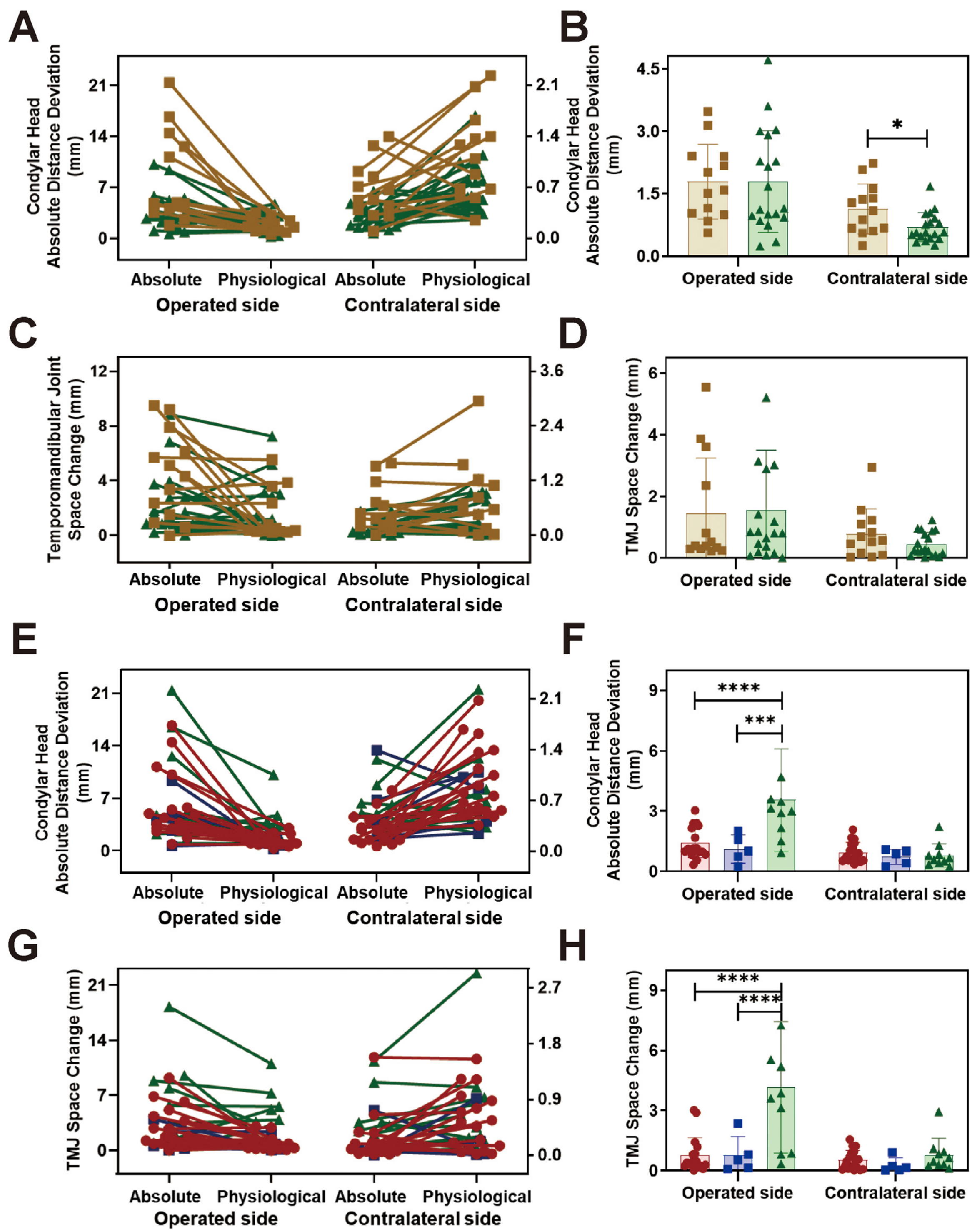

Fig. 6. Physiological deviations of the TMJ after oncological mandibular reconstruction. Images (A) to (D) show the physiological deviations of the TMJ between the study group and control group: control group (brown squares), conventional surgical plates; study group (green triangles), 3D-printed patient-specific surgical plates. Images (E) to (H) show the physiological deviations of the TMJ according to the preservation or removal of the condyle and ramus: group A (red circles), with condyle, with ramus; group B (blue squares), with condyle, without ramus; group C (green triangles), without condyle, without ramus. For images A, C, E, and G, 'absolute' is the spatial accuracy, or absolute deviations of the TMJ measured using algorithm 1; 'physiological' is the physiological deviations of the TMJ measured using algorithm 2. Significant differences: *$P <$ 0.05, **$P < 0.01$, ***$P < 0.001$, ****$P < 0.0001$ (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

study, unilateral mandibular reconstruction affected the physiological position of the whole mandible, including the contralateral TMJ and occlusion, which is in line with the results of some preclinical studies[23–25].

Some data outliers were noticed in the study patients, especially among those with both the condyle and ramus resected. In patients with severe TMJ deviations, besides the abnormal position of the condyle and joint space, patients might also suffer from malocclusion and chewing disabilities[4,5]. This study provides evidence that for better postoperative rehabilitation, more attention should be paid to the possible preservation of the condylar head[1,3], in order to improve the initial stability and minimize physiological deviations of the TMJ[1,3,9,10,26]. The study results are consistent with those of a recent study by Goormans et al.[10]. They included 18 patients in whom the condyle was preserved, and the reconstruction accuracy was better than in the six patients who had their condyles resected[10].

Compared to the whole mandible, TMJ deviations cause more significant functional and aesthetic sequelae[10]. The benefits of CAS and patient-specific surgical plates should be highlighted to enhance the overall accuracy of reconstruction, thereby ensuring the predictability, reproducibility, and quality control of mandibular reconstruction in different cohorts and centres[18,19]. However, the direct relationship between quantitative accuracy and clinical outcomes is far from established. There is no knowledge of the minimal clinical important difference (MCID) in mandibular reconstruction due to the relative recency and lack of studies in this field[6,10,19]. The present quantitative study may therefore provide a reference for future studies to define the role of accuracy in occlusion, aesthetics, and functional movements[27].

A few limitations of this study should be considered in order to better interpret the results. First, although the study included a large cohort of patients who underwent CAS, the sample size was not large enough for compelling subgroup analyses. Second, it is important to instruct the patient to bite their teeth together during the CT scan to maintain a stable closed mouth position under physiological conditions, but not necessarily at maximum intercuspation, especially in the postoperative stage. However, for edentulous patients, we recommend taking CT scans in the physiological rest position, which is relatively repeatable and should be further confirmed in patients who have undergone reconstruction. Third, the short-term postoperative CT was included for comparison, thus the focus was mainly on the surgical outcomes. The role of long-term condylar remodelling and adaptation was neglected, which should be investigated further in future research.

In conclusion, 3D-printed patient-specific surgical plates improved the spatial accuracy of the TMJ after oncological mandibular reconstruction. Moreover, a new algorithm was defined to study the physiological deviations by superimposing the preoperative and postoperative mandibles based on the maxilla. In the physiological state, the impact on the contralateral condyle was smaller in the 3D-printed plate group. TMJ deviations were mainly affected by the preservation of the condyle. The removal of both the condyle and ramus resulted in more severe spatial interference of the TMJ.

Funding

The study was supported by the Health and Medical Research Fund (Project Number05161626), Food and Health Bureau, Hong Kong; Guangdong Science and Technology Department (Project Number2019A050516001).

Competing interests

The authors declare that there are no conflicts of interest.

Ethical approval

Ethical approval for this study was granted by the Institutional Review Board of the University of Hong Kong/Hospital Authority Hong Kong West Cluster (UW 16-315). All procedures were executed strictly according to the tenets of the Declaration of Helsinki.

Patient consent

Patient written consent was obtained routinely.

References

1. Wax MK, Winslow CP, Hansen J, MacKenzie D, Cohen J, Andersen P, Albert T. A retrospective analysis of temporomandibular joint reconstruction with free fibula microvascular flap. *Laryngoscope* 2000;**110**:977–81.
2. Brown JS, Barry C, Ho M, Shaw R. A new classification for mandibular defects after oncological resection. *Lancet Oncol* 2016;**17**:e23–30.
3. Nahabedian MY, Tufaro A, Manson PN. Improved mandible function after hemimandibulectomy, condylar head preservation, and vascularized fibular reconstruction. *Ann Plast Surg* 2001;**46**:506–10.
4. Engroff SL. Fibula flap reconstruction of the condyle in disarticulation resections of the mandible: a case report and review of the technique. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2005;**100**:661–5.
5. Carlson ER. Disarticulation resections of the mandible: a prospective review of 16 cases. *J Oral Maxillofac Surg* 2002;**60**:176–81.
6. Powcharoen W, Yang WF, Yan Li K, Zhu W, Su YX. Computer-assisted versus conventional freehand mandibular reconstruction with fibula free flap: a systematic review and meta-analysis. *Plast Reconstr Surg* 2019;**144**:1417–28.
7. Schiffman E, Ohrbach R, Truelove E, Look J, Anderson G, Goulet JP, List T, Svensson P, Gonzalez Y, Lobbezoo F, Michelotti A, Brooks SL, Ceusters W, Drangsholt M, Ettlin D, Gaul C, Goldberg LJ, Haythornthwaite JA, Hollender L, Jensen R, John MT, De Laat A, de Leeuw R, Maixner W, van der Meulen M, Murray GM, Nixdorf DR, Palla S, Petersson A, Pionchon P, Smith B, Visscher CM, Zakrzewska J, Dworkin SF, I. a. f. D. R. International Rdc/Tmd Consortium Network. I. A. f. t. S. o. P. Orofacial Pain Special Interest Group. Diagnostic Criteria for Temporomandibular Disorders (DC/TMD) for Clinical and Research Applications: recommendations of the International RDC/TMD Consortium Network* and Orofacial Pain Special Interest Group†. *J Oral Facial Pain Headache* 2014;**28**:6–27.
8. Sawh-Martinez R, Parsaei Y, Wu R, Lin A, Metzler P, DeSesa C, Steinbacher DM. Improved temporomandibular joint position after 3-dimensional planned mandibular reconstruction. *J Oral Maxillofac Surg* 2017;**75**:197–206.
9. Wang L, Liu K, Shao Z, Shang ZJ. Management of the condyle following the resection of tumours of the mandible. *Int J Oral Maxillofac Surg* 2017;**46**:1252–6.
10. Goormans F, Sun Y, Bila M, Schoenaers J, Geusens J, Lubbers HT, Coucke W, Politis C. Accuracy of computer-assisted mandibular reconstructions with free fibula flap: results of a single-center series. *Oral Oncol* 2019;**97**:69–75.
11. Zheng GS, Su YX, Liao GQ, Chen ZF, Wang L, Jiao PF, Liu HC, Zhong YQ, Zhang TH, Liang YJ. Mandible reconstruction assisted by preoperative virtual surgical simulation. *Oral Surg Oral Med Oral Pathol Oral Radiol* 2012;**113**:604–11.
12. Zheng GS, Su YX, Liao GQ, Liu HC, Zhang SE, Liang LZ. Mandibular reconstruction assisted by preoperative simulation and accurate transferring templates: preliminary report of clinical application. *J Oral Maxillofac Surg* 2013;**71**:1613–8.

13. Yang WF, Powcharoen W, Su YX. Computer-assisted surgery increases efficiency of mandibular reconstruction with fibula free flap. *Plast Reconstr Surg* 2020;**146**(5):687e–8e.
14. Yang WF, Choi WS, Leung YY, Curtin JP, Du R, Zhang CY, Chen XS, Su YX. Three-dimensional printing of patient-specific surgical plates in head and neck reconstruction: a prospective pilot study. *Oral Oncol* 2018;**78**:31–6.
15. Wang X, Xu S, Zhou S, Xu W, Leary M, Choong P, Qian M, Brandt M, Xie YM. Topological design and additive manufacturing of porous metals for bone scaffolds and orthopaedic implants: a review. *Biomaterials* 2016;**83**:127–41.
16. Yang WF, Choi WS, Zhu WY, Su YX. ‘‘One-piece’’ patient-specific reconstruction plate for double-barrel fibula-based mandibular reconstruction. *Int J Oral Maxillofac Surg* 2020;**49**:1016–9.
17. Yang WF, Zhang CY, Choi WS, Zhu WY, Li DTS, Chen XS, Du R, Su YX. A novel ‘surgeon-dominated’ approach to the design of 3D-printed patient-specific surgical plates in mandibular reconstruction: a proof-of-concept study. *Int J Oral Maxillofac Surg* 2020;**49**:13–21.
18. Yang WF, Su YX. ASO Author Reflections: Accuracy of maxillary and mandibular reconstruction enhanced by advances in technology. *Ann Surg Oncol* 2020;**27**(Suppl 3):787–8.
19. Yang WF, Choi WS, Wong MC, Powcharoen W, Zhu WY, Tsoi JK, Chow M, Kwok KW, Su YX. Three-dimensionally printed patient-specific surgical plates increase accuracy of oncologic head and neck reconstruction versus conventional surgical plates: a comparative study. *Ann Surg Oncol* 2021;**28**(1):363–75.
20. van Baar GJC, Forouzanfar T, Liberton N, Winters HAH, Leusink FKJ. Accuracy of computer-assisted surgery in mandibular reconstruction: a systematic review. *Oral Oncol* 2018;**84**:52–60.
21. Roser SM, Ramachandra S, Blair H, Grist W, Carlson GW, Christensen AM, Weimer KA, Steed MB. The accuracy of virtual surgical planning in free fibula mandibular reconstruction: comparison of planned and final results. *J Oral Maxillofac Surg* 2010;**68**:2824–32.
22. Tang NSJ, Ahmadi I, Ramakrishnan A. Virtual surgical planning in fibula free flap head and neck reconstruction: a systematic review and meta-analysis. *J Plast Reconstr Aesthet Surg* 2019;**72**:1465–77.
23. Perez Del Palomar A, Doblare M. Finite element analysis of the temporomandibular joint during lateral excursions of the mandible. *J Biomech* 2006;**39**:2153–63.
24. Xie Q, Yang C, He D, Cai X, Ma Z, Shen Y, Abdelrehem A. Will unilateral temporomandibular joint anterior disc displacement in teenagers lead to asymmetry of condyle and mandible? A longitudinal study. *J Craniomaxillofac Surg* 2016;**44**:590–6.
25. Kofod T, Cattaneo PM, Melsen B. Three-dimensional finite element analysis of the mandible and temporomandibular joint on simulated occlusal forces before and after vertical ramus elongation by distraction osteogenesis. *J Craniofac Surg* 2005;**16**:421–9.
26. Mercuri LG, Edibam NR, Giobbie-Hurder A. Fourteen-year follow-up of a patient-fitted total temporomandibular joint reconstruction system. *J Oral Maxillofac Surg* 2007;**65**:1140–8.
27. Xiao Y, Liang Y, Yang L, Yang W, Liao G. Long-term quality of life in patients with maxillofacial malignancies who have undergone craniofacial resection: a cross-sectional survivorship study. *J Oral Maxillofac Surg* 2019;**77**:2573–83.

Address:
Yu-xiong Su
Oral and Maxillofacial Surgery
Faculty of Dentistry
The University of Hong Kong
Prince Philip Dental Hospital
34 Hospital Rd
Sai Ying Pun
Hong Kong SAR
China
Tel.: +852 28590267; Fax: 28575570
E-mail: richsu@hku.hk