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Registration methods for surgical navigation of the mandible: a systematic review

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Abstract. Image-to-patient registration in navigated mandibular surgery is complex due to the mobile nature of the mandible compared with other craniofacial bones. As a result, surgical navigation is rarely employed in the mandibular region. This systematic review provides an overview of the different registration methods that are used for surgical navigation of the mandible. A systematic search was performed in the MEDLINE Ovid, Scopus, and Embase databases on March 25, 2021. Search terms included synonyms for mandibular surgery, surgical navigation, and registration methods. Articles about navigated mandibular surgery, where the registration method was explicitly mentioned, were included. The database search yielded a total of 2952 articles, from which 81 articles remained for analysis. Four main registration methods were identified: point registration, surface registration, hybrid registration, and computer vision-based registration. The mobility of the mandible is accounted for by either keeping the mandible in a fixed position during preoperative imaging and surgery, or by tracking the mandibular movements. Although different registration methods are available for navigated mandibular surgery, there is always a trade-off between accuracy, registration time, usability, and invasiveness. Future studies should focus on testing the different methods in larger patient studies and should report the registration accuracy.

Key words: jaw surgery; mandible; surgical navigation systems; surgical navigation; computer-assisted surgery; maxillofacial surgery.

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The mandible plays an important role in mastication, speech, and swallowing function and represents the contour of the lower third of the face. Losses of mandibular continuity can result in limited range of motion, malocclusion, and proprioceptive problems. Therefore, an important aim during surgery of the mandible is to maintain or restore its shape and function.

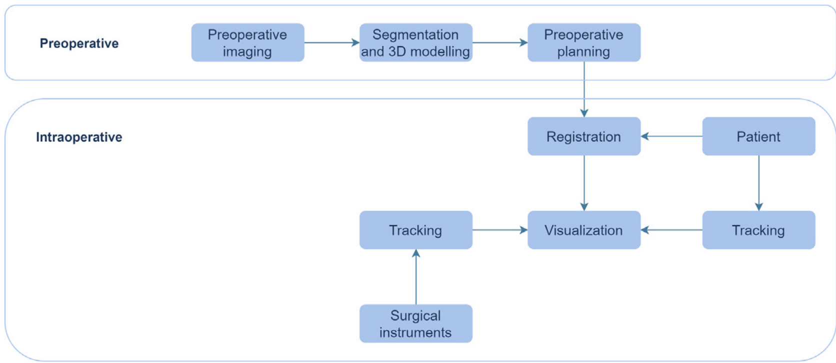

Fig. 1. Flowchart of the steps of surgical navigation.

Computer-assisted surgery (CAS) techniques can be applied to enhance the surgeon's orientation within the surgical field and provide intraoperative guidance[1].

In CAS, a virtual three-dimensional (3D) model of the mandible is constructed from a computed tomography (CT) scan. A preoperative plan is then made based on this model. Often, the preoperative plan is translated to the patient in the operating room (OR) through the use of 3D-printed patient-specific cutting guides[2]. However, these cutting guides are not ideal: the preparation time can take up to several weeks before surgery, the guides are costly to produce, and there is no possibility to adjust the surgical plan shortly before or during surgery (e.g. in oncological surgery when tumour growth has occurred between the preoperative planning and the actual surgery)[2,3]. As an alternative to cutting guides, surgical navigation can be used to translate the preoperative plan to the patient in the OR.

Surgical navigation provides real-time visualization of the position and orientation of surgical instruments in relation to the patient's anatomy. Two main methods exist for tracking of the patient and surgical instruments: optical tracking and electromagnetic (EM) tracking. Optical methods use a camera system for tracking, while EM methods use a magnetic field, which induces currents in sensors on the surgical instruments and patient[4]. Accurate image-to-patient registration, i.e. registration of the preoperative imaging data with the intraoperative anatomy, is essential for these tracking systems to work[5,6]. For a complete overview of the steps of surgical navigation, see Fig. 1.

Surgical navigation has been used increasingly in oral and maxillofacial surgery over the last 20 years[7]. In standard registration procedures, a tracker is fixed onto the patient's cranium to measure head movements[4]. However, the mandible moves independently of the rest of the craniomaxillofacial skeleton, which acts as one solid structure. Consequently, registration of the mandible with the preoperative CT scan is complex[5,8]. As a result, navigation is not routinely applied in mandibular surgery in clinical practice. Moreover, studies researching the application of navigation in mandibular surgery have often used inconsistent quantification methods for the registration accuracy, or have not reported the registration method used and/or accuracy values at all[9–13].

The aim of this systematic review was to provide an overview of the different registration methods for navigated mandibular surgery. This overview could help surgeons and technicians to gain an insight into the available options, which could be useful when choosing a registration method for navigation in different applications of mandibular surgery. The main research question of this review was: Which registration methods are used for surgical navigation of the mandible? To answer this question, the following secondary research questions were addressed: For which applications of mandibular surgery is navigation employed? Which variants of navigation are used in mandibular surgery? How is the mobility of the mandible accounted for in the reported registration methods? What is the accuracy of the reported registration methods?

Methods

This systematic review is reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement[14]. Risk of bias was not applicable and, therefore, a bias assessment was not performed.

This review was not registered. The review protocol can be found in **Supplementary Material** File S1. No amendments to the protocol were made during the review process.

Database search

A systematic literature search was conducted using the MEDLINE Ovid (Ovid MEDLINE ALL resource), Scopus, and Embase databases on March 25, 2021. The search queries were built using both free terms and indexed terms for mandibular surgery, surgical navigation, and registration methods. The full search queries are provided in **Supplementary Material** File S2.

Study selection

Identified articles were de-duplicated in Endnote X9 (Clarivate Analytics, Philadelphia, PA, United States) using the method described by Bramer et al.[15], and the remaining references were screened manually for duplicates. References indexed as 'conference abstracts' in the databases were removed. Afterwards, the Endnote file was loaded into Rayyan for title and abstract assessment[16]. Two researchers (FG and SBK) independently assessed the articles based on title and abstract. In the case of disagreement, the researchers discussed the article until a consensus was reached. The inclusion criteria used for title and abstract screening were as follows: (1) it is clear from the title or abstract that the study is about mandibular, orthognathic, or maxillofacial surgery; (2) at least one navigation-related term, such as 'navigation', 'augmented reality', 'guided surgery', 'computer-assisted surgery', 'image-guided surgery', 'registration', or 'tracking', is mentioned in the title or abstract. Articles about dental implant navigation were excluded, as were expert views, reviews, clinical guidelines, and editorial letters.

The full-text assessment was performed by FG, following which the inclusion or exclusion of articles was checked by SBK. The following inclusion criteria were applied for full-text assessment: (1) the article is about surgical navigation of the mandible; (2) the registration method, used for image-to-patient registration, is reported; (3) in articles that report surgical navigation in areas additional to the mandible, the registration method used for the mandible is explicitly mentioned. Phantom studies, animal studies, cadaver studies, technical reports, case reports, case series, cohort studies, and clinical trials were included. Articles were excluded for the following reasons: (1) the article is not about surgical navigation of the mandible;

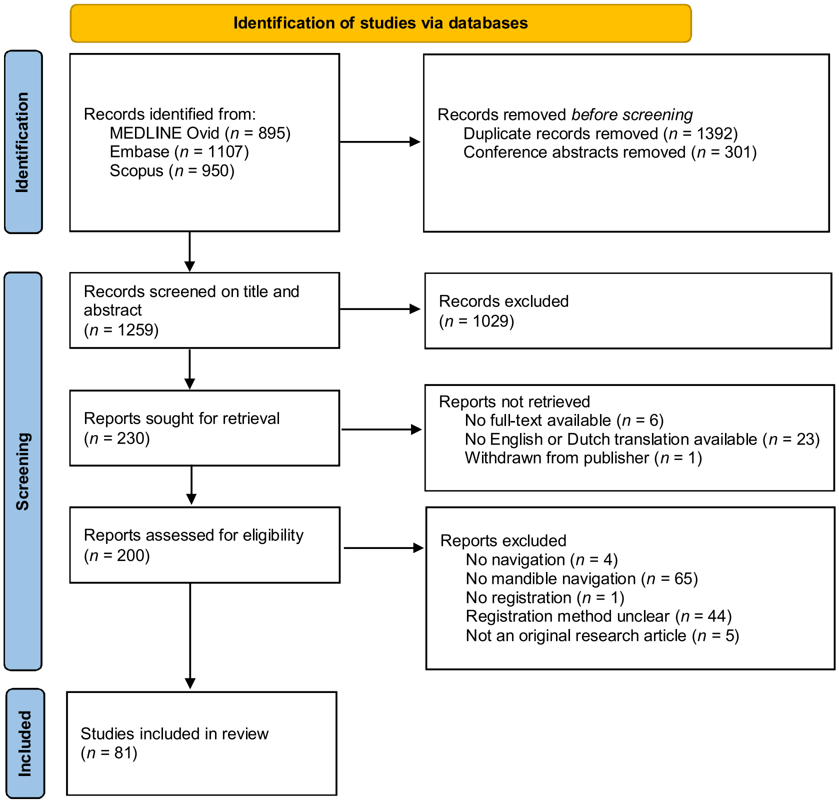

Fig. 2. PRISMA flowchart of the literature search and article selection process.

(2) the registration method is not reported, or it is not reported how the researchers accounted for mandibular mobility; (3) in articles that describe surgical navigation in areas additional to the mandible, the registration method used for the mandible is not explicitly mentioned; (4) no full-text is available; (5) no Dutch or English translation is available.

Data extraction

The data extraction was performed by FG using a predefined data extraction sheet created in Excel (**Supplementary Material** File S3). Baseline features such as study focus, surgery type, and number of subjects were recorded for each article. Moreover, the navigated procedure, mandibular mobility, tracking method, (commercial) navigation system used, registration method, registration time, registration markers, marker location, registration accuracy metrics, and surgical outcome metrics were extracted. In addition, a short explanation of the registration procedure was written for each article.

Results

Search results

The search yielded a total of 2952 articles, of which 1259 remained after duplicate and conference abstract removal (Fig. 2). During title and abstract screening, 1029 articles were excluded. The full-text version of six articles could not be retrieved, one article was withdrawn from the publisher, and 23 full-text articles were excluded based on language, leaving 200 articles eligible for assessment. During the full-text assessment, 119 articles were excluded based on the predefined exclusion criteria (Fig. 2). Some articles described the use of surgical navigation in the mandibular region and seemed to meet the inclusion criteria[17–30]. However, these articles were excluded because the authors did not report how the mandibular mobility was accounted for during the registration. Finally, 81 articles were included for analysis. Seven types of study were identified in the articles: one study with a healthy volunteer[31], two simulation studies[32,33], 24 case reports (one or two patients)[5,12,13,34–54], 24 patient studies (three or more patients)[1,2,55–76], 19 phantom studies[3,6,8,77–92], three (animal) cadaver studies[93–95], and three animal studies[96–98]. Five articles used a combination of study types: a cadaver and patient study[99], a phantom and patient study[100], a cadaver and animal study[101], a phantom and volunteer study[102], and a combined phantom, volunteer, and case study[103].

Applications of surgical navigation

Navigation is currently being utilized in different fields of mandibular surgery. In oncological surgery, navigation is used to guide tumour resection and/or bone reconstruction[1,5,43,45,49,53,59,62,65,67,68,71,72,99]. Often, the osteotomies and bone reconstruction are planned preoperatively based on CT and magnetic resonance imaging (MRI) data. During surgery, navigation is used to determine the location of the osteotomy in the resection phase and the positioning of bone segments in the reconstruction phase.

In orthognathic surgery, small misalignments can lead to aesthetic and functional problems[9]. Therefore, surgical navigation is used to guide osteotomies and to reposition bone segments. Orthognathic procedures that use navigational technology include bimaxillary surgery[37,38,92], sagittal split ramus osteotomy[100], high oblique sagittal split osteotomy[56], intraoral vertical ramus osteotomy[81], distraction osteogenesis[55,57,66,75,83,84,95–97], genioplasty[12,54,73,75], gonioplasty[73], condyle resection[12,48,58,70], mandibular angle reduction surgery[69,74–76,79,82], condyle repositioning after Le Fort I osteotomy[63], and temporomandibular joint replacement[64].

In foreign body removal surgery of the mandible or pterygomandibular space, removal is complex when the foreign body is close to critical structures, such as the inferior alveolar nerve[13,34–36,39–41,43,44,46,50,62]. In these cases, surgical navigation is used to determine the exact location of the foreign body and to guide removal, while reducing the risk of secondary injury caused by nerve or blood vessel damage.

Finally navigation is used for cyst removal[47,51], guidance during osteosynthesis[78], removal of osteosynthesis material[60], and secondary mandibular reconstruction[52].

Variants of surgical navigation

Three different variants of surgical navigation were used in the included articles: traditional navigation, augmented reality-based navigation, and robotic navigation.

Table 1. Overview of different image-to-patient registration methods and reported accuracy ex vivo (phantom studies) and in vivo (patient, healthy volunteer, animal, and cadaver studies), and the total number of patients included in the articles for each registration method. The minimum and maximum mean values reported in the articles are reported in this table, together with the corresponding standard deviation. If multiple experiments were performed in an article, for example experiments with different splints or numbers of registration points, the best results are reported in this table. The TRE values only include the TREs measured with target points on the mandible.

Registration method	Markers	Tracking method	Mandibular mobility	Registration time	Accuracy ex vivo Mean (SD) (mm)	Accuracy in vivo Mean (SD) (mm)	Total number of patients in articles	References
Point registration	Anatomical	EM	Mobile	NR	TRE: 2.10 (0.88)	NR	5	56,94,101
		Optic	Fixed	NR	NR	FRE: <1.00 TRE: 0.20–0.50	13	65,93
			Mobile	NR	FRE: 1.50[a] TRE: 1.70–1.93	FRE: 0.70 (0.30)–0.80	12	3,34,63,81,90,99,100
	Fiducial markers on bone	EM	Mobile	2–3 min	FRE: 0.40 (0.30)[b]–0.73[b] TRE: 1.28[c]–2.62[c]	FRE: 1.20 (1.10)[b] TRE: 2.60 (1.50)[c]–3.20 (1.10)[c]	11	2,47,89
		Optic	Fixed	12 min	NR	FRE: 0.73 (0.14)–1.04 TRE: ≤1.00	69	36,58,68,69,78,97
			Mobile	NR	FRE: <1.00 TRE: 0.86–1.76	TRE: ≤1.00	12	48,54,61,70,80,81,87,88,96,100
	Fiducial markers on splint	EM	Mobile	NR	FRE: 0.36[b] TRE: 0.83[c]	TRE: 1.90[b]	1	6,38
		Optic	Fixed	3–10 min	FRE: <1.00 TRE: 0.50–1.47[b]	FRE: 0.31–1.00 TRE: 0.40–0.94[b]	31	8,12,37,40,41,44,51,62,64,73,77,83,92
			Mobile	NR	TRE: 0.98	TRE: <0.50	9	5,50,100
Surface registration	Skin surface contour	Optic	Fixed	4–20 min	NR	FRE: <1.00 TRE: 1.90–2.10	51	39,43,45,51–53,59,60,67,71,72,95
			Mobile	NR	NR	FRE: <0.70	4	1
	Bone surface	Optic	Mobile	NR	NR	TRE: 1.00	3	42,49
Hybrid registration		EM	Fixed	10 min	NR	NR	3	13,46,47
		Optic	Fixed	NR	NR	FRE: <1.00 TRE: 0.10–4.00	16	5,35,55,57
			Mobile	NR	FRE: <1.00	NR	0	84
Computer vision-based registration	Contour matching	Optic	Mobile	3 s	TRE: 0.42–0.89[b] Overlay error: Image registration: 0.34–0.75 Image overlay: 0.23–1.01	TRE: 0.30[b]	1	31–33,85,86,91,102,103
	Marker detection	Optic	Mobile	NR	TRE: 0.95 (0.14)–1.89 (0.51)	NR	76	66,74–76,79,82,98

EM, electromagnetic; FRE, fiducial registration error; NR, not reported; SD, standard deviation; TRE, target registration error.

[a] Median error.

[b] Root mean square error.

[c] Euclidean distance.

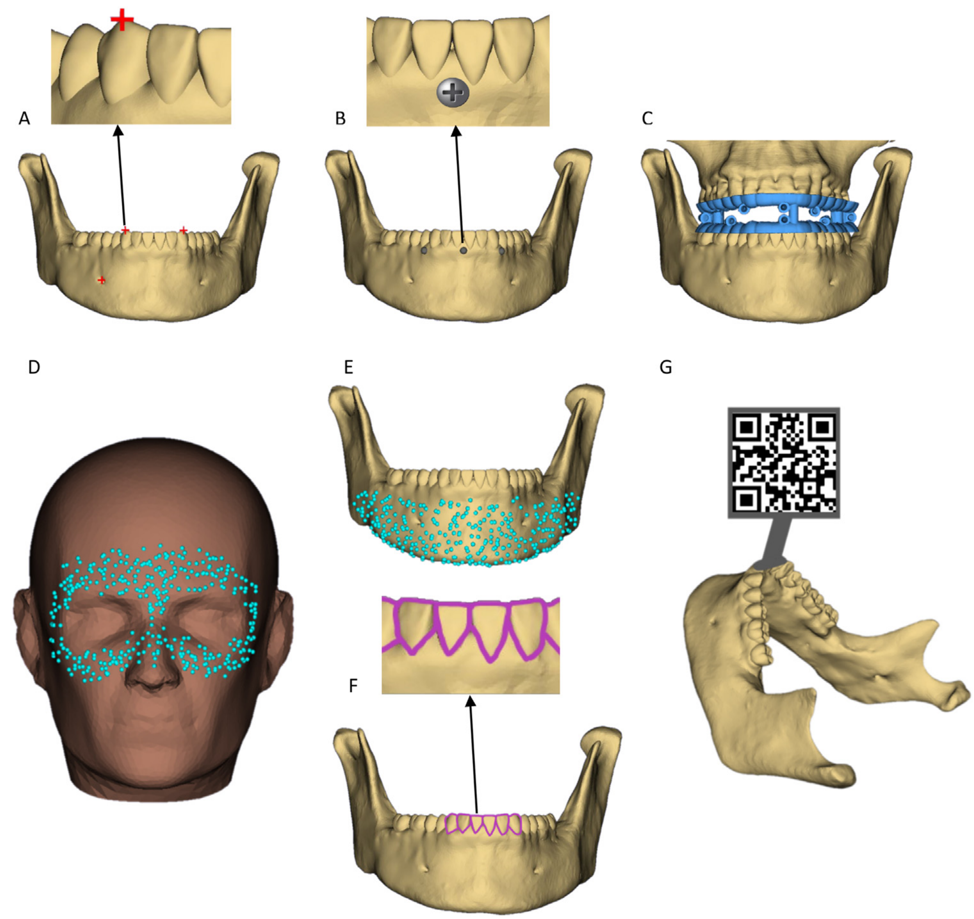

Fig. 3. Visualization of the different image-to-patient registration methods for surgical navigation of the mandible: (A) point registration using anatomical landmarks; (B) point registration using implanted bone screws; (C) point registration using notches on a dental splint; (D) surface registration using points on the facial skin contour; (E) surface registration using points on the mandibular bone surface; (F) computer vision-based registration with automatic teeth contour detection; (G) computer vision-based registration with automatic marker detection.

Most articles reported the use of traditional navigation surgery, where surgical instruments and the patient's anatomy are visualized on a monitor in the OR[1–3,5,6,8,12,13,34–48,50–65,67–73,77,78,80,81,83,84,87,89,90,94–97,99–101]. The surgeon looks at the monitor for guidance during surgery. However, the need to observe the monitor negatively affects the surgeon's eye–hand coordination[88]. To tackle this problem, together with recent progress in hardware, augmented reality (AR) has emerged as a new technology to guide the surgeon during complex operative procedures[31–33,49,66,74–76,79,82,88,91,98,102,103]. In AR, computer-generated 3D images are superimposed onto the surgical area. With the co-display of the virtual plan and the real-time situation, the surgeon is able to utilize and interact with the components of both worlds simultaneously[31].

Navigation can also be performed robotically[82,85,86,92,93]. Surgeries of the mandible, especially mandible reconstruction surgery, can last 8 hours or even longer[85]. Furthermore, surgeons often operate through the patient's mouth cavity resulting in a limited workspace[86]. Robot arms can help the surgeon to maintain the correct position during surgical procedures and facilitate working in a narrow area[85]. Navigated robot arms can assist surgeons in various tasks such as drilling, sawing, and positioning of bone segments according to a preoperative plan[85,92,93]. Currently, research is being conducted with autonomous robot systems, where the robot is the main operator of the surgery instead of being merely the assistant of the surgeon[85]. In these systems, a camera works as the surgeon's eyes, the robot works as the surgeon's hands, and a tracking system connects them working as the surgeon's brain[86].

Mandibular mobility problems

The mandible moves independently from the other craniofacial bones, which makes image-to-patient registration difficult[5]. The literature revealed that two strategies are currently being employed to tackle this 'mobility' problem: either keeping the mandible in the same position during preoperative imaging and surgery (41 articles), or attaching a dynamic reference frame (DRF) to the mandible that tracks the mandibular movements during surgery (41 articles)[34,39]. For an overview of which strategy was used in specific studies, see Table 1.

In the first approach, the mandible is fixed in a specific position during preoperative imaging and during surgery; the mandible is kept occluded against the maxilla, either with a dental splint or by intermaxillary fixation with wires. Since the mandible now acts like a solid structure with the maxilla, common registration methods that are used in craniofacial surgery can be applied.

In the second approach, the mandible can move freely during surgery. By attaching a DRF to the mandible, for example a DRF with reflecting spheres or an EM tracked sensor, its movements are tracked. This method enables the surgeon to move the mandible during surgery.

Registration methods

Different methods can be used for image-to-patient registration. In the included studies, four main registration methods were used: point registration, surface registration, hybrid registration, and computer vision-based registration. In the next paragraphs, these methods are explained along with their accuracy.

Registration accuracy

Registration accuracy is usually assessed in terms of the 'fiducial registration error' (FRE) or 'target registration error' (TRE) (**Supplementary Material** Fig. S1)[104].

The FRE, or 'image-to-tracker' error, is a measure of how closely the preoperative CT scan is registered to the patient[3,89,99]. The FRE is defined as the distance between the registration points on the patient and the virtual registration points on the preoperative plan, after registration. The FRE is often calculated by the navigation system software. According to Maurer et al.[105], this distance (between *n* registration points) can be calculated as the root mean square error (RMSE):

$$FRE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(x_{patient,n}-x_{ct,n})^2+(y_{patient,n}-y_{ct,n})^2+(z_{patient,n}-z_{ct,n})^2}$$

The TRE is a measure of how closely the location of virtual predefined target points (other than the registration points) correspond to their actual intraoperative location after registration[94,104]. Usually, the TRE is measured with a tracked probe by pinpointing different landmarks on the mandible and comparing them to their location in the preoperative plan[81,94,100]. For every target point (n), the TRE can be calculated as the Euclidean distance between the location of the point on the patient and the point on the preoperative plan[105]:

$$TRE_n = \sqrt{(x_{patient,n}-x_{ct,n})^2+(y_{patient,n}-y_{ct,n})^2+(z_{patient,n}-z_{ct,n})^2}$$

The overall TRE (i.e. for multiple target points in an area of interest) can be calculated as the RMSE or the mean of the individual TREs[2,6,91].

Point registration

In point registration, or point-to-point registration, a minimum of three points is required to register the preoperative plan with the patient[80]. Before surgery, specific points on the preoperative plan are chosen and their coordinates in 3D space are saved. During surgery, the surgeon touches these predefined points on the patient with a tracked probe. The coordinates of the virtual points are then matched to the coordinates of the actual points to complete the registration process[6]. Both anatomical landmarks and artificial markers can be used for point registration.

In the former method, registration is performed with anatomical landmarks that are clearly visible on both the preoperative imaging data and the patient during surgery. Often, tooth cusps or the mental or mandibular foramina are used as landmarks (Fig. 3A)[3,63,81,90]. Reported FREs and TREs ranged from 0 to 1.50 mm and from 0.20 mm to 2.10 mm, respectively, depending on the tracking method, ex vivo or in vivo usage, and the mandibular mobility (Table 1).

Alternatively, artificial markers can be attached to the patient for registration purposes, for example bone screws (Fig. 3B). Alveolar bone screws can be placed in the outpatient clinic before surgery[48,58,61,68,70]. Next, preoperative CT scanning is performed and the locations of the screws are saved in the preoperative plan. During surgery, the screws are touched with a tracked probe to obtain their intraoperative positions and registration is performed automatically by the navigation software. Another way to use bone screws is by implanting them during surgery instead of in the outpatient clinic[2]. The exact location of the screws can be determined by performing a cone beam CT scan (CBCT) during surgery. Reported FREs and TREs with the use of artificial bone markers ranged from 0 to 1.20 mm and from 0 to 3.20 mm, respectively (Table 1).

A third way of using artificial markers is by incorporating them in a dental splint (Fig. 3C). Markers such as gutta-percha markers, notches, or screws can be attached to a splint preoperatively, and the preoperative CT scan is acquired while the patient is wearing the splint[6,62,77]. Registration is performed in the same way as with the artificial bone markers described above. Different types of splints can be used, either maxillomandibular splints that fixate the mandible against the maxilla or splints that are only attached to the mandible, enabling mandibular movements during surgery[40,100]. Moreover, maxillomandibular splints can put the mandible in an 'open' or in an 'occluded' position against the maxilla. With open splints, the polygon between the markers is often bigger than with closed splints, resulting in a better registration[8]. Reported FREs and TREs for using splint markers ranged from 0 to 1.00 mm and from 0 to 1.90 mm, respectively (Table 1).

Surface registration

Surface registration is a marker-free registration method, using a series of points on anatomical surfaces, such as the facial skin contour (Fig. 3D). Either an infrared laser surface scanner or a tracked probe can be used to capture the surface contours[43,46]. Mostly, the periorbital and frontal facial areas are used for surface scanning[52,53]. Reported FREs were <1.00 mm and TREs ranged from 1.90 mm to 2.10 mm (Table 1).

Another potential area to apply surface registration is the mandibular bone surface itself, after removal of the soft tissue (Fig. 3E). In cases with facial swelling, trauma, or incomplete imaging of the soft tissues, this can be an alternative to facial surface scanning[42]. Only two studies described the use of this method to perform registration. However, in the first study, the registration attempts failed due to an incongruence of the surfaces of the mandible[42]. The laser scanner used could only make a single scan and parts of the mandible were always covered with soft tissue. The other study used a tracked probe to sweep the surface of the mandible, resulting in a successful registration with a TRE of 1.00 mm (Table 1)[49].

Hybrid registration

Hybrid registration uses a combination of point registration and surface registration. Some studies started with point registration and used surface registration for optimization[5,55,57,84]. For example, Badiali et al.[55] used point registration with the aim of obtaining a TRE < 3.0 mm, and continued with surface registration to obtain a final TRE ≤ 0.5 mm. Other articles started with surface registration and used point registration for refinement[13,35,46,47]. For hybrid registration, the reported FREs were <1.00 mm and TREs ranged from 0.10 mm to 4.00 mm (Table 1).

Computer vision-based registration

In studies using augmented reality as the navigation method, computer vision-based registration methods were often used. These registration methods included automatic contour detection (marker-free) and automatic marker detection (marker-based).

Several articles used automatic contour detection methods to register the preoperative plan to the intraoperative anatomy (Fig. 3F)[31–33,85,86,91,102,103]. Preoperatively, a two-dimensional (2D) contour model, from the lower teeth or mandible, is constructed from 3D imaging data. During surgery, the contour model is automatically matched with real-time images, obtained by stereo cameras or a single monochrome or colour camera, and overlaid onto the surgical site[85]. The matching procedure is often based on a shape-based method for 2D–3D matching developed by Ulrich et al.[106], refined by an iterative closest point (ICP) algorithm[32,33,103]. In these articles, registration accuracy was reported in terms of TRE or overlay error, defined as the difference between the projected scene and actual scene[33]. The reported TREs ranged from 0.30 mm to 0.89 mm. The overlay error for image registration ranged from 0.34 mm to 0.75 mm and for image overlay from 0.23 mm to 1.01 mm (Table 1).

Another commonly used registration method in AR applications is registration by automatic marker detection (Fig. 3G)[66,74–76,79,82,98]. In this method, AR software is used for the recognition of specific patterns (often black squares or a QR code) on a marker plate using a single camera or stereo cameras. When the software recognizes the pattern, automatic registration is performed and the marker plate is tracked in real-time. The marker plate is fixed to a dental splint as a fulcrum in order to keep the mandible and the marker in a permanent relationship. The reported TREs ranged from 0.95 mm to 1.89 mm (Table 1).

Discussion

The mandible plays a vital role in various functions. Hence, it is important to maintain or restore its shape and function after surgery[1]. Surgical navigation can be used to enhance the surgeon's orientation within the surgical field and provide intraoperative guidance. To translate the preoperative plan to the intraoperative situation, accurate image-to-patient registration is vital[8]. However, due to the mobile nature of the mandible with regard to the other craniofacial bones, registration is complex[5,8]. As a result, surgical navigation is rarely used in the mandibular region in clinical practice. The aim of this systematic review was to provide an overview of the different registration methods that are used for navigated mandibular surgery.

In the studied articles, two different methods for accounting for the mandibular mobility were identified: either the mandible is kept in a fixed position or the mandible can move freely and its movements are tracked. Casap et al.[5] used both approaches in the same patient and concluded that tracking mandibular movements results in a more precise registration than fixing the mandible against the maxilla. This is due to the fact that fixation needs to eliminate every possible movement of the mandible, since even slight changes in mandible position negatively impact the navigation accuracy. Moreover, the ability to move the mandible is an advantage, as the surgical working field can be enlarged by changing the position of the mandible[5]. Especially in oncological surgery for tumours involving multiple structures in the oral cavity, this is preferred to enable good visibility and an accurate tumour resection.

Registration methods for navigated mandibular surgery can be divided into four main categories: point registration, surface registration, hybrid registration, and computer vision-based registration. Every method has its limitations and strengths; this should be kept in mind when choosing a specific method. There is always a trade-off between accuracy, registration time, usability, and invasiveness for the patient. For example, point registration with bone screws is often more accurate than with anatomical landmarks, since the latter method is user-dependent[81]. If a surgeon is asked to pinpoint the same anatomical landmark multiple times, the exact location varies slightly every time. In addition, in edentulous patients or in patients where the foramina are not visible during surgery, it can be difficult to find three anatomical landmarks[2]. However, implanting bone screws during the outpatient clinic is invasive for the patient and, therefore, usually not the first choice. Implanting bone screws during surgery is also not preferred, since a hybrid OR with a CBCT scanner is required to obtain the 'preoperative' imaging with screws so they can be used for registration[2]. This lengthens the OR time and leads to extra ionizing radiation for the patient. Surface registration using points on the facial skin is easier when compared to using the mandibular bone surface, because with the latter method, soft tissue attached to the bone needs to be removed first[42]. However, facial scanning results in a less accurate registration than bone matching. For hybrid registration, multiple time-consuming steps are required, which makes it a less user-friendly method. Registration with markers on dental splints is non-invasive[77], but splints are patient-specific, which requires separate fabrication for every single patient. Moreover, to enable accurate registration, the splints should fit perfectly onto the teeth. This demands skilled people and special equipment for fabrication[8,82]. Furthermore, splints cannot be used in edentulous patients or patients with tooth loosening[8,82]. The same applies for automatic teeth contour registration, although this is a quick and user-friendly method for surgeons. Another quick registration method is automatic marker detection. This method, however, requires complex and expensive software and is often unfavourable because of the bulky marker, which limits the surgical working space[85].

Apart from to the choice of registration method, users should also decide on which tracking method to use. EM tracking is often less accurate than optical tracking due to field distortions because of ferromagnetic materials in the vicinity of the EM field in the OR, such as the bed[56]. However, for optical tracking, a continuous line-of-sight between the optical camera and the tracked tools and tracked area is required, which limits the surgeon's movements and is, therefore, challenging in small working areas such as the oral cavity[2,94]. In addition, EM trackers are usually much smaller in size compared to optical trackers.

Although this review provides an overview of different registration methods, the results should be interpreted carefully for several reasons. First, the majority of the studied articles reported phantom studies or case reports. From the number of included articles ($N = 81$) it would seem that navigation is widely used in mandibular surgery. However, navigation was used in three or more patients in only 26 articles. This indicates that navigation in mandibular surgery is still under development.

Unfortunately, it was not possible to quantitatively compare the registration methods based on the reported accuracies. The majority of the articles described the registration method used but did not report registration accuracy in terms of FRE[5,8,37,38,51,54,55,57,60,77,80,81,94,100], TRE[1,3,32–35,39,59,62,64,66,68,69,73,74,76,83–86,88,89,98,99], or both[12,13,36,40,42–48,50,52,53,56,58,61,63,65,70–72,78,90,92,95,101]. Another essential point is the way in which the TRE is measured. In some studies the TRE was measured using anatomical landmarks[31,37,38,51,54,55,90,93,96,97], while in other studies the TRE was measured using artificial markers[6,8,75,77,79–82,87,91,94,102,103] or using a combination of the two[2,5,100]. Often, artificial markers yield a lower TRE as a result of more objective marker identification[2]. Furthermore, different formulae to calculate the FRE and TRE were used in the articles. Most articles reported the mean FRE and mean TRE, but some articles calculated the FRE or TRE in terms of the RMSE or Euclidean distance (Table 1). For these reasons, the reported accuracy of the registration methods described cannot be compared one-to-one. This should be borne in mind when interpreting the reported registration accuracy values.

This review does not report the surgical outcomes of the navigated procedures. Many studies reported the surgical outcomes in terms of 'image-to-image' error, surgical precision, osteotomy accuracy, or reconstruction accuracy[1,3,37,38,45,52,53,55,56,63–69,71–73,75,76,83,84,86–89,92,94–97,99–101]. To calculate these metrics, often a postoperative CT scan was registered with the preoperative plan, and cutting planes or landmark positions were compared. Until recently, there was no gold standard for reporting the accuracy of CAS in mandibular surgery[107]. Therefore, various distance and angular deviation metrics have been used, which makes it impossible to compare the different studies[108]. In addition, beneficial surgical outcomes are not solely the result of an accurate registration. Several other factors can influence the surgical outcome, such as the surgeon's eye–hand coordination and the sawing or drilling equipment used. For these reasons, it was decided not to include surgical outcomes in this review.

Given the high technological complexity that comes with surgical navigation of the mandible, it can be challenging to find an optimal balance between the usability, registration time, accuracy, and invasiveness of a registration method. Future studies should focus on developing registration methods with an optimal balance between these metrics. In addition, the existing registration methods should be compared within the same study to enable quantitative comparisons between the accuracies of the methods. Also, there is a need for studies testing the applicability of the registration methods in larger patient studies, since the majority of the included articles in this review reported phantom studies and case reports. In future studies, it is recommended that registration accuracy is reported in terms of both FRE and TRE. In the authors' opinion, the TRE of individual target points should be calculated as the Euclidean distance and the overall TRE of a specific area of interest should be calculated as the RMSE of the individual TREs, as large individual errors are penalized more severely in RMSE calculation compared to mean calculation.

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None.

Ethical approval

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Patient consent

Not applicable.

Data availability

The authors are willing to share the research data. The data extraction sheet can be found in the **Supplementary Material**.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ijom.2022.01.017.

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