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ORIGINAL ARTICLE

A hybrid registration method using the mandibular bone surface for electromagnetic navigation in mandibular surgery

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Abstract

Purpose To utilize navigated mandibular (reconstructive) surgery, accurate registration of the preoperative CT scan with the actual patient in the operating room (OR) is required. In this phantom study, the feasibility of a noninvasive hybrid registration method is assessed. This method consists of a point registration with anatomic landmarks for initialization and a surface registration using the bare mandibular bone surface for optimization.

Methods Three mandible phantoms with reference notches on two osteotomy planes were 3D printed. An electromagnetic tracking system in combination with 3D Slicer software was used for navigation. Different configurations, i.e., different surface point areas and number and configuration of surface points, were tested with a dentate phantom (A) in a metal-free environment. To simulate the intraoperative environment and different anatomies, the registration procedure was also performed with an OR bed using the dentate phantom and two (partially) edentulous phantoms with atypical anatomy (B and C). The accuracy of the registration was calculated using the notches on the osteotomy planes and was expressed as the target registration error (TRE). TRE values of less than 2.0 mm were considered as clinically acceptable.

Results In all experiments, the mean TRE was less than 2.0 mm. No differences were found using different surface point areas or number or configurations of surface points. Registration accuracy in the simulated intraoperative setting was—mean (SD)—0.96 (0.22), 0.93 (0.26), and 1.50 (0.28) mm for phantom A, phantom B, and phantom C.

Conclusion Hybrid registration is a noninvasive method that requires only a small area of the bare mandibular bone surface to obtain high accuracy in phantom setting. Future studies should test this method in clinical setting during actual surgery.

Keywords Surgical navigation · Electromagnetic tracking · Registration · Computer-assisted surgery · Mandible surgery · Mandibular reconstruction

Introduction

During mandibular reconstructive surgery, computer-assisted surgery (CAS) techniques are routinely applied [1]. Preoperatively, a 3D model of the mandible is constructed from a computed tomography (CT) scan. Next, the positions and orientations of the osteotomies are planned virtually to ensure adequate tumor margins and an accurate fit of the bone segments needed for reconstruction. During surgery, the virtual plan is translated to the patient using 3D printed patient-specific cutting guides [2, 3]. However, these cutting guides are not ideal. The most important shortcoming is their lack of adaptability: If the intraoperative situation is different than expected, the planning cannot be adapted. Moreover, the design and fabrication process of such cutting guides is costly and often takes several weeks. In the meantime, tumor

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progression can occur in which case the produced cutting guides cannot be used because the virtually planned margins will be inadequate [4, 5].

A possible solution to overcome these problems is to use universal, navigated cutting guides that can be adapted for any patient [6]. The preoperative planning is similar to the current workflow. However, during surgery, the cutting guides are positioned on the bone using surgical navigation. This enables the surgeon to change the virtual plan shortly before or even during surgery. To enable navigation, accurate alignment of the preoperative CT scan (including the virtual plan) with the patient in the operating room (OR) is required, i.e., image-to-patient registration [7].

Two main registration methods exist for navigated (maxillofacial) surgery: point registration and surface registration [8]. In point registration, at least three distinct points are required to register the preoperative plan with the patient [9]. The surgeon pinpoints these points on the patient with a tracked probe, and their coordinates are matched with the corresponding points on the CT scan. Both anatomic landmarks and artificial markers can be used as registration points. In neurosurgery, artificial markers implanted in the cranium are commonly used [10]. Surface registration is a marker-free method using a series of points on anatomical surfaces such as the facial skin contour. In surgery of the sinonasal cavity, the periorbital and frontal facial skin areas are often used for registration; the surgeon captures 200–300 surface points with an infrared laser surface scanner or a tracked probe which are registered with the 3D model [11, 12].

Although navigation is commonly used in maxillofacial surgery, its use in mandibular surgery is limited since the registration procedure is complex due to the mobile character of the mandible [7, 13]. During navigation, the mandible should either be kept in a fixed position or its movements should be tracked [13]. The first method is known to be prone to errors since even minor movements of the mandible decrease the navigation accuracy [7]. The latter method is currently being used for dental implant surgery [14–16]. These navigation systems use optical tracking with a large patient tracker that requires a continuous line-of-sight. This continuous line-of-sight, however, is difficult to guarantee during oncologic surgery with large tumors invading the oral cavity since the surgical working space is limited. In electromagnetic (EM) navigation, patient trackers are smaller and no line-of-sight is required. EM tracking is currently being researched by others for its use in orthognathic surgery [17, 18].

In two prior studies, our research group investigated EM-based navigation of the mandible using different point registration methods; registration with screws inserted in the alveolar bone or with notches on a dental splint [1, 4]. However, these registration methods were either invasive or required complex and time-consuming preoperative steps. In the current study, a simple, noninvasive registration method using a hybrid technique is proposed and evaluated, consisting of two phases: (1) point registration; performed for initialization by using anatomic landmarks on the mandible, i.e., teeth or mental foramen, and (2) surface registration; performed for optimization using the bare bone surface of the mandible after removal of soft tissue. Using phantom experiments, the feasibility of this hybrid registration technique for EM navigated surgery of the mandible was assessed. Various configurations were investigated to determine the optimal approach for accurate registration. Target registration error (TRE) values of < 2.0 mm were considered as clinically acceptable [19].

Methods

Phantoms

Three mandible phantoms (one dentate mandible, two (partially) edentulous mandibles with atypical anatomy based on CT scans from patients treated in our institute) were 3D printed using a Form3B printer using Clear V4 resin (Formlabs, Somerville, Massachusetts, USA). Reference notches were added at two intended osteotomy locations; for the dentate phantom two frequently occurring locations were chosen; for the edentulous phantoms, the actual intended osteotomy locations at time of surgery were used (Fig. 1). The notches were designed to fit an EM trackable probe (Northern Digital Inc., Waterloo, Ontario, Canada): The inner surfaces of the notches were cone shaped with a maximum diameter of 3.0 mm that equals the largest diameter of the probe. A CT scan was acquired for each phantom with 0.60 mm slice thickness (Siemens Somatom Confidence, Siemens Healthineers, Erlangen, Germany).

Navigation system

An EM tracking system (Aurora V2, Northern Digital Inc., Waterloo, Canada) in combination with 3D Slicer software (https://www.slicer.org/) was used to perform the navigation. 3D Slicer is an open-source software platform for research applications in medical imaging [20]. 3D Slicer was connected to the EM tracking system by using 'PLUS' (https://plustoolkit.github.io/) and 'OpenIGTLink' (http://openigtlink.org/) [21, 22]. The 'SlicerIGT' extension was used to perform the registration and validation procedure [23].

To track the position of the mandible during the experiments, a 6 degree-of-freedom (DOF) EM tracked sensor (Aurora cable tool, Northern Digital Inc., Waterloo, Canada) was used. To attach the sensor to the phantoms, an applicator was developed and 3D printed with the Form3B printer, again using Clear V4 resin. The sensor was glued (Elastosil,

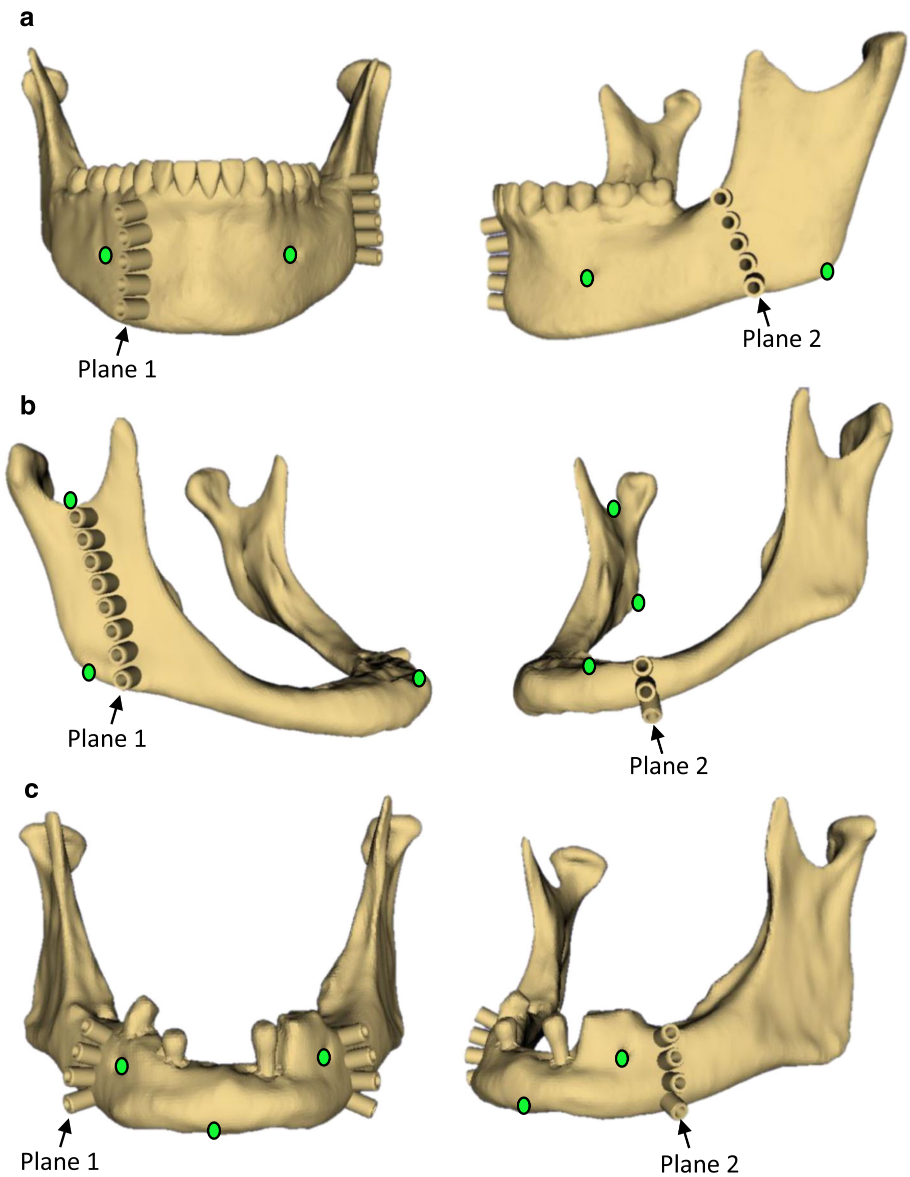

Fig. 1 Three mandible phantoms that were used for the experiments. The three anatomic landmarks that were used for initial point registration are annotated on each phantom. For each phantom, two views are shown to enable a view of both osteotomy planes with reference notches. **a** Phantom A, **b** phantom B, **c** phantom C

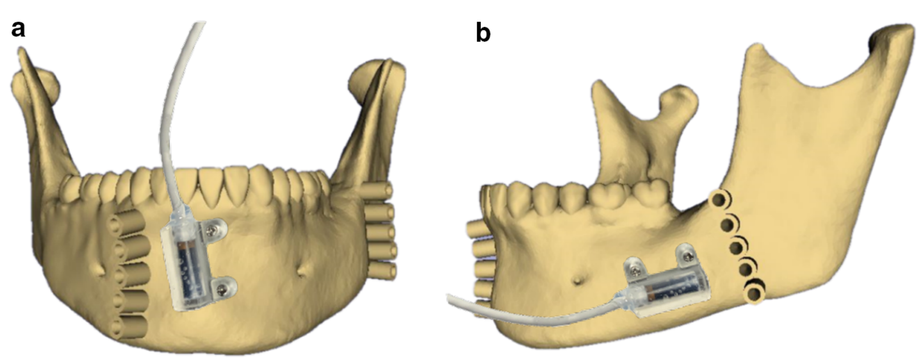

Fig. 2 Sensor positioned on phantom A during **a** Experiments 1–3, **b** Experiments 4–5

Wacker Chemie AG, München, Germany) into the applicator, and the applicator was attached to the phantoms with two 1.5 mm diameter × 5.0 mm long titanium screws (Drill-Free maxDrive, KLS Martin, Tuttlingen, Germany) (Fig. 2). During surgery, the sensor is attached to bone that is removed to prevent damage from the screw holes in the remaining mandible. Therefore, to simulate intraoperative use, the sensor was attached to the phantoms between the osteotomy planes. The phantoms were positioned such that the distance between the sensor and the EM field generator was approximately 25 cm, similar to intraoperative use.

Workflow

For each phantom, a 3D model was constructed from the CT scan in 3D Slicer by segmentation with thresholding. Next, three anatomic landmarks, visible on both the CT scan and the phantom, were chosen, and their coordinates on the CT scan were saved. The registration procedure consisted of two steps: initial registration with the anatomic landmarks (point registration) and final registration with mandible surface points (surface registration). The initial registration points were pinpointed on the phantom using an EM tracked probe. The coordinates of these points were matched with their CT coordinates by a rigid transformation using the 'Fiducial Registration Wizard' module in 3D Slicer. Next, the probe was swept over the phantom surface to capture surface points (the number of points varied in the experiments). These points were rigidly registered with the 3D model using the 'Fiducials-Model Registration' module, by applying an Iterative Closest Point (ICP) algorithm with 100 iterations.

Registration accuracy

For each experiment, registration accuracy was calculated after initial point registration and after surface registration. The registration accuracy was assessed in terms of 'fiducial registration error' (FRE) and 'target registration error' (TRE) [24, 25].

The FRE is a measure of how accurately the phantom is registered with the CT scan. The FRE is defined as the root mean squared distance between the pinpointed registration points on the phantom (in physical space) and the virtual registration points on the CT scan (in image space), after registration. The FRE was calculated and shown by 3D Slicer after point registration and surface registration.

The TRE is a measure of how closely the location of virtual predefined target points (other than the registration points) correspond to their actual location after registration. The notches on the osteotomy planes were used as target points to calculate the TRE. Prior to the experiments, the locations of the notches were marked on the CT scan. After each registration step (point registration and surface registration), the notches were pinpointed on the phantom with the tracked probe. For every notch (n), the distance between the coordinates on the CT data and the corresponding point on the phantom was calculated in terms of Euclidean distance (ED):

$$\mathrm{TRE}_n = \sqrt{\left(x_{\mathrm{phantom},n} - x_{ct,n}\right)^2 + \left(y_{\mathrm{phantom},n} - y_{ct,n}\right)^2 + \left(z_{\mathrm{phantom},n} - z_{ct,n}\right)^2} \quad (1)$$

The overall TRE, for both osteotomy planes together and for each plane separately, was calculated as the root mean squared error (RMSE) of the individual TREs:

$$\mathrm{TRE}_{\mathrm{overall}} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(\mathrm{TRE}_n\right)^2} \quad (2)$$

Experiments

The dentate phantom (A) was used for Experiments 1–4, for Experiment 5 both the dentate phantom and the (partially) edentulous phantoms (B and C) were used. All experiments were repeated 10 times by one researcher. Experiments 1–4 were performed in a metal-free environment to minimize EM field distortions. Experiment 5 was performed in an intraoperative environment on an OR bed.

The area of the mandible surface that can be prepared free from soft tissue depends on the tumor location, tumor size, and individual anatomy of the patient. Therefore, in *Experiment 1*, four different surface areas with a varying number of surface points were tested. The goal of this experiment was to simulate four different surface are configurations that would be exposed during various clinical situations and determine the registration accuracy. First, point registration was performed with three anatomic landmarks (mental foramen left and right, mandibular angle left, Fig. 1a). Next, four different surface area locations were tested (areas A to D), as shown in Fig. 3. Area A resembled the surface that needs to be prepared free from tissue to attach the cutting guide during mandibular reconstructive surgery (70 points; 35 around each osteotomy plane). For area B, extra points were added on the surface where the reconstruction plate would be attached (120 points; 60 around each osteotomy plane). For area C, additional points were added between the osteotomy planes (200 points). Area D resembled exposing the inferior border of the mandible (100 points).

In *Experiment 2*, using area B, the number of surface points was varied to determine how many surface points are required for an accurate registration, either in a line configuration or randomly located within the specified area. After

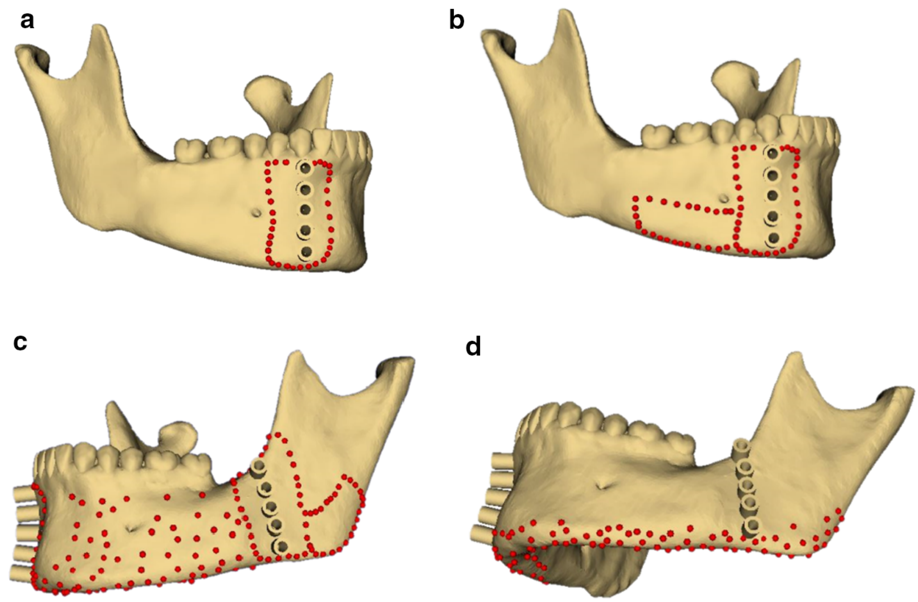

Fig. 3 Surface areas for Experiment 1; the red points indicate the used points for surface registration. **a** Area A, **b** area B, **c** area C and **d** area D

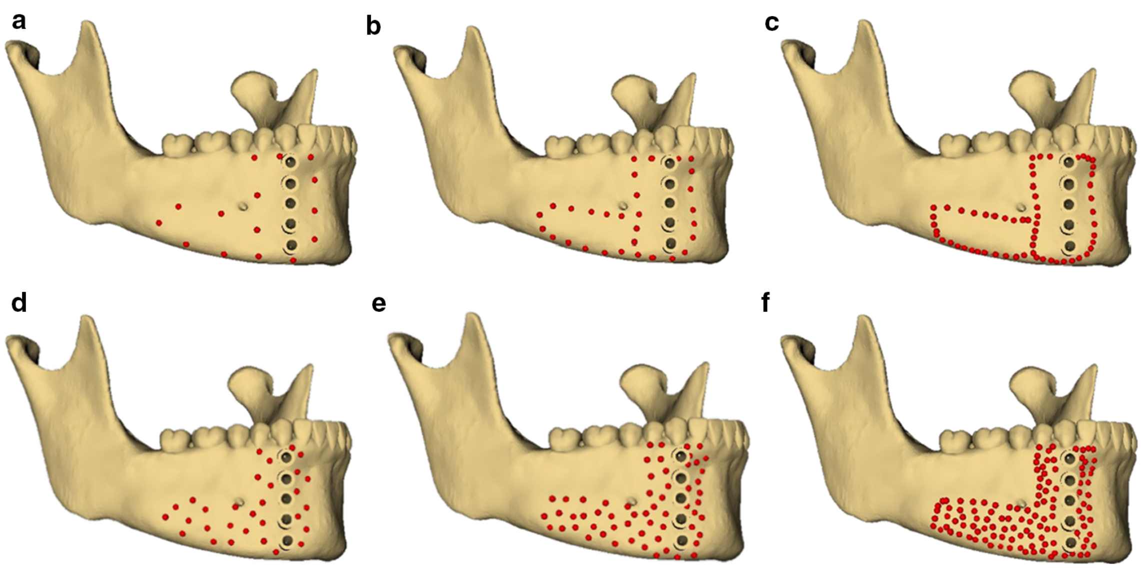

Fig. 4 Surface point configurations for Experiment 2; the red points indicate the used points for surface registration (the points used for one osteotomy plane are shown). **a** 30 points in line configuration, **b** 60 points in line configuration, **c** 120 points in line configuration, **d** 60 points in random configuration, **e** 120 points in random configuration **f** 240 points in random configuration

point registration, similar to Experiment 1, surface registration was performed with 30, 60 and 120 surface points in line configuration, and 60, 120 and 240 points randomly located within area B (Fig. 4). For pragmatic reasons, only a partial overlap between the number of points was tested since 240 points on a line would have been very dense.

In *Experiment 3*, the effect of the initial point registration on the final registration accuracy was determined. During surgery, anatomic landmarks on the mandible are often difficult to pinpoint exactly which can result in large initial registration errors. To simulate this, instead of pinpointing exactly on the anatomic landmarks on the phantom, the tracked probe was pinpointed at a range of 10 mm from the landmarks. Next, surface registration was performed with area B using 120 points in line configuration.

In *Experiment 4*, the effect of the sensor location (on the mandible) on the registration accuracy was determined. The sensor was placed at a different position and orientation compared to Experiments 1, 2 and 3 (Fig. 2b). Area B and 120 points in line configuration were used for surface registration.

In *Experiment 5*, the registration procedure was tested in the OR on a standard OR bed to determine the influence of

Table 1 Registration accuracies for Experiment 1

	Area A ($n = 10$)	Area B ($n = 10$)	Area C ($n = 10$)	Area D ($n = 10$)
Overall	1.03 ± 0.20 (0.75–1.43)	1.00 ± 0.15 (0.77–1.27)	0.98 ± 0.20 (0.60–1.23)	1.21 ± 0.29 (0.72–1.59)
Plane 1	0.78 ± 0.31 (0.41–1.29)	0.84 ± 0.26 (0.56–1.44)	0.86 ± 0.42 (0.30–1.45)	0.96 ± 0.34 (0.47–1.72)
Plane 2	1.20 ± 0.18 (0.98–1.65)	1.11 ± 0.23 (0.74–1.50)	1.04 ± 0.17 (0.79–1.36)	1.39 ± 0.39 (0.74–1.86)

The overall TRE is given and the TRE for each osteotomy plane. Values are given as mean ± SD (range) (mm)

the metal in the OR bed. For this experiment, the dentate phantom (A) was used, but also the (partially) edentulous phantoms (B and C) to determine whether the current registration method works for different individual anatomies and different osteotomy locations (Fig. 1). For each phantom, the sensor was attached between the osteotomy planes. Surface registration was performed with area B using 120 points in line configuration for phantom A and 90 points in line configuration for the phantoms B and C (since less mandibular surface was available due to atypical anatomy).

Results

In *Experiment 1*, determining the registration accuracy of different surface area configurations that simulate clinical situations, the mean *FRE* was 0.22 ± 0.04, 0.28 ± 0.05, 0.31 ± 0.06, and 0.39 ± 0.07 mm for area A, area B, area C, and area D, respectively. The mean overall *TRE* values ranged from 0.98 to 1.21 mm (Table 1).

In *Experiment 2*, determining the effect of different numbers and configurations of surface points on the registration accuracy, the mean *FRE* was 0.22 ± 0.03, 0.22 ± 0.03, and 0.23 ± 0.01 mm for 30, 60, and 120 points in a line configuration and 0.28 ± 0.04, 0.26 ± 0.04, and 0.25 ± 0.04 mm for 60, 120, and 240 points randomly located within the specified surface area. The mean overall *TRE* values ranged from 0.98 to 1.05 mm (Table 2).

In *Experiment 3*, determining the effect of the initial registration accuracy on the final registration accuracy, the mean $\mathrm{FRE}_{\mathrm{initial}}$ (after point registration) was 4.96 ± 1.71 mm and the mean final *FRE* (after surface registration) was 0.32 ± 0.09 mm. The mean overall $\mathrm{TRE}_{\mathrm{initial}}$ values ranged from 3.98 to 15.01 mm, and the mean overall final *TRE* values ranged from 0.89 to 1.48 (Table 3). Figure 5 shows the correlation between $\mathrm{TRE}_{\mathrm{initial}}$ and final *TRE* for all experiments.

In *Experiment 4*, determining the effect of the sensor location on the registration accuracy, the mean *FRE* was 0.32 ± 0.03 mm. The mean overall *TRE* values ranged from 0.85 to 1.32 mm (Table 4).

In *Experiment 5*, determining the registration accuracy in the OR with different patient anatomies and osteotomy plane locations, the mean *FRE* values were, respectively, 0.28 ± 0.04, 0.43 ± 0.08, and 0.28 ± 0.07 mm for phantom A, phantom B, and phantom C. The mean overall *TRE* values ranged from 0.93 to 1.50 mm (Table 5).

No statistical analysis was performed since all the measured *TRE* values fell within the clinically acceptable range.

Discussion

In this phantom study, the feasibility of a noninvasive hybrid registration technique, combining point- and surface registration, for navigated mandibular surgery was assessed. The results showed that hybrid registration is an accurate registration method with a mean TRE < 2.0 mm in all experiments. This meets the requirements of clinical practice for mandibular reconstructive surgery according to literature and surgeons from our institute [19]. Moreover, the results suggest that the accuracy of this method is hardly affected by different patient anatomies and osteotomy plane locations.

Registration accuracy did not improve by using a larger surface area with more registration points, more registration points within the same surface area, different surface point configurations, a different sensor position, or when initial point registration was more accurate, showing the robustness of this approach. During oncologic mandibular reconstructive surgery, the mandible needs to be prepared free from soft tissue and periosteum to attach the cutting guides (before resection) and the reconstruction plate (during reconstruction). Ideally, only this surface is used for registration, obviating the necessity of exposing extra bone. For sensor placement, surgeons can use any accessible location on the segment that will be extirpated since its position and orientation does not affect the registration accuracy. Similarly, the results suggest that the final registration accuracy is hardly affected by the accuracy of the initial point registration (Fig. 5). Therefore, less distinct landmarks such as the mandibular angle or the incisura can be used, which can be useful in edentulous patients with few distinct landmarks.

Although the overall accuracy (of both osteotomy planes together) in most experiments was about 1.0 mm, small differences were noticed between the two osteotomy planes. For

Table 2 Registration accuracies for Experiment 2

	30 points line ($n = 10$)	60 points line ($n = 10$)	120 points line ($n = 10$)	60 points random ($n = 10$)	120 points random ($n = 10$)	240 points random ($n = 10$)
Overall	1.05 ± 0.26 (0.64–1.35)	1.00 ± 0.15 (0.81–1.22)	0.98 ± 0.20 (0.64–1.29)	1.03 ± 0.14 (0.78–1.21)	1.04 ± 0.18 (0.76–1.34)	1.01 ± 0.20 (0.69–1.49)
Plane 1	0.76 ± 0.39 (0.25–1.68)	0.68 ± 0.18 (0.43–0.97)	0.66 ± 0.40 (0.29–1.67)	0.61 ± 0.17 (0.39–0.88)	0.69 ± 0.21 (0.44–1.00)	0.66 ± 0.31 (0.30–1.12)
Plane 2	1.20 ± 0.41 (0.57–1.76)	1.21 ± 0.29 (0.73–1.61)	1.15 ± 0.32 (0.69–1.65)	1.32 ± 0.22 (1.03–1.64)	1.26 ± 0.34 (0.90–1.82)	1.23 ± 0.27 (0.87–1.78)

The overall TRE is given and the TRE for each osteotomy plane. Values are given as mean ± SD (range) (mm)

Table 3 Registration accuracies for Experiment 3

	TRE after initial registration ($n = 10$)	TRE after final registration ($n = 10$)
Overall	7.82 ± 3.61 (3.98–15.01)	1.19 ± 0.20 (0.89–1.48)
Plane 1	8.35 ± 4.44 (2.21–17.76)	0.99 ± 0.37 (0.29–1.54)
Plane 2	7.00 ± 3.23 (3.75–12.82)	1.32 ± 0.19 (1.08–1.64)

The overall TRE is given and the TRE for each osteotomy plane. Values are given as mean ± SD (range) (mm)

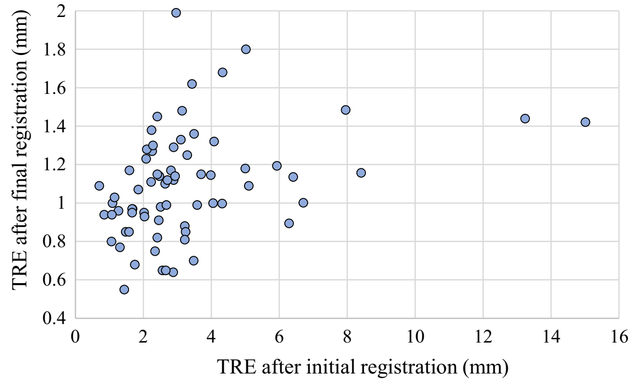

Fig. 5 Correlation between initial TRE (target registration error) after point registration and final TRE after surface registration. Results from all experiments ($n = 70$) are shown (from Experiment 1, the measurements with area B are used, from Experiment 2 the measurements with 120 points in line configuration are used)

phantom A, in almost all measurements the registration was more accurate in the frontal plane than in the lateral plane. For phantom C, the accuracy was better in the left osteotomy plane compared to the right plane. These differences may have been caused by several reasons, such as segmentation errors or tracking errors due to EM field distortions. Since it is known that registration points should be placed over a large area around the surgical site but also as close to the surgical site as possible to increase the accuracy, an additional experiment was performed with phantom A with separate registrations for each osteotomy plane (Table 6) [26, 27]. In this additional experiment, initial point registration and the collection of surface points was performed similarly to the other experiments. However, the surface registration was split into two separate registrations; first, the surface points around the frontal osteotomy plane were used for registration and the accuracy of this plane was validated by pinpointing the notches. Next, the registration transform was reset and the surface points around the lateral osteotomy plane were used for registration and accuracy of this plane was assessed. This method resulted in comparable accuracy for both planes with mean TRE values around 0.85 mm. However, during surgery this method of two separate registrations may add 10 min extra to the registration procedure since registration needs to be performed twice and consequently the accuracy needs to be verified two times. Moreover, the two cutting guides cannot be positioned at the same time since they require different registrations.

Although the results of this study are promising, there are some limitations to keep in mind when interpreting the results. Although the notches on the phantoms were designed to fit the tracked probe, some pivoting of the probe was possible due to minor 3D printing inaccuracies. The variability in pinpointing the notches with the probe was determined by pinpointing the notches ten times and calculating the mean deviation, which was 0.23 mm. Another fact to keep in mind is that all experiments were performed by the same person to eliminate inter-observer/operator variability. However, during surgery, not always the same surgeon performs the navigational procedure. Therefore, multiple surgeons need

Table 4 Registration accuracies for Experiment 4

	Different sensor location ($n = 10$)
Overall	1.09 ± 0.15 (0.85–1.32)
Plane 1	1.04 ± 0.35 (0.62–1.65)
Plane 2	1.10 ± 0.15 (0.88–1.29)

The overall TRE is given and the TRE for each osteotomy plane. Values are given as mean ± SD (range) (mm)

to be trained to perform the registration procedure. Furthermore, 'clean' phantoms were used in this study to simulate the bare bone surface, while during surgery residual soft tissue specimens may remain on the bone, which could affect the registration accuracy. Lastly, although the intraoperative environment was simulated in Experiment 5 by using an OR bed, during surgery there will probably more distortion of the EM field due to other metal in the OR such as instrument tables.

To our knowledge, this is the first study assessing a combination of point registration, using anatomic landmarks, and surface registration, using the bare bone surface, as a hybrid registration method for EM navigation of the mandible. Until now, three studies used the mandibular bone surface for registration during optical navigation of the mandible, either as standalone method or as part of a hybrid technique. However, in a study by Marmulla et al. (2007) the registration failed due to an incongruence of the mandibular surface [28]. Sun et al. (2020) achieved a successful registration in three patients with a TRE of 1.0 mm and Lubbers et al. (2010) achieved a deviation of less than 1 mm in a phantom study [19, 29]. Some studies did use a hybrid registration method for EM navigated mandibular surgery, just using the facial skin surface instead of the bare mandibular bone [30–32]. In

Table 5 Registration accuracies for Experiment 5

	Phantom A ($n = 10$)	Phantom B ($n = 10$)	Phantom C ($n = 10$)
Overall	0.96 ± 0.22 (0.65–1.38)	0.93 ± 0.26 (0.55–1.25)	1.50 ± 0.28 (1.09–1.99)
Plane 1	0.79 ± 0.25 (0.42–1.07)	0.91 ± 0.32 (0.36–1.29)	1.68 ± 0.40 (1.12–2.38)
Plane 2	1.09 ± 0.30 (0.81–1.78)	0.95 ± 0.20 (0.67–1.35)	1.28 ± 0.21 (1.02–1.65)

The overall TRE is given and the TRE for each osteotomy plane. Values are given as mean ± SD (range) (mm)

Table 6 Registration accuracy for phantom A using separate registrations for both osteotomy planes

	Phantom A ($n = 10$)
Overall	0.86 ± 0.28 (0.59–1.33)
Plane 1	0.86 ± 0.47 (0.43–1.78)
Plane 2	0.80 ± 0.26 (0.57–1.31)

The overall TRE is given and the TRE for each osteotomy plane. Values are given as mean ± SD (range) [mm]

these studies, surface registration was used for initialization and point registration for optimization. Accuracies were not reported.

Compared to other registration methods, such as point registration with bone screws or a dental splint, the proposed hybrid method, employing bare bone registration, has several advantages. First, it obviates the need for implanting invasive bone screws. Screws can be implanted preoperatively in the outpatient clinic before preoperative CT scanning is performed or during surgery. However, the latter requires intraoperative Cone Beam CT scanning (to obtain a 'preoperative' CT scan with the screws visible) which lengthens OR time and leads to extra ionizing radiation for the patient. Alternatively, artificial markers can be attached to a noninvasive dental splint. However, splints are patient-specific and require separate fabrication for every patient for which skilled people and special equipment are needed. In addition, splints cannot be used in edentulous patients or patients with tooth loosening. The proposed hybrid registration method is both simple, since standard preoperative imaging data can be used, and noninvasive, since only anatomic points and surfaces are used and no artificial markers are required. Therefore, this technique has greater potential for implementation into clinical practice.

Pilot tests by the authors in a clinical setting during oncologic mandibular reconstructive surgery (with registration performed on bare bone, before the cutting guide is attached) showed that registration can be performed within 15 min and visual validation (pinpointing multiple anatomic landmarks on the patient after registration and simultaneously looking at the monitor to see were the probe is located at the 3D model) confirmed the accuracy. However, further testing should be performed to objectively and quantitatively assess the accuracy and to validate the current findings in clinical setting.

Conclusion

This study assessed the feasibility of a noninvasive hybrid registration method for EM navigated mandibular surgery. This method consists of two phases: (1) point registration; performed for initialization by using anatomic landmarks on the mandible, and (2) surface registration; performed for optimization using the bare bone surface of the mandible after removal of soft tissue. In phantom experiments, accurate registration was obtained with mean TRE < 2.0 mm, which meets the practical clinical requirements for mandibular reconstructive surgery. A small surface area, marked by limited surface points, was sufficient for accurate registration. Moreover, anatomical variations of the mandible, different osteotomy plane locations, initial point registration accuracy, and sensor location had no observable effect on the TRE, demonstrating the robustness of this approach. Future studies should test this method in clinical setting during surgery.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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