Published in final edited form as:

J Oral Maxillofac Surg. 2015 October ; 73(10): 2005–2016. doi:10.1016/j.joms.2015.03.017.

Assessment of the OsteoMark-Navigation System for Oral and Maxillofacial Surgery

Zachary S. Peacock, DMD, MD¹, John C. Magill, PhD², Brad J. Tricomi, MS³, Brian A. Murphy, PhD², Vladimir Nikonovskiy², Nobuhiko Hata, PhD⁴, Laurent Chauvin, MS⁵, and Maria J. Troulis, DDS, MSc

¹ Assistant Professor, Department of Oral and Maxillofacial Surgery, Massachusetts General Hospital, Boston MA

²Physical Sciences, Inc. Andover, MA

³ Masters Student, University of Massachusetts Boston; Research Fellow, Massachusetts General Hospital, Boston, MA

⁴ Assistant Professor of Radiology, Harvard Medical School; Director, Surgical Navigation and Robotics Laboratory, Brigham and Women's Hospital, Boston, MA

⁵ Research Associate, Surgical Navigation and Robotics Laboratory, Brigham and Women's Hospital, Boston, MA

⁶ Associate Professor, Department of Oral and Maxillofacial Surgery, Massachusetts General Hospital, Boston, MA

Abstract

Purpose—To assess the accuracy of a novel navigation system for maxillofacial surgery using human cadavers and a live minipig model.

Methods—We describe and test an electromagnetic tracking system (OsteoMark Navigation) that uses simple sensors to determine position and orientation of a hand held pencil-like marking device. The device can translate 3-dimensional computed tomographic data intraoperatively to allow the surgeon to localize and draw a proposed osteotomy or the margins of a tumor on the bone. The accuracy of OsteoMark-Navigation in locating and marking osteotomies and screw positions in human cadaver heads was assessed. In Group 1 (n=3, 6 sides), Osteomark-Navigation marked osteotomies and screw positions were compared to virtual treatment plans In Group 2 (n=3, 6 sides), marked osteotomies and screw positions for distraction osteogenesis devices were compared to those carried out using fabricated guide-stents. Three metrics were used to document precision and accuracy. In Group 3 (n=1), the system was tested in a standard operating room environment.

Address Correspondence to: Zachary S. Peacock, DMD, MD, Massachusetts General Hospital, Warren Building 1201, 55 Fruit St., Boston, MA 02114, zpeacock@partners.org.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Results—For Group 1, the mean error between points was 0.7mm (horizontal) and 1.7mm (vertical). When compared to the posterior and inferior mandibular border the mean error was 1.2 and 1.7mm, respectively. For Group 2, the mean discrepancy between points marked by Osteomark-Navigation and the surgical guides was 1.9 mm (range 0-4.1 mm). The system maintained accuracy on a live minipig in a standard operating room environment.

Conclusion—Based on this research OsteoMark-Navigation is potentially a powerful tool for clinical use in maxillofacial surgery. It has accuracy and precision comparable to existing clinical applications.

Introduction

Virtual treatment-planning software currently available allows oral and maxillofacial surgeons to simulate osteotomies, 3-dimensional (3-D) movements, fracture reduction and positioning of hardware based on computed tomographic (CT) data.¹⁻⁶ Once the surgeon develops the simulated 3-D treatment plan, however, it must be accurately and precisely transferred to the patient during the live operation. Most vendors provide polymeric, 3-D printed templates and guide splints to help execute the plan intraoperatively. These devices are actually primitive navigation systems. Large incisions and bone exposure are often required to place and fixate the templates without soft tissue interference.⁷⁻⁹ Surgical navigation systems use electronic position measurements to facilitate accurate transfer of a virtual plan to the patient by the operating surgeon.¹⁰⁻¹¹

The current generation of navigation systems utilize line-of-sight, optical measurement of position.¹²⁻¹⁶ Brainlab (Brainlab, Inc. Munich, Germany), for example, uses head or face sensors and metallic instruments to record position. Although accurate (within 1.5 mm), the system requires the surgical team to maintain line-of-sight, and to use additional bulky instruments often without other uses to calibrate and provide position.^{12-13, 17} Currently available systems cannot detect and adjust to movement of the patient relative to the sensor, which limits the ability to track the mobile mandible relative to the rest of the craniofacial skeleton.

OsteoMark-Navigation was conceived as a simple, easy to use system that interfaces with any CT scan data set.¹⁸ (**Figure 1**) It also requires minimal preoperative planning on the patient. OsteoMark-Navigation contains a pencil-like device, which can mark bone surfaces as part of its tracking system. The pencil is non-metallic, which enables the use of a less-intrusive electromagnetic tracking system. The transmitter is secured beneath the patient and a small sensor is affixed to a tooth which is less bulky than-frames and facial masks currently in use.^{12-13, 19} Once a registration (geometric relationship) has been established between the patient and tracking system, a virtual image of the pencil is displayed alongside a 3-D skeletal image. It can then be used to mark planned osteotomies, pilot holes, and fixation-hardware location according to any 3-D image and/or preoperative plan. After the plan has been transferred, the surgeon can complete the procedure in the standard fashion.¹⁸ Unlike other systems, any preoperative CT (no special markers) may be used.

The purpose of this study was to assess the accuracy of OsteoMark-Navigation in transferring virtual surgical plans to the actual procedure. We hypothesized that OsteoMark-

Navigation would be as accurate and precise as commercially available virtual surgical planning systems for marking the position of osteotomies and screw-holes. We also hypothesized that the system would be ‘easily’ used and adapted to a standard operating room environment.

Materials and Methods

Hardware

The OsteoMark-Navigation platform (**Figures 1A**) was designed from a compact high-performance personal computer (PC) (Shuttle Computer Group, City of Industry, CA) and an electromagnetic tracking system (3-D Guidance driveBay2, Ascension Technology, Burlington, VT). The tracking electronics are located in the drive bay of the PC connected to the stainless steel metallic transmitter (60 cm by 60 cm by 2.5 cm) that is placed under the patient's head and cushion. It creates an electromagnetic field that is detected by the position sensors (Model 180, Ascension Technology, Burlington, VT). The tracking system reports the position and orientation for as many as four sensors at 80 Hz. In the current study, one sensor was located in the pencil and another attached to a mandibular tooth. A USB-connected, digital Input/Output device (USB-6501, National Instruments, Inc, Austin, TX) detects when the surgeon presses the buttons on the pencil.

The computer and hardware are mounted on the OsteoMark-Navigation portable workstation containing a touch screen which can be draped to be sterile. The system can be controlled by wireless keyboard and mouse, multi-touch finger gestures on the touch-screen, or the buttons on the pencil.

Pencil Design

The prototype pencil (**Figure 1B**) was created by adding a tracking sensor within the carbon-fiber shaft of a Bovie electrocautery tool (Bovie Medical Corp., Clearwater, FL). The end of the shaft was designed to allow for 3 interchangeable tips: a straight graphite pencil, a 45° pencil, and a straight, steel registration stylus. The steel registration stylus was created to improve accuracy of registration due to the intrinsic lubricity of graphite against teeth or bone.

Software Algorithm

The primary function of the OsteoMark-Navigation software is to determine and simulate the relationship between the pencil and patient to a CT-generated image of the patient anatomy (**Figure 1C**). The orientation and location of the pencil and the reference sensor (relative to the transmitter) are measured by the tracker every 12.5 milliseconds. With the sensor bonded to a tooth on the subject, tracking is maintained with head repositioning.

Registration

Registration is required to determine the position and orientation of the bony anatomy after bonding the sensor to a tooth. At least three registration points are selected on the virtual anatomy. Then, using the stainless steel tip, the pencil is placed on each corresponding point on the patient. Both the pencil and bone are displayed on the screen.

Accuracy

The accuracy and precision of OsteoMark-Navigation were tested in 2 groups of 3 cadaver heads. This study was approved by the Massachusetts General Hospital (MGH) Institutional Review Board (Protocol #2011P002576)

In Group 1, CT scans were acquired for each cadaver head and then 3D models of the mandible were created using the freeware software, Slicer3® (Brigham and Women's Hospital, Boston, MA). OsteoPlan®, a companion to OsteoMark-Navigation for treatment planning, was used to virtually plan the position and orientation of a vertical ramus osteotomy and screw fixation position. Initial registration points were selected from identifiable features of the teeth and posterior mandible for each cadaver and the surgical plan transferred (via a submandibular incision). The vertical ramus osteotomy and positions of 8 fixation screws were marked on the mandible using the navigation pencil. Then, bilateral hemi-mandibles were harvested and photographed for comparison to the virtual plans.

In Group 2, CT images of each cadaver (n=3) were uploaded to both OsteoPlan® and Materialise ProPlan CMF® (Materialise, Plymouth, MI) software. Alginate impressions and stone models were made for the mandibular dentition of each cadaver. The models were then superimposed over the teeth to improve accuracy of the dental anatomy for surgical planning and registration of OsteoMark-Navigation. A virtual plan for bilateral mandibular osteotomies and distraction device placement was completed via an online treatment planning session. Surgical guides that adapted to the mandibular angle depicting the osteotomy and 4 screw holes to secure the device on either side of the osteotomy were fabricated via 3-D printing (**Figure 2**).

The stereolithography (.stl) files of the treatment plan, showing the location of screws and osteotomies were then added to OsteoPlan® to allow comparison to OsteoMark®. After establishing 4 registration points (3 on the cusps of mandibular teeth and 1 on the mandibular angle), a submandibular incision was used, the osteotomy and screw positions were marked using the navigation pencil. Then the surgical guides were placed on the mandible and the osteotomy and screw positions were marked using indelible ink of a different color. The hemi-mandibles (n=3) were harvested and photographed for analysis.

In Group 3, Osteomark-Navigation was assessed in a standard animal operating room on a live Yucatan minipig. The care and use of the minipigs for this study met the requirements of the Accreditation of Laboratory Animal Care standards and was approved by the MGH Subcommittee on Research Animal Care (SRAC 2010N000119). OsteoPlan® was used to plan a vertical ramus osteotomy of the mandible, setback and fixation screw position.

After a 12 hour fast, the animal was sedated with telazol (4.4 mg/kg), xylazine (2.2 mg/kg), and atropine (0.04 mg/kg) intramuscularly as previously described.²⁰ Registration was obtained from 3 teeth cusps and the right mandibular angle after a submandibular incision exposed the right mandibular ramus. OsteoMark-Navigation was used to mark the ramus according to the planned osteotomy and screw positions. The animal was then euthanized and the right hemimandible harvested and photographed for comparison of accuracy.

Metrics for Determining Accuracy

The OsteoMark-Navigation system was evaluated by 3 performance metrics. Metric 1 is the distance between marked points as compared to the distance between corresponding points on the treatment plan (**Figure 3** – Measurements A and B). Metric 1 is a measure of the precision with which OsteoMark-Navigation can track motion of the pencil tip.

Metric 2 is the distance between the location of the markings by the pencil and the virtually planned location. This metric measures the quality of the registration and accuracy of the navigation. The photograph of the mandible marked by OsteoMark-Navigation was compared to a 3-D rendering of the CT showing the osteotomy and screw locations. The positions of the osteotomies and screw positions were measured using the inferior border and posterior border as references (**Figure 3**- measurements C and D)

Metric 3 is the distance between points marked by OsteoMark-Navigation and the corresponding points marked by the surgical guides in Group 2. A single scaling factor was determined by measuring the spacing between holes marked with the template and scaling this to match the actual dimensions of the template.

Group 1 was evaluated with metrics 1 and 2, and Group 2 was evaluated with metric 3. To standardize the measurements and eliminate distortion, a line from the center of the sigmoid notch to the inferior border (drawn parallel to the posterior border) served as the vertical length reference. A horizontal line across the ramus between identifiable points was used as the horizontal length reference. Two raters (BM and JM) made measurements on all hemi-mandibles. The average of the rater's signed errors for each measurement was used in subsequent analyses for each metric. The Pearson correlation coefficient was used to determine inter-rater agreement.

Results

Group 1

Metric 1 characterized the error within the pattern of points marked on the bone (i.e. precision). The mean horizontal error measurements between the superior, middle, and inferior drill-hole pairings in group 1 were 0.7 mm (range 0 – 3.7 mm). The mean error of the four vertical distance measurements was 1.5 mm (range 0 – 7.1). (**Table 1, Figures 4-5**).

Metric 2 assessed the error in markings referenced to the posterior (horizontal) and inferior borders (vertical) of the mandible. The mean horizontal and vertical error was 1.2 mm (range 0.2 – 3.3 mm) and 1.7 mm (range 0 – 4.5 mm), respectively (**Table 1, Figure 5**).

Group 2

For metric 3 (assessed in Group 2), the mean error between the template-based marks and those produced using OsteoMark-Navigation for all of the experiments were 1.9 mm (range: 0 to 4.1 mm). The Pearson correlation coefficient for the two raters was 0.95. As with the Group 1 tests, the pattern of marked screw positions (precision) was excellent and the greatest error was seen in accuracy of the pattern (**Figure 6**)

Group 3

The OsteoMark-Navigation system was successfully registered to the minipig dentition and mandible after bonding the sensor to a mandibular tooth. There were no interferences with diathermy and navigation did not affect electrocardiography or other anesthesia monitor. The osteotomy and screw positions were marked with similar accuracy and precision to the cadaver heads (metrics 1 and 2 were within 2 mm of the virtual plan).

Discussion

This study was performed to assess the accuracy of OsteoMark-Navigation for transferring preoperative virtual surgical plans to procedures on human cadaver heads and a live minipig. We hypothesized that OsteoMark-Navigation would be comparable in accuracy and precision to available virtual surgical planning systems and to templates for osteotomy and screw-hole positioning in cadavers.

The OsteoMark-Navigation system had reasonable precision and accuracy in marking osteotomies and screw positions within the mandible. The magnitude of errors were comparable to that found for optical navigation systems in the literature.^{11, 21-22} The errors between points were small with most less than 1 mm (mean 1.2 mm; range 0 – 7.1 mm). The screw holes indicated on the CT have a 2 mm diameter and the pencil marks were approximately 1 mm. Consequently, most of the Metric 1 errors (0.9 mm; range 0 - 2.4 mm) were within the limit of our ability to determine mark location from 2-dimensional images. The largest errors were found at the superior points (near the sigmoid notch) where access for marking from a submandibular incision was the most challenging. In addition, the left side of cadaver 3 seemed to be an outlier. Eliminating that side decreased the average error for metrics 1 and 2 to 1.0 mm (range 0-4.4 mm)

The mean error determined by Metrics 2 and 3 (1.5 and 1.9 mm) were larger than that determined by Metric 1. Essentially, the pattern is easily reproduced but can be systematically shifted from the planned location (i.e. more precise than accurate). From this it is concluded that the errors associated with OsteoMark-Navigation are not the result of tracking noise. A distortion in the calibration of the tracker could produce such systematic results, but previous experiments on regular geometries (i.e. plastic testing blocks) did not produce these errors.¹⁸

Systematic error can be explained by imperfect registration of the CT image to the bone. The registration process is limited by the ability to precisely locate anatomical points in wide distribution (i.e. large distances between them). The most accessible points are the cusps of teeth, but are not well representation on today's CT scans thus leading to potential registration errors. This could be rectified by scanning the dental anatomy and incorporating that data into the CT scan as is currently done in some virtual planning systems. Since accuracy decreases as the distance from the registration points increases, the best registration is one based on points on both sides of the jaw including the anterior and posterior extremes.²³⁻²⁴ Including easily identifiable osseous points in registration also improved accuracy.

Another source of systematic error is the use of a 2-D image (the screen) to represent the 3-D skeleton and pencil. When the viewing axis is not parallel to the bone being marked, the pencil tip image appears to be displaced from its true location. If all of the points are marked while viewing the image from the same direction a systematic shift of all points occurs (i.e. loss of accuracy, but maintenance of precision). This effect is largely eliminated with practice and confirming position in two views, but must be considered by the surgeon.

Current virtual planning and guides to transfer the plan to the patient are generally thought to decrease the length of and improve the accuracy of complex operations.²⁵⁻²⁷ A comparison by Strong et al. of 3 optical based navigation systems using a head frame for reference yielded an error of 1.00-1.34 mm.²² Casap et al. compared 2 navigation systems for mandibular positioning.¹¹ The IGI (DenX Advanced Dental Systems, Moshav Ora, Israel) system uses an occlusal template that relates to a head frame and yielded an accuracy of less than 0.5 mm. The other system, the LandmarX (Medtronic Xomed, Inc, Jacksonville, FL) used a headframe sensor and required immobilization of the mandible and had an accuracy of 3-4 mm. Both systems have limitations of being bulky and require head frames.

OsteoMark-Navigation has several advantages over current systems. It allows for navigation to determine 3-D positioning without the need for an intact line-of site to an overhead registration device which can limit positioning of surgeons and assistants. Current instruments that determine position typically are pointed probes that only provide position and cannot be used for other functions.⁶ Positioning devices that can mount to existing tools are bulky and can impair visualization.¹⁹ OsteoMark-Navigation utilizes a marking tool to mark the identified position, after which the procedure is completed without tracking. This eliminates the possibility of interference from metal instruments, an existing limitation of electromagnetic tracking.²⁸

OsteoMark-Navigation can mark the surgical plan through small incisions and be used in endoscopic surgery. The system potentially could eliminate the need for 3-D printing of surgical guides decreasing cost. Current cutting and screw-hole guides require large incisions to ensure the guide can be placed and secured to the bone without soft tissue interference. For oral and maxillofacial surgery, the biggest advantage of OsteoMark-Navigation is its ability to determine position on and mark planned osteotomies and screw positions on the mandible. Most existing optical systems only allow accurate positioning on the mandible if it is in the same position as the preoperative CT scan.^{11, 22} Other systems require attachment of an occlusal reference sensor that needs to be present when the CT scan is obtained.⁶ Placement of the small sensor on a mandibular tooth as in this system will work with a pre-existing CT scan and can adapt to mandibular movement.

OsteoMark-Navigation has several potential applications in craniomaxillofacial surgery. The system can be used to mark osseous margins for ablative operations without the need for fixed splints. After application of reconstruction plate, OsteoMark-Navigation could verify that the positions of the residual mandibular segments have been maintained. OsteoMark-Navigation will aid in transferring a virtual treatment plan for osteotomies, device (DO) or implant placement to the patient. With the reference sensor on the mandible, the position of the mandibular condyle could be confirmed during orthognathic, or other reconstructive

surgery. Patients with traumatic facial injuries typically have a CT scan prior to consultation of a surgeon. As no registration markers are needed for the scan, Osteomark-Navigation could be employed without the need for additional imaging.

This is a pilot study with several limitations. Our comparisons are based on existing virtual surgical treatment planning and templates. Clinical application indicates excellent accuracy, but little is known of the true accuracy considering the inevitable error with 3-D rendering of CT data, the planning process, and fabrication of guides. Three-dimensional CT rendering is derived from density threshold segmentation with some generated smoothing, which leads to differences in the surface of the virtual mandible compared to the actual mandible. Comparison of markings on the surface of the mandible to the virtual plan proved difficult. Due to the limitations of slice thickness and the resultant pixel size, this experiment was limited by the 0.6 mm³ CT scan resolution. The implication of this error for navigation is unclear. It appears that increasing the number and distribution of registration points may decrease this error.²⁴ Additional factors of error include the actual marking by the surgeon and the use of caliper measurements along curved surfaces. We have not yet tested the device using alternative sensor placement locations as would be necessary with orthodontic appliances and edentulism. For these situations, the sensor could be attached to a fixation screw and osseous registration points could be used.

In conclusion, the OsteoMark-Navigation system is easy to use with accuracy and precision comparable to other methods of translating virtual surgical plans to the operating room. The less obstructive form-factor and ability ease in registration and tracking the mandible make it potentially useful for a variety of oral and maxillofacial procedures.

Acknowledgements

The authors acknowledge Leonard B. Kaban, DMD, MD, Carl Bouchard, DMD, Paul E. Gordon, DMD, MD and Jennifer Faubeau for their contributions in the development and implementation of this project.

Funding

This work was funded by NIH/NIDCR SBIR grant (5R44DE019047-03), the MGH Department of Oral and Maxillofacial Surgery Education and Research Fund, and the Hanson Foundation (Boston, MA, USA)

References

1. Adolphs N, Haberl EJ, Liu W, et al. Virtual planning for craniomaxillofacial surgery--7 years of experience. *J Craniomaxillofac Surg*. 2014; 42:e289. [PubMed: 24286863]
2. Farrell BB, Franco PB, Tucker MR. Virtual Surgical Planning in Orthognathic Surgery. *Oral Maxillofac Surg Clin North Am*. 2014; 26:459. [PubMed: 25246324]
3. Orentlicher G, Abboud M. Guided surgery for implant therapy. *Oral Maxillofac Surg Clin North Am*. 2011; 23:239. [PubMed: 21492799]
4. Saad A, Winters R, Wise MW, et al. Virtual surgical planning in complex composite maxillofacial reconstruction. *Plast Reconstr Surg*. 2013; 132:626. [PubMed: 23985637]
5. Stokbro K, Aagaard E, Torkov P, et al. Virtual planning in orthognathic surgery. *Int J Oral Maxillofac Surg*. 2014; 43:957. [PubMed: 24746388]
6. Bell RB, Markiewicz MR. Computer-assisted planning, stereolithographic modeling, and intraoperative navigation for complex orbital reconstruction: a descriptive study in a preliminary cohort. *J Oral Maxillofac Surg*. 2009; 67:2559. [PubMed: 19925972]

7. Thomas CV, McMillan KG, Jeynes P, et al. Use of a titanium cutting guide to assist with raising and inset of a DCIA free flap. *Br J Oral Maxillofac Surg.* 2013; 51:958. [PubMed: 23725739]
8. Troulis MJ, Everett P, Seldin EB, et al. Development of a three-dimensional treatment planning system based on computed tomographic data. *Int J Oral Maxillofac Surg.* 2002; 31:349. [PubMed: 12361065]
9. Seeberger R, Davids R, Kater W, et al. Use of stereolithographic drilling and cutting guides in bilateral mandibular distraction. *J Craniofac Surg.* 2011; 22:2031. [PubMed: 22067855]
10. Ewers R, Schicho K, Undt G, Wanschitz F, Truppe M, Seemann R, Wagner A. Basic research and 12 years of clinical experience in computer-assisted navigation technology: a review. *Int J Oral Maxillofac Surg.* 2005; 34:1. [PubMed: 15617960]
11. Casap N, Wexler A, Eliashar R. Computerized navigation for surgery of the lower jaw: comparison of 2 navigation systems. *J Oral Maxillofac Surg.* 2008; 66:1467. [PubMed: 18571032]
12. Barnett GH, Miller DW, Weisenberger J. Frameless stereotaxy with scalp-applied fiducial markers for brain biopsy procedures: experience in 218 cases. *J Neurosurg.* 1999; 91:569. [PubMed: 10507376]
13. Willems PW, van der Sprenkel JW, Tulleken CA, et al. Neuronavigation and surgery of intracerebral tumours. *J Neurol.* 2006; 253:1123. [PubMed: 16988793]
14. Schmelzeisen R, Gellrich NC, Schoen R, et al. Navigation-aided reconstruction of medial orbital wall and floor contour in cranio-maxillofacial reconstruction. *Injury.* 2004; 35:955. [PubMed: 15351656]
15. Chen W, Zhang G, Lin C, et al. Clinical use of a neuronavigation system in hemangioblastoma resection of posterior cranial fossa. *Minim Invasive Ther Allied Technol.* 2012; 21:234. [PubMed: 22049944]
16. Nottmeier EW, Pirris SM. Placement of thoracic transvertebral pedicle screws using 3D image guidance. *J Neurosurg Spine.* 2013; 18:479. [PubMed: 23473471]
17. Pillai P, Sammet S, Ammirati M. Application accuracy of computed tomography-based, image-guided navigation of temporal bone. *Neurosurgery.* 2008; 63:326. [PubMed: 18981839]
18. Bouchard C, Magill JC, Nikonovskiy V, et al. Osteomark: a surgical navigation system for oral and maxillofacial surgery. *Int J Oral Maxillofac Surg.* 2012; 41:265. [PubMed: 22103996]
19. Bell RB, Weimer KA, Dierks EJ, et al. Computer planning and intraoperative navigation for palatomaxillary and mandibular reconstruction with fibular free flaps. *J Oral Maxillofac Surg.* 2011; 69:724. [PubMed: 20888108]
20. Peacock ZS, Tricomi BJ, Murphy BA, et al. Automated Continuous Distraction Osteogenesis May Allow Faster Distraction Rates: A Preliminary Study. *J Oral Maxillofac Surg.* 2013; 71:1073. [PubMed: 23499159]
21. d'Hauthuille C, Taha F, Devauchelle B, Testelin S. Comparison of two computer-assisted surgery techniques to guide a mandibular distraction osteogenesis procedure. Technical note. *Int J Oral Maxillofac Surg.* 2005; 34:197. [PubMed: 15695051]
22. Strong EB, Rafii A, Holweg-Majert B, Fuller SC, Metzger MC. Comparison of 3 optical navigation systems for computer-aided maxillofacial surgery. *Arch Otolaryngol Head Neck Surg.* 2008; 134:1080. [PubMed: 18936355]
23. Luebbbers H-T, Messmer P, Obwegeser JA, et al. Comparison of different registration methods for surgical navigation in cranio-maxillofacial surgery. *J Craniomaxillofac Surg.* 2008; 6:109.
24. Eggers G, Mühling J, Marmulla R. Image-to-patient registration techniques in head surgery. *Int J Oral Maxillofac Surg.* 2006; 35:1081. [PubMed: 17095191]
25. Hanken H, Schablowsky C, Smeets R, et al. Virtual planning of complex head and neck reconstruction results in satisfactory match between real outcomes and virtual models. *Clin Oral Investig.* Aug 8.2014 [Epub ahead of print].
26. Shqaidef A, Ayoub AF, Khambay BS. How accurate are rapid prototyped final orthognathic surgical wafers? A pilot study. *Br J Oral Maxillofac Surg.* 2014; 52:609. [PubMed: 24933576]
27. Chen XY, Chen SL, Zhang X, et al. Accuracy of intraoral vertical ramus osteotomy with a stereolithographic template. *Ann Plast Surg.* 2011; 66:88. [PubMed: 20842002]
28. Birkfellner, W.; Hummel, J.; Wilson, E., et al. Tracking Devices. In: Peters, T.; Cleary, K., editors. *Image-Guided Interventions.* Springer US; New York, NY: 2008. p. 23-44.

Pencil on Model Screen Display

Figure 1.

A. The wheeled cart with two screens can be controlled by keyboard/mouse or touch screen, B. The OsteoMark-Navigation system pencil prototype was constructed from an electrocautery pen. Pencil tips are interchangeable. C. OsteoMark-Navigation demonstrated on a model mandible

Figure 2.

A. Materialise ProPlan® services were used to an osteotomy and placement of a curvilinear distraction device and (B) produce a surgical guide.

Figure 3. Screw location ID and measurements to characterize locations. Measurements A and B determine Metric 1 and measurements C and D determine Metric 2.

Figure 4.

A. Location of registration points and B-C, assessment of accuracy using transferred virtual plan of vertical ramus osteotomy and screw positions to cadaver mandible.

Figure 5.

A. Histogram for Metric 1 error with most errors are within 1 mm (less than the size of holes in a plate). B. Histogram for Metric 2 errors from inferior and posterior border

Figure 6.

A comparison of position of osteotomy and screw holes with OsteoMark-Navigation (pencil marks) and that of the 3-D printed templates (blue ink) for right (A) and left (B) side. The right side shows precise but inaccurate markings compared to the surgical guide. C. Metric 3 histogram distances between screw hole locations as marked by OsteoMark-Navigation and templates

Table 1

Distances between pairs of points (Metric 1) and from the inferior and posterior borders (Metric 2).

Points	Head 1		Head 2		Head 3	
	Right	Left	Right	Left	Right	Left
Horizontal distance between points (Metric 1)						
SA-SP	0.5	NV	0.6	0.6	0.6	0.4
MA-MP	0.5	0.3	0.3	0.5	0.8	3.7
IA-IP	0.9	0.3	0.2	NV	0.3	1.2
Vertical distance between points (Metric 1)						
SA-MA	0.1	NV	0.9	1.7	1.6	4.0
MA-IA	0.5	0.3	0.0	0.3	2.3	3.2
SP-MP	0.9	1.9	1.5	0.3	2.4	7.1
MP-IP	1.0	1.2	0.5	NV	0.6	0.2
Distances from posterior border (Metric 2)						
SP	1.7	0.9	1.2	2.0	1.0	2.8
SA	0.7	NV	1.7	2.6	0.8	1.3
MP	1.6	1.2	1.0	1.6	0.3	1.3
MA	2.6	1.5	2.0	1.6	0.7	0.9
IP	0.7	2.4	0.4	NV	0.2	0.5
IA	3.3	1.5	0.5	0.2	0.5	3.1
Distances from inferior border (Metric 2)						
	Right	Left	Right	Left	Right	Left
SP	3.3	4.4	0.2	1.9	3.5	4.5
SA	0.9	NV	0.3	2.4	1.8	0.7
MP	2.3	1.3	0.9	1.0	0.9	3.6
MA	1.0	1.6	0.7	1.3	1.1	4.5
IP	3.4	3.7	1.3	NV	1.3	1.6
IA	0.2	2.3	0.0	0.7	3.1	0.6

NV = not visible in photographs of mandible