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Abstract

Purpose: Computer-assisted surgical (CAS) planning tools have become widely available in cranio-maxillofacial surgery, but are time-consuming and often require professional technical assistance to simulate a case. We aimed to evaluate an initial oral and maxillofacial surgery (OMS) user experience with a newly developed CAS system featuring a bimanual sense of touch (haptic).

Methods: Three volunteer OM surgeons received a five-minute verbal introduction to the use of a newly developed haptically enabled planning system. The surgeons were instructed to simulate mandibular fracture reductions of three clinical cases, within a 15-minute time limit and without a time limit, and complete a questionnaire to assess their subjective experience with the system. Standard landmarks and linear and angular measurements between the simulated results and the actual surgical outcome were compared.

Results: After the five-minute instruction, all three surgeons were able to use the system independently. The analysis of standardized anatomic measurements showed that the simulation results within a 15-minute time limit were not significantly different from those without a time limit. Mean differences between measures of surgical and simulated fracture reductions were within current resolution limitations in collision detection, segmentation of CT scans, and haptic devices. All three surgeons reported that the system was easy to learn and use, and that they would be comfortable integrating it into their daily clinical practice for trauma cases.

Conclusion: A CAS system with a haptic interface that capitalizes on touch and force-feedback experience similar to operative procedures is fast and easy for OM surgeons to learn and use.

Introduction

The introduction of computer-assisted surgery (CAS) simulation into oral and maxillofacial surgery (OMS) has led to a possible paradigm shift in treatment planning of cranio-maxillofacial traumatic injuries, tumors, and congenital deformities. Conventional and cone beam CT provide accurate data from which a digital model of an individual patient can be reconstructed for surgery simulation, procedure rehearsal, or education (1-7).

In general, the correction of craniofacial defects or trauma involves bone surgery, i.e., cutting, movement, and alignment of bone. Accordingly, virtual tools have been developed to simulate bone cutting, removal, and movement of bone segments. An attractive benefit of this approach is that various treatment alternatives can be simulated for each patient, increasing the possibility of a successful outcome. Recognizing the advantages of virtual surgical simulation and planning, interactive planning software is commercially available for craniofacial procedures (8). However, the user interfaces of these systems are complex and based on the WIMP (Windows, Icons, Menus, Pointer) paradigm, with workflows of drop-down menus that often require interactive planning sessions with a specialist trained in the software.

Haptic force feedback in virtual environments has been shown to significantly improve task performance, perceived task performance, and perceived virtual presence (9, 10). Despite these apparent advantages, haptic interfaces have rarely been used in craniofacial surgery simulation (11, 12). Other surgical fields have begun to implement haptic feedback into their systems and have reported that haptics can allow for greater precision, faster completion, and reduction in errors in virtual surgical planning (13, 14).

The purpose of this study was to test a newly developed haptic CAS system aimed to improve the user experience for surgeons. We hypothesized that: (1) use of the haptic force-feedback CAS system would require very little training, (2) experienced OM surgeons would be able to simulate a fracture reduction using the CAS system in a short timeframe, creating a result that closely resembles a clinically acceptable postoperative one, and (3) the surgeons would find the haptic CAS system easy to learn and use regardless of prior experience with virtual reality in games or surgical simulation. To test these hypotheses, we introduced the new haptic CAS system to senior OM surgeons, compared their simulated results with actual surgical outcomes using standard anatomic mandibular landmarks and linear and angular measurements, and assessed their subjective experience with the system via questionnaire.

Materials and Methods

Study design/sample

To address the research purpose, we designed and implemented an evaluation of our newly developed 3D advanced visuohaptic trauma planning system, in which we investigated the user experience and assessed the accuracty of simulations of fracture reduction. Three senior OM surgeons each with more than 20 years of experience in maxillofacial trauma surgery and little or no experience with virtual reality gaming participated in this initial user evaluation. Our haptic CAS system permits bimanual manipulation of fractured bone segments derived from the patient’s preoperative CT scan data, utilizing high-fidelity haptic devices with six degrees-of-freedom (6-DOF). The haptic devices utilized in this study were Phantom Omni devices (SensAble Technology, GeoMagic, US). The system provides haptic tactic feedback whenever bone fragments that are moved with the haptic devices collide.

All three volunteer attending OM surgeons received a five-minute verbal introduction to the haptic CAS system, which included an overview of the basic functions of moving and aligning the bone, collision feedback, and locking the bone into position after reduction. The surgeons were able to manipulate the individual bone segments or group and ungroup one to three segments to move multi-segment units. The segments can be rotated and locked into position, allowing visualization and review of the fracture reduction from multiple angles.

We aimed to select three mandibular fracture cases for this study that had varying complexity: unilateral vs. bilateral, dentate vs. non-dentate, defect fracture vs. non-defect fracture. Based on this selection criteria, two of the cases chosen were patients with edentulous bilateral fractures, one of which presented with a defect fracture, and the final case was a dentate patient with a unilateral fracture. All cases were segmented so that each fractured segment could be manipulated separately. The CT-derived cranial base image was featured for each case, allowing the surgeon to have anatomical points of reference, such as the condylar fossa and the maxilla (Figure 1). It should be noted that the system cannot simulate occlusal contacts with sufficient accuracy at this time, as it is based on segmented CT data and the simulation of fracture reduction is, therefore, solely based on the force feedback of the colliding surfaces that the surgeons “feel”.

Each surgeon was then given a 15-minute time limit to virtually plan each of three mandibular fracture cases simulations using the visuohaptic planning system without any technical assistance, and after completing the simulations once, they were allowed a second opportunity to work on each case with unlimited time.

The goal specified in the instructions to the surgeons was to align the bone fragments to achieve the best possible fracture reduction. The study was carried out under IRB approval (IRB 8004).

Study variables

In this study, the independent variable is a binary variable for the fracture being treated surgically or virtually. The dependent variables were standard mandibular measurements (Figure 2) (15) taken after the actual and the virtual surgical repairs.

Data collection methods

Standard landmarks and measurements:

To describe the discrepancy between the simulated results and the actual surgical outcome, the following standard landmarks and linear and angular measurements were defined in each case (Figure 2) (15):

1. Anatomic mandibular landmarks
   - Gonion
   - Condyle lateral
   - Coronoid process
   - Mental foramen
   - Gnathion
2. Linear and angular measurements based on these landmarks
   - Mandibular angle (angle between ganthion, goinion, lateral condyle)
   - Mandible length (summed distance between gnathion, mental foramen,

gonion)

- Coronoid width (distance between coronoids)
- Gonion width (distance between gonions)
- Lateral condyle width (distance between lateral condyles)

User Study Questionnaire:

To address the subjective experience of the surgeons and their demographic background relevant to this task, each surgeon completed a questionnaire prior to the simulation experiment, assessing their previous experience using haptic devices, CAS programs, and videogames. After the experiment, they were given a second questionnaire regarding their experience with our haptic CAS. The answers were graded on a five-point Likert scale.

Data Analyses

The standard mandibular measures described above were compared between the surgically repaired and the virtually repaired fractures for each of the three cases using Prism version 6.0 statistical software. The measurements were standardized by setting the postoperative control measures to 0 and each of the simulated values to the difference from the control (in milimeters or degrees as appropriate). The Friedman test, similar to repeated measures ANOVA for non-parametric data, was used to compare the postoperative control value to the simulated values for each measurement in the three surgical cases. The Wilcoxon test was used to compare the means of the standardized values in the simulations with a 15 minute time limit to those with unlimited time. The Wilcoxon test was also used to compare each surgeon’s simulated measurements to the actual postoperative measurements and to each other. Significance was determined as $p<.05$

Results

There were no significant differences between the three surgeons' simulated results and the actual postoperative result in any of the three cases using the Friedman test. For all three cases the most varied results between the four surgeries (one actual surgery and three simulated surgeries for each of the three fracture cases) were on the right mandibular angle and the gonion width with p-values of .18 and .15, respectively. The Wilcoxon test showed there was no significant difference between the mean of the three surgeons' simulations for each measure with and without a 15 minute time constraint (p=.37).

None of the three surgeons using the simulation performed significantly differently from the surgeon performing the actual surgery when all of their measures (standardized to difference from postoperative value in milimeters or degrees as appropriate) were analyzed using the Wilcoxon test, with p values of .31, .06, and .48. Their respective median differences from the actual postoperative values (.27, .30, and .27 mm) are all well within 1mm of the postoperative values, which is the margin of error in the CT scan.

Case 1

The first case was a right paramandibular fracture in a dentate patient. All three of the surgeon's results were similar to each other and to the postoperative result with respect to the mandibular angle (MAR) and length (MLR). However, coronoid and gonion width (CW, GW) measurements indicated a difference between the postoperative outcome and the results of the simulations of all three surgeons, showing a relative increase in the measurements of the lateral condylar width (LCW), an indication of mandibular splaying and outward rotation of the coronoids. There was no improvement of the results when the 15-minute time limit was lifted (Figure 3a).

Case 2

The second patient was edentulous and had a right parasymphyseal and left angle fracture. Whereas the bilateral mandibular length (MLL, MLR), the mandibular right angle (MAR) and the lateral condylar width (LCW) were very similar between the simulations of all three surgeons and the postoperative result, the simulation reduction of all three surgeons differed from the postoperative result in terms of the left mandibular angle and the CW and GW, indicating a malpositioning of the segment. Again, the results were not altered if the surgeons were allowed unlimited time for the simulation task (Figure 3b).

Case 3

The final edentulous patient had a bilateral mandibular body fracture that included a small defect on the left side. The measurements of the mandibular angles (MAL, MAR) yielded largely similar results; however, the mandibular length measurements of all three surgeons were similar to each other, but different from the postoperative result (MLL, MLR). The CW and GW measurements varied widely among the surgeon's simulations, whereas discrepancies in the width of the lateral condyles were relatively small (Figure 3c).

In the questionnaire, all three surgeons reported that they felt comfortable using the haptics program and that it was intuitive to use. The surgeons stored and loaded all different points of view offered by the haptic framework. Furthermore, all three surgeons reported that they would be comfortable incorporating the system into their daily clinical practice for trauma cases (Figure 4).

Discussion

Over the past two decades, the field of 3D user interface technology has evolved rapidly beyond the WIMP concept to include direct manipulation and technologies such as free space trackers, bimanual interaction, and haptic feedback. Not surprisingly, as the bimanual sense of touch (haptic) is the most integral part of surgery, virtual surgical simulation has become one of the primary applications for haptic rendering (16). The addition of haptic force feedback has enhanced the realism of the surgical simulation experience and combined haptic-visual training modes have an advantage over either haptic or visual modes alone for tasks that have a force component, such as surgical simulation (17, 18). Interfaces that include haptic feedback allow novice and experienced surgeons to perform a simulated task faster and significantly more accurately than without haptic feedback (19). However, there also appear to be limitations to surgical training with a haptic feedback simulator. In one study, haptic feedback enabled a significant improvement in a laparoscopic suturing and knot-tying task with a higher learning rate; however, the subjects reached a plateau after five hours of training with the haptic device (20).

Active haptic devices, such as the Phantom Omni (SensAble Technology, GeoMagic, US) used in this study, are interfaces to the computer that exchange power, e.g., forces and vibration, through contact with an object such as a virtual bone. Allowing a surgeon to reposition and interact with virtual bone models (rigid bodies) using both hands requires advanced software that enables 6-DOF haptic rendering and collision detection. The three-degree-of-freedom (3-DOF) point-object interaction model has been extensively studied in haptics, rendering forces proportional to depth of penetration by maintaining a point on the object surface closest to the haptic device's point location, subject to the constraints of the object’s surface (21, 22). Recent work by our group includes full 6-DOF constraint-based haptic rendering, but is limited to uni-modal manipulation (23). Olsson et al. described an immersive virtual environment setup that includes a co-located visuohaptic display and head tracking. This system also provides uni-manual haptic feedback and secondary hand control for camera movement, as well as an interaction technique called snap-to-fit that can help assist the surgeon to find an optimal fit of bone fractures (24).

Based on our previous work, we developed algorithms that support bimanual interaction for our visuohaptic craniofacial simulation system. One of the very few studies that describes a system with both bimanual direct manipulation and haptic feedback showed that task completion time is shorter with a bimanual setup. However, the study used a limited haptic algorithm that cannot support an interaction between two rigid bodies (25).

In this study, we hypothesized that a bimanual haptic simulation system would be easy for surgeons to learn and that experienced surgeons could achieve reasonable simulated fracture reduction results within a short timeframe using the haptic CAS system.

In this initial user study we evaluated the performance of three senior OM surgeons with our new bimanual visuohaptic simulation system, and found that, indeed, they were able to simulate the reduction of a mandibular fracture within a 15-minutes time limit without technical assistance that closely resembled the actual surgical outcome that was deemed clinically acceptable. Most importantly the surgeons did not improve significantly when they used the system for a second time without a time limit to simulate the same cases.

Interestingly, all surgeons produced similar “mistakes”. In *Case 1*, a unilateral parasymphyseal fracture, the largest variation and discrepancies of all three surgeon’s simulations in comparison with the actual postoperative outcome were found in the position of the condyle, gonion, and coronoid indication rotation of the proximal segment (Figure 3a). In *Case 2 and 3*, a right parasymphyseal and left angle fracture and a bilateral fracture with a small defect, the position of the gonion and coronoid again varied widely (Figure 3b). In addition, the three surgeons showed similar results that diverged in comparison to the postoperative outcome in the mandibular angle reduction on the fractured side and the length of the mandible in the defect fracture. These results are limited by the sample size and the of use of the the postoperative outcomes as the control, since the systematic errors seen by simulations could be due to a surgical error. However, they may indicate a systemic problem that is most likely due to the limited fidelity of the CAS system based on segmentations of CT images, resulting in limitations of the collision detection algorithms that the surgeon “feels” when manipulating the segments. In addition, our system cannot reproduce occlusal contacts or soft tissue restraints, e.g. the condylar capsule or muscle attachments at this time, that could help anatomical positioning and reduce the errors in the position of the proximal fragments that we observed in our simulation series.

Overall, the surgeons reported that the simulation tool was easy to use and that they would be comfortable implementing the approach in daily clinical practice and education, particularly because it required relatively little time. We believe this is a significant improvement compared to the current WIMP-based simulations systems that are commercially available. The WIMP systems usually require more time for the surgeon to learn how to use them and interaction with the systems often require technical assistance with the simulation task. Furthermore, commercially available WIMP-based systems are designed for orthognathic surgery and dental implant placement (26).

In summary, we have shown that the use of our advanced visuohaptic surgical planning system enables surgeons to simulate mandibular fracture repair quickly and without technical assistance, while achieving acceptable fracture reduction. In future work, we plan to refine the force feedback features of the system to further improve the collision detection between bone fragments (27), using a continuous collision detection algorithm to increase the fidelity and precision of the contacts. In addition, we will include the ability to select virtual osteosynthesis plates and screws from a library, and virtually bend and place the hardware in the computational environment; this will allow for accurate prediction of the specific hardware needs for every case. Our long-term goals are to utilize this system for resident education and to merge this technology into a tele-consultation or tele-consultation network (28, 29). We plan to expand the technology's application for bone reconstructive surgery for maxillary and midface fractures. This technology has the promise of broad application for bony reconstructive surgery in the fields of oral- and maxillofacial, craniofacial, and orthopedic reconstructive surgery in the future.

References:

1. Zinser MJ, Mischkowski RA, Dreiseidler T, Thamm OC, Rothamel D, Zoller JE: Computer-assisted orthognathic surgery: waferless maxillary positioning, versatility, and accuracy of an image-guided visualisation display. Br J Oral Maxillofac Surg, 2013.

2. Benazzi S, Senck S: Comparing 3-dimensional virtual methods for reconstruction in craniomaxillofacial surgery. J Oral Maxillofac Surg 69(4):1184-94, 2011.

3. Hsu SS, Gateno J, Bell RB, Hirsch DL, Markiewicz MR, Teichgraeber JF, Zhou X, Xia JJ: Accuracy of a computer-aided surgical simulation protocol for orthognathic surgery: a prospective multicenter study. J Oral Maxillofac Surg 71(1):128-42, 2013.

4. Liu XZ, Shu DL, Ran W, Guo B, Liao X: Digital surgical templates for managing high-energy zygomaticomaxillary complex injuries associated with orbital volume change: a quantitative assessment. J Oral Maxillofac Surg 71(10):1712-23, 2013.

5. Orentlicher G, Goldsmith D, Horowitz A: Applications of 3-dimensional virtual computerized tomography technology in oral and maxillofacial surgery: current therapy. J Oral Maxillofac Surg 68(8):1933-59, 2010.

6. Schendel SA, Jacobson R, Khalessi S: 3-dimensional facial simulation in orthognathic surgery: is it accurate? J Oral Maxillofac Surg 71(8):1406-14, 2009.

7. Tucker S, Cevidanes LH, Styner M, Kim H, Reyes M, Proffit W, Turvey T: Comparison of actual surgical outcomes and 3-dimensional surgical simulations. J Oral Maxillofac Surg 68(10):2412-21, 2010.

8. Bell RB: Computer planning and intraoperative navigation in orthognathic surgery. J Oral Maxillofac Surg 69(3):592-605, 2011.

9. Sallnäs EL R-GK, Sjöström C.: Supporting presence in collaborative environments by haptic force feedback. ACM Transactions on Computer-Human Interaction (TOCHI 7(4):461-476, 2000.

10. Forsslund J, Chan S, Selesnick J, Salisbury K, Silva RG, Blevins NH: The effect of haptic degrees of freedom on task performance in virtual surgical environments. Stud Health Technol Inform 184:129-35, 2012.

11. Murray DJ, Edwards G, Mainprize JG, Antonyshyn O: Optimizing craniofacial osteotomies: applications of haptic and rapid prototyping technology. J Oral Maxillofac Surg 66(8):1766-72, 2008.

12. Wang Q, Chen H, Wu W, Jin H, Heng P: Real-time Mandibular Angle Reduction Surgical Simulation with Haptic Rendering. IEEE J Biomed Health Inform, 2012.

13. Singapogu RB, Smith DE, Long LO, Burg TC, Pagano CC, Burg KJ: Objective differentiation of force-based laparoscopic skills using a novel haptic simulator. J Surg Educ 69(6):766-73, 2012.

14. Panait L, Akkary E, Bell RL, Roberts KE, Dudrick SJ, Duffy AJ: The role of haptic feedback in laparoscopic simulation training. J Surg Res 156(2):312-6, 2009.

15. Whyms BJ, Vorperian HK, Gentry LR, Schimek EM, Bersu ET, Chung MK: The effect of computed tomographic scanner parameters and 3-dimensional volume rendering techniques on the accuracy of linear, angular, and volumetric measurements of the mandible. Oral Surg Oral Med Oral Pathol Oral Radiol 115(5):682-91, 2013.

16. MacLean K: Haptic Interaction Design for Everyday Interfaces. In: Reviews of Human Factors and Ergonomics; 2008.

17. Han X, Wan H: A framework for virtual hand haptic interaction. In: Transactions on edutainment; 2010. p. 229-240.

18. Morris D, Sewell C, Barbagli F, Salisbury K, Blevins NH, Girod S: Visuohaptic simulation of bone surgery for training and evaluation. IEEE Comput Graph Appl 26(6):48-57, 2006.

19. Cao CG, Zhou M, Jones DB, Schwaitzberg SD: Can surgeons think and operate with haptics at the same time? J Gastrointest Surg 11(11):1564-9, 2007.

20. Zhou M, Tse S, Derevianko A, Jones DB, Schwaitzberg SD, Cao CG: Effect of haptic feedback in laparoscopic surgery skill acquisition. Surg Endosc 26(4):1128-34, 2012.

21. Ruspini DC KK, Khatib O. The haptic display of complex graphical environments. In: ACM SIGGRAPH; 1997; 1997. p. 345-52.

22. Zilles C SJ. A Constraint-based god-object method for haptics display. In: IEEE/RSJ (International Conference on Intelligent Robotics and Systems); 1995; 1995. p. 146-51.

23. Chan S CF, Blevins NH, Salisbury K. Constraint-based six degree-of-freedom haptic rendering of volume-embedded isosurfaces. In: Proceedings of the 2011 IEEE World Haptics Conference (WHC); 2011 Jun 21-24; Istanbul, Turkey; 2011. p. 89-94.

24. Olsson P, Nysjo F, Hirsch JM, Carlbom IB: A haptics-assisted cranio-maxillofacial surgery planning system for restoring skeletal anatomy in complex trauma cases. Int J Comput Assist Radiol Surg 8(6):887-94, 2013.

25. Ullrich S KT, Law YC, Grottke O, Kuhlen T. Influence of the bimanual frame of reference with haptics for unimanual interaction tasks in virtual environments. In: 3D User Interfaces (3DUI), 2011 IEEE Symposium; 2011 19-20 March; 2011. p. 39,46.

26. Schlickum MK, Hedman L, Enochsson L, Kjellin A, Fellander-Tsai L: Systematic video game training in surgical novices improves performance in virtual reality endoscopic surgical simulators: a prospective randomized study. World J Surg 33(11):2360-7, 2009.

27. Weller R: A Brief Overview of Collision Detection. In: New Geometric Data Structures for Collision Detection and Haptics; 2013. p. 9-46.

28. Polushin I, Xiaoping P, Lung C-L: Stability of bilateral teleoperators with generalized projection-based force reflection algorithms. Automatica 48:1005-1016, 2012.

29. Truppe M, Schicho K, Kawana H, Ewers R: Perspectives of teleconsultation in craniomaxillofacial surgery. J Oral Maxillofac Surg 69(3):808-12, 2011.

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Figure 1: Simulation environment with cranial base

Figure 2: Anatomic landmarks and measurements

Figure 3: Simulation of fracture reduction in comparison with postoperative result

Figure 3a: Case 1

Figure 3b: Case 2

Figure 3b: Case 3

Figure 4: Surgeon's questionnaire assessing their experience with the haptic simulation system. The answer are graded on a Likert scale with 1 = not at all /no and 5 = very much/yes.

Figure 1: Simulation environment with cranial base

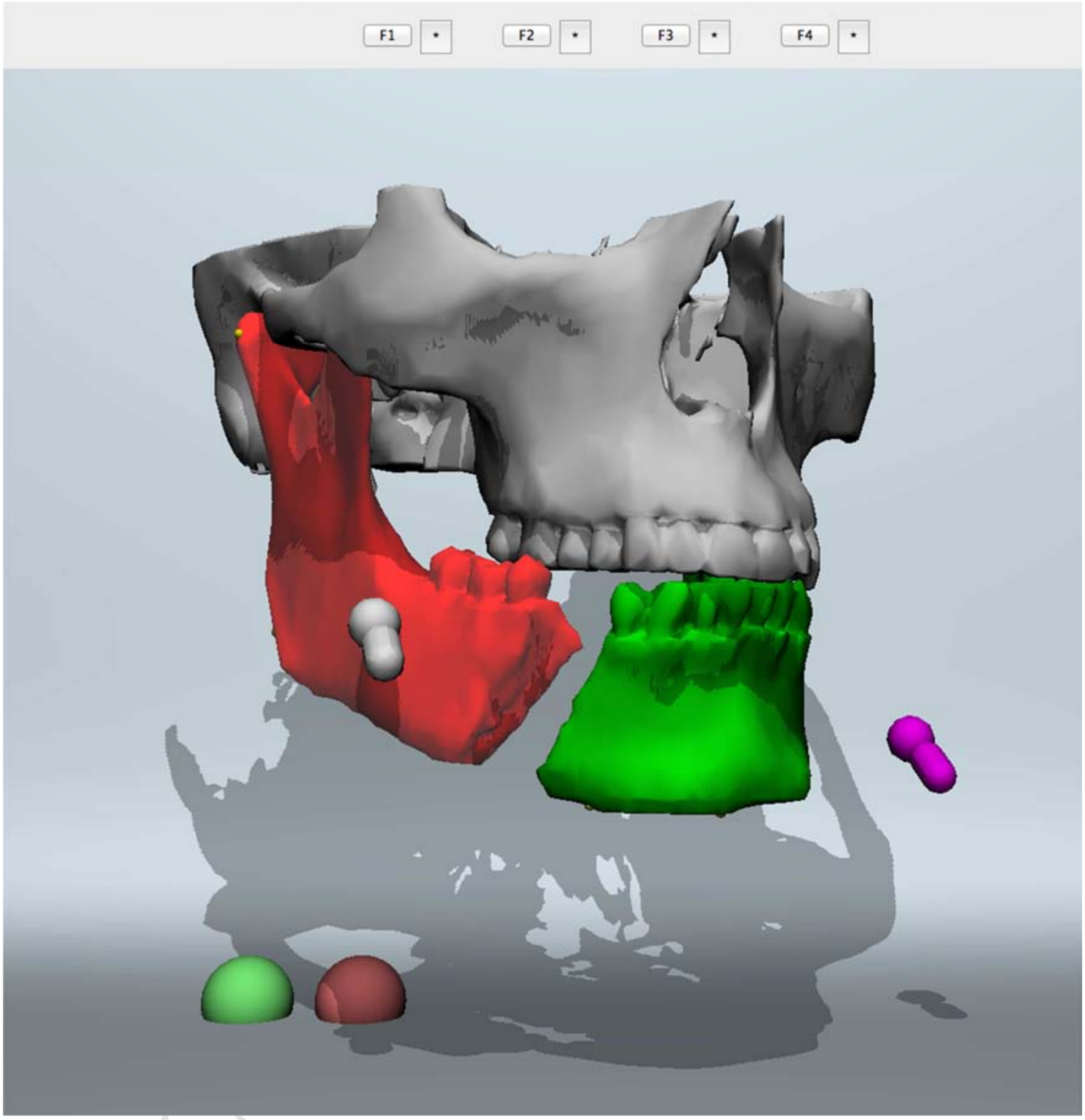
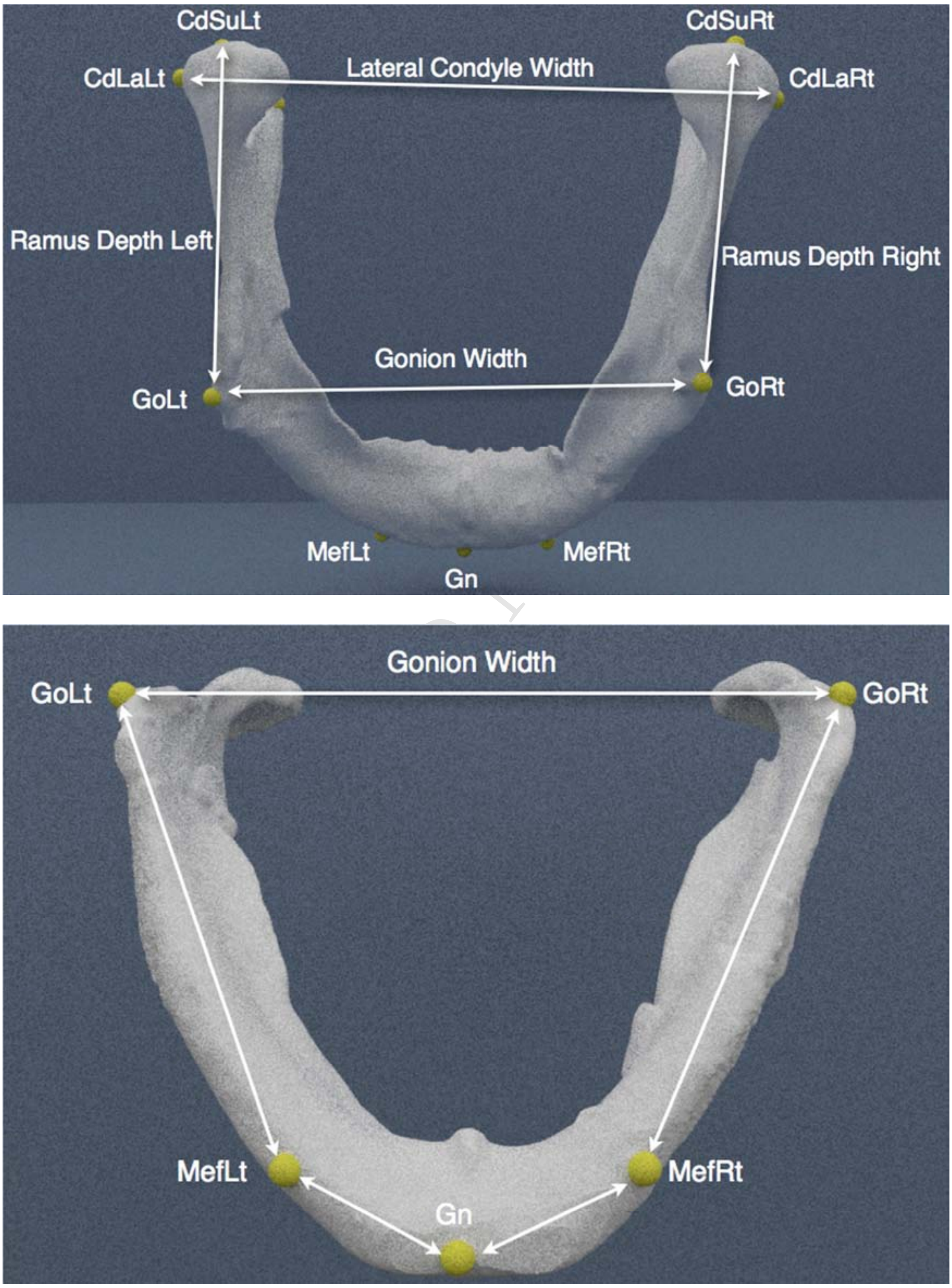


Figure 2: Anatomic landmarks and measurements

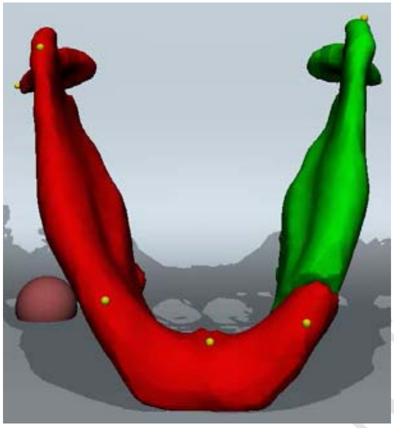


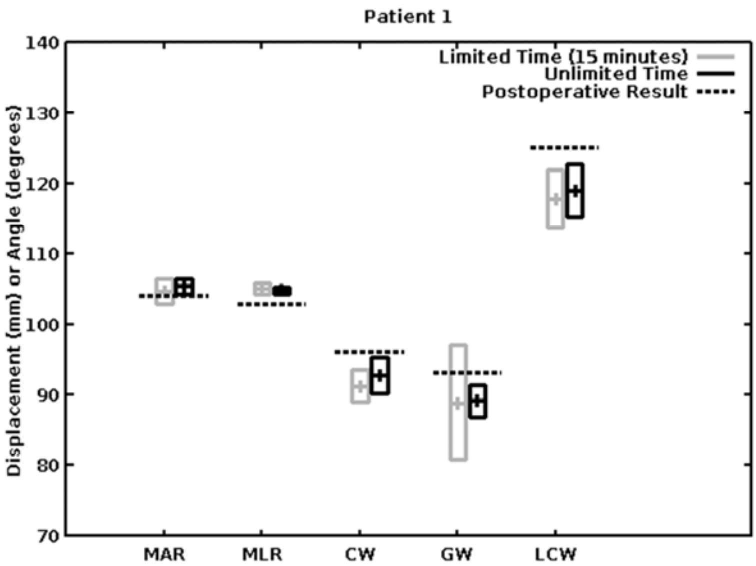
LANDMARK	SIDE	ABBREVIATION
Gonion	Left	GoLt
	Right	GoRt
Condyle Lateral	Left	CdLaLt
	Right	CdLaRt
Condyle Superior	Left	CdSuLt
	Right	CdSuRt
Coronoid process	Left	CoLt
	Right	CoRt
Mental Foramen	Left	MefLt
	Right	MefRt
Gnathion	Central	Gn

MEASUREMENT	ABBREVIATION	SIDE	DEFINITION
Mandible Angle	MAL	Left	<CdLaLt – GoLt - Gn
	MAR	Right	<CdLaRt – GoRt - Gn
Mandible Length	MLL	Left	GoLt-MefLt + MefLt-Gn
	MLR	Right	GoRt-MefRt + MefRt-Gn
Coronoid Width	CW	Left-Right	CoLt-CoRt
Gonion Width	GW	Left-Right	GoLt-GoRt
Lateral Condyle Width	LCW	Left-Right	CdLaLt-CdLaRt

Figure 3: Simulation of fracture reduction in comparison with postoperative result

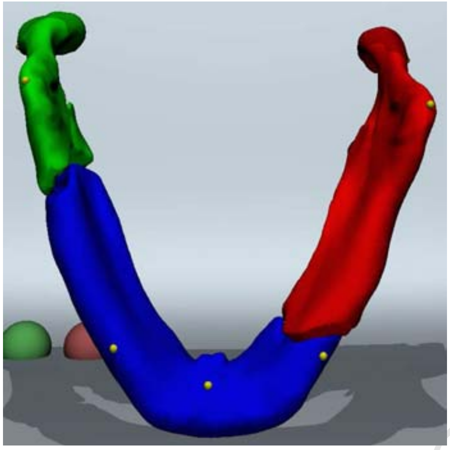
Figure 3a: Case 1





		MAR	MLR	CW	GW	LCW
Postop		**104.130**	**103.023**	**96.084**	**93.242**	**125.144**
15-minute time limit	**Mean**	**104.766**	**105.125**	**91.286**	**88.967**	**117.941**
	Standard Deviation	**±1.748**	**±0.830**	**±2.280**	**±8.142**	**±4.119**
Without time limit	**Mean**	**105.466**	**104.912**	**92.849**	**89.209**	**119.034**
	Standard Deviation	**±1.123**	**±0.479**	**±2.577**	**±2.207**	**±3.653**

Figure 3b: Case 2



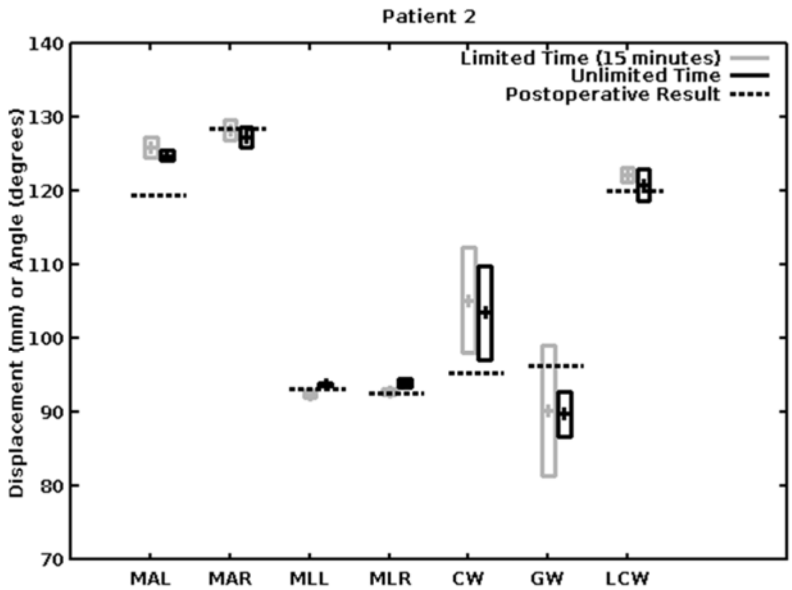


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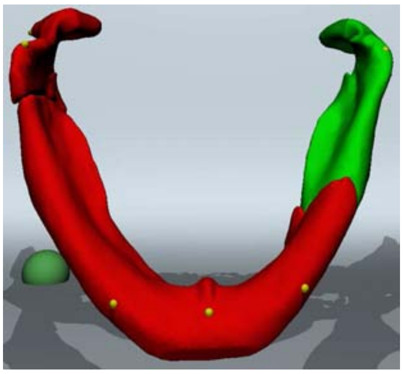
Figure 3b: Case 3



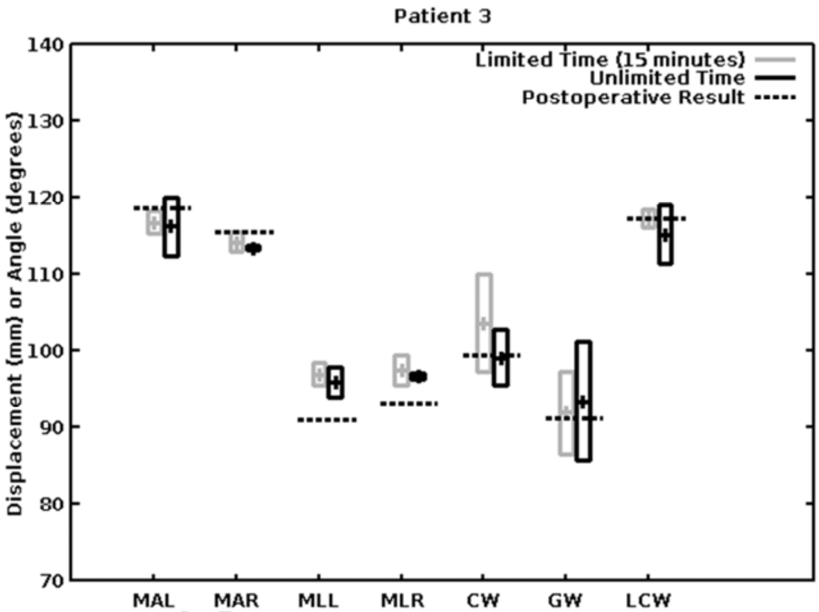


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Figure 4: Surgeon's questionnaire assessing their experience with the haptic simulation system. The answer are graded on a Likert scale with 1 = not at all /no and 5 = very much/yes.