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Development of a surgical navigation system based on 3D Slicer for intraoperative implant placement surgery

Xiaojun Chen^{1,*}, Lu Xu¹, Huixiang Wang², Fang Wang², Qiugen Wang², and Ron Kikinis³

¹Institute of Biomedical Manufacturing and Life Quality Engineering, State Key Laboratory of Mechanical System and Vibration, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, China

²Shanghai First People's Hospital Affiliated to Shanghai Jiao Tong University School of Medicine, Shanghai, China

³Surgical Planning Laboratory, Harvard Medical School, Boston, United States

Abstract

Implant placement has been widely used in various kinds of surgery. However, accurate intraoperative drilling performance is essential to avoid injury to adjacent structures. Although some commercially-available surgical navigation systems have been approved for clinical applications, these systems are expensive and the source code is not available to researchers. 3D Slicer is a free, open source software platform for the research community of computer-aided surgery. In this study, a loadable module based on Slicer has been developed and validated to support surgical navigation. This research module allows reliable calibration of the surgical drill, point-based registration and surface matching registration, so that the position and orientation of the surgical drill can be tracked and displayed on the computer screen in real time, aiming at reducing risks. In accuracy verification experiments, the mean target registration error (TRE) for point-based and surface-based registration were 0.31 ± 0.06 mm and 1.01 ± 0.06 mm respectively, which should meet clinical requirements. Both phantom and cadaver experiments demonstrated the feasibility of our surgical navigation software module.

Keywords

implant placement; 3D Slicer; surgical navigation

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* Address correspondence to: Xiaojun Chen, PhD, Room A-805, School of Mechanical Engineering, Shanghai Jiao Tong University, Dongchuan Road 800, Minhang District, Shanghai, China, Post Code: 200240, xiaojunchen@163.com, Tel: (+86)-21-34204851, Fax: (+86)-21-34206847.

Conflicts of Interest

None declared.

Competing Interests

None declared.

Ethical Approval

The authors confirm that the use of cadaveric tissues was approved by Institutional Review Board (IRB) of Shanghai First People's Hospital affiliated to Shanghai Jiao Tong University School of Medicine, and all ongoing and related trials were registered.

Introduction

Various applications of implant placement have been utilized for clinical treatments in the fields of orthopedics, oral and maxillofacial surgery, spine surgery, and more [1–3]. For example, zygoma implants are used for functional reconstruction of maxillary defects [4], iliosacral screw insertions are utilized for treating pelvic fractures [5], and pedicle screw placement is adopted for spine surgery [6]. However, intraoperative drilling performance still poses a significant challenge for surgeon due to anatomic intricacies in the surgical region. Aiming at improving the safety of surgery, the intraoperative guidance may help avoid damaging critical adjacent structures such as nerves and blood vessels since it can control the position and orientation of the surgical drill during the surgery.

Over the past decades, the field of computer-aided surgery has experienced tremendous development due to the rapid growth of computing power and improvements in imaging modalities [7]. Based on the guidance of preoperative planning with Computed Tomography (CT), Magnetic Resonance Imaging (MRI), and other volumetric image data associated with the patient, surgical navigation systems are being widely used in various kinds of surgery (such as neurosurgery, orthopedics, ENT, oral and maxillofacial surgery, etc.) to minimize the risks and improve the precision of surgery [8]. Some commercially available surgical navigation systems have been approved for clinical applications, including Curve (Brainlab AG, Germany), StealthStation (Medtronic, USA), eNLight and NavSuite (Stryker Corporation, USA), and Navigation Panel Unit (Storz, Germany). However, the main disadvantages of commercially available surgical navigation systems lie in two aspects: for one thing, their high-costs limit the utilization in clinical applications; for another, the source code is not available to researchers regarding the calibration of surgical instruments, registration, intraoperative motion tracking, etc.

In this study, a free, open source powerful software package for visualization and medical image computing called 3D Slicer, or Slicer (Brigham Women's Hospital, Boston, MA), was used as a platform for developing a surgical navigation loadable module named "Surgical Navigation System" (SNS). The source code can be cloned or downloaded using GitHub or checkout with SVN via the web URL: <https://github.com/lucien7/SNS.git>. This module was then evaluated through both phantom and cadaver experiments, demonstrating that the risks of intraoperative drilling performance could be reduced in anatomically complex operation sites.

Materials and Methods

The navigation software workflow based on Slicer

Figure 1 shows the workflow and functions of the surgical navigation system based on Slicer (green) and the supporting algorithms and techniques (yellow). The framework of the software starts with loading the preoperative CT data and ends with the real-time navigation, the details of which are described as follows:

1. Loading of the original CT data: The patient is CT scanned and the acquired images are automatically transferred to the Slicer interface via the “DICOM” module.
2. Image processing: Based on the CT data, the images can be segmented via the “Editor” module. Slicer provides various image segmentation methods for satisfying different requirements such as threshold segmentation, region growing, and manual modification, so that hard and soft tissues can be marked.
3. 3D-Reconstruction: After image segmentation, the 3D surface models are reconstructed using the Marching Cubes algorithm [9]. All of the 3D modelling in this step is processed through the “Models” module of 3D Slicer.
4. Preoperative planning: On the basis of these CT images and the 3D models, the user implements preoperative surgical planning and 3D geometrical measurements via the Slicer ruler. When the entry point and target point are selected, the user can create a trajectory connecting these two points and it can be adjusted in real-time. The virtual optimal path will be rendered on all of the 2D/3D views.
5. Communication with the optical tracking device: The Polaris Vicra optical tracking device is activated and initialized via the “SNS” module.
6. Calibration of the surgical instruments: Since the Polaris optical tracking system can only allow localization of the reference frames with the mounted sphere-shaped retro-reflective markers, it is necessary to determine the spatial relationship between the surgical instruments and the reference frames via the “SNS” module.
7. Registration: The basic requirement for any surgical navigation technique is registration, which is the process of bringing two coordinate systems into spatial alignment [7]. In the most common clinical scenario, the patient’s position must be registered (aligned) with the preoperative image data set. There are a variety of registration methods, including paired points [10–12] and surface matching [13, 14] concepts, which have been proposed in this study.

Navigation system setup

Figure 2(a) is a schematic layout of the navigation system in which the tracking device is used for intraoperative motion tracking and the all-in-one computer running 3D Slicer is responsible for visualization.

The tracking data are acquired using the Polaris Vicra optical tracking device through a position sensor that detects infrared-emitting or retro-reflective markers affixed to a tool or object with a maximum rate of 20Hz. The all-in-one computer has an IntelCorei7 processor, 8GB RAM, and an AMD Radeon HD 7650A graphics card, and it runs under the Windows 7 operating system.

This navigation system has been validated by a relevant cadaver experiment for percutaneous implantation of a sacroiliac joint screw in an operating room. Major changes

are not required to the existing layout in order to integrate it into a clinical environment, and the setup time is not long (approximately 10 min).

Calibration and Registration

A calibration tool was designed and manufactured in this study. The “Pivot Calibration” is conducted to calculate the offset values of the tip point of the instrument. To do so, the surgical instrument must be slowly pivoted around the tip for approximately half a minute in the Polaris optical tracking system. The offset values can be calculated on the basis of the collected data (about 250 frames regarding the movement of the reference frame) [15]. As for the calibration of the axis of the surgical drill, the drill is inserted into the pre-fabricated axial hole (shown in Figure 2(b)) so that the direction vector of the drill, relative to the coordinate system of the reference frame can be obtained using the algorithms described in reference [15].

As for real time motion tracking, the spatial relationship among the various coordinate systems in the navigation system (shown in Figure 2(c)) can be determined using the method described in reference [2], so that the movements of the patient and surgical instruments can be rendered in real time in the preoperative image coordinate system. Nevertheless, the registration plays an important role in this procedure, and there are two registration methods provided in the “SNS” module. One is fiducial point-based method, the other one is anatomical landmark combined with surface-based method. In actual surgery, the fiducial point-based registration method is usually with high precision. However, the fiducial titanium screw markers cannot always be inserted in patients, since this procedure is invasive and sometimes patients cannot accept it. Therefore, anatomical landmark combined with surface-based method [16] is another alternative in the “SNS” module to improve the accuracy of the initial registration based on anatomical landmark pairs. The principle of this method is to seek the closest measured point corresponding with the target point set through repeated iterations. It is an optimal matching algorithm based on the least square method, and the registration will be accomplished until the residual sum of squares is less than the preset threshold.

Phantom experiment

The feasibility of the navigation system was validated through a phantom experiment in which an iliosacral screw was inserted into a plastic anatomic model of the human pelvis. First, on the basis of the CT-scanned data of the phantom, a 3D pelvic model was reconstructed through the “Models” module in Slicer and a preoperative planned drilling trajectory was designed. Then, the calibration of instruments, including the positioning probe and the surgical drill, was conducted in the “SNS” module.

The anatomical landmark combined with surface-based registration method was adopted in this phantom experiment. First, three pelvic osteal landmarks (the anterior superior spine, tuberculum pubicum and posterior superior iliac spine) were selected in the images as the fiducials. After the initialization of the Polaris optical tracking device, the coordinates of the fiducials under the reference coordinate system (RCS) were obtained using the positioning probe (shown in Figure 3(a)). With these two paired lists of fiducial points (shown in Figure

3(b)), an initial registration transformation matrix was generated. Then, the positioning probe was used to obtain the point cloud of the pelvic model for further surface-based registration aiming at the accuracy improvement. Finally, the movement of the surgical drill was rendered in the preoperative image coordinate system in real time (shown in Figure 3(c)). In addition, a volumetric image of the patient can be resliced with the plane along the surgical tool and the sectional image can be visualized on the 2D and 3D viewers in the 3D Slicer window in the “Volume Reslice Driver” module, which is particularly useful for stereotactic surgical navigation (also shown in Figure 3(c)).

After the guide pin for the sacroiliac screw was inserted into the pelvic model under the image-guided system, a post-operative CT scan was conducted. Thus, the angular error and distance deviations of the entry and exit points of the guide pin could be measured in Slicer (shown in Figure 3(d)). The results demonstrated that the distance deviations of the entry and exit points between the preoperative planned and post-operative drilling trajectory were 0.37mm and 0.72mm, respectively, and the angular error was 1.53°.

This navigation system can be also used for other kinds of surgeries, such as oral implantology and pedicle screw insertion. Figure 3(e) shows its application in the zygoma implant placement surgery. The drill can be navigated on the computer screen in real time, according to the preoperative planned drill trajectory. The implant can then be inserted into the appropriate position and orientation. Figure 3(f) shows a case of translaminar screw fixation in cervical spine surgery. The translaminar screw placement was precisely performed in the navigation environment.

Cadaver experiment

We have also conducted a cadaver experiment for the percutaneous implantation of sacroiliac joint screws in an operating room. Before the cadaver was CT scanned, six titanium miniscrews were inserted into the pelvis as fiducial markers for the registration. Based on these 3D-reconstructed anatomical structures (pelvis, bladder, etc.) and the CT data, intraoperative planning was conducted. The surgeon determined the inserted point of the sacroiliac joint screw and adjusted its axial orientation to avoid important anatomical structures. Figure 4(a) shows an optimal surgical drill trajectory created in preoperative planning. Then, the surgeon used the “SNS” module to perform the pivot calibration and axis calibration of the positioning probe and surgical drill. After the completion of registration (shown in Figure 4(c)), the surgeon was able to insert the sacroiliac joint screw in the appropriate position and orientation under the intraoperative navigation environment, avoiding injury to critical anatomical structures (shown in Figure 4(b)).

In terms of accuracy, postoperative CT scanning data showed that the screw was precisely placed in the ideal position and orientation. The deviation between the planned and the inserted screw position was 0.84mm at the bony entry point of the screw, and 1.57mm at the tip of the screw. The angular deviation was 1.85°.

Results

Accuracy verification of the navigation system

The verification process for accuracy includes all procedures during the navigation surgery. Figure 5(a) shows the precision verification device designed and manufactured in this study, which is composed of three components: a metal base, an organic glass substrate, and a nylon cranio-maxillofacial model. The accuracy verification was performed as follows: The nylon cranio-maxillofacial and organic glass substrate were 3D reconstructed through CT scanning and assembled with the metal base modeled by the UG (Unigraphics NX, Siemens PLM Software, Germany) software. The point-based registration and surface-based registration were then implemented using the fiducial landmarks on the metal base and on the surface of the nylon cranio-maxillofacial model respectively. The result data of the accuracy verification for the navigation system were obtained on the basis of these fiducial landmarks.

In order to ensure the validity and reliability of the accuracy verification, the workflow of the experiment is consistent with the actual navigation surgery. It is described as follows:

1. Fix the reference frame on the verification device so that it can be tracked by the NDI Polaris Vicia optical localizer.
2. Using the methods presented above, calibrate the probe, including the “Pivot Calibration” and “Axis Calibration”.
3. Collect 5 or 6 fiducial landmarks on the surface of the metal base through the probe, and pick corresponding points on the virtual 3D model using the mouse. The least number of fiducial landmarks for rigid body registration is 3 points. However, the accuracy of point-based registration can be improved using 5 or 6 points since it can avoid near-collinear configurations, and ensure that the centroid of the fiducial points is as near as possible to the target [11]. The point-based registration can then be performed.
4. Use the probe to pick 175 fiducial landmarks on the surface of the metal base in succession, and record the actual coordinate of each point $P_i (P_{ix}, P_{iy}, P_{iz})$. The actual coordinate is then compared with the theoretical coordinate of each point $P_i^* (P_{ix}^*, P_{iy}^*, P_{iz}^*)$ to obtain the distance error P_{ierr}

$$P_{ierr} = \sqrt{(P_{ix} - P_{ix}^*)^2 + (P_{iy} - P_{iy}^*)^2 + (P_{iz} - P_{iz}^*)^2}, (i=0, 1, 2 \dots, 174) \quad (1)$$

5. Insert the probe into the 40 axial holes, and record the actual axial direction $A_j (A_{ix}, A_{iy}, A_{iz})$. The actual axial direction is compared with the theoretical axial direction $A_j^* (A_{ix}^*, A_{iy}^*, A_{iz}^*)$ to obtain the angle error A_{jerr}

$$A_{ierr} = \cos^{-1}[(A_{ix} \cdot A_{ix}^* + A_{iy} \cdot A_{iy}^* + A_{iz} \cdot A_{iz}^*) / (\sqrt{A_{ix}^2 + A_{iy}^2 + A_{iz}^2} \times \sqrt{A_{ix}^{*2} + A_{iy}^{*2} + A_{iz}^{*2}})], (i=0, 1, 2 \dots, 39)$$

(2)

For the accuracy of surface-based registration, the point cloud on the surface of the nylon craniomaxillofacial model was collected. The distance and angle errors were then obtained by repeating procedures of (4) and (5).

The results of the accuracy verification experiment

Figure 5(b) and Figure 5(c) show the regional division for fiducial landmarks and axial holes on the metal base.

As for the point-based registration experiment, the different fiducial landmarks in regions 6 and 4 were selected as registration points for three repeated measurements of distance and angle errors (the results are shown in Table 1). During the three point-based registration processes, the maximum distance errors of all fiducial landmarks were 0.75mm, 0.92mm and 0.79mm, and the mean distance errors were 0.30 ± 0.07 mm, 0.31 ± 0.06 mm and 0.30 ± 0.05 mm. The maximum angle errors of all axes were 0.94° , 0.43° and 0.76° , and the mean angle errors were $0.66 \pm 0.16^\circ$, $0.26 \pm 0.09^\circ$ and $0.40 \pm 0.16^\circ$. These results indicate that the distance and angle errors in each point-based registration process remain at similar values in the same region, and that error distribution is also relatively average in different regions.

The surface-based registration experiment was based on anatomical landmark-based registration. The result of each anatomical landmark-based registration was set as the initial value for the surface-based registration. The point cloud was collected on the surface of the nylon cranio-maxillofacial model to complete the surface-based registration so that the distance and angle errors of all fiducial landmarks could be measured, and the results of three repeated measurements are shown in Table 2. During the three surface-based registration processes, the maximum distance errors of all fiducial landmarks were 1.16mm, 1.12mm and 1.20mm, and the mean distance errors were 1.00 ± 0.04 mm, 0.98 ± 0.04 mm and 1.01 ± 0.06 mm. The maximum angle errors of all axes were 1.46° , 1.43° and 1.39° , and the mean angle errors were $1.07 \pm 0.10^\circ$, $1.06 \pm 0.11^\circ$ and $1.09 \pm 0.09^\circ$.

Discussion

Implant placement surgery has been widely used for clinical applications in orthopedics, oral implantology, spine surgery, and more. Compared with traditional open reduction and internal fixation, the advantages of the screw insertion technique in the clinical treatment lie in that it results in less trauma, less intraoperative blood loss, a lower infection and necrosis rate, and speeds up recovery time [17]. However, due to the anatomic intricacies and the screw length, it is still a challenge to control the intraoperative position and orientation of the surgical drill.

Currently, compared to the traditional X-ray C-arm system, 2D or 3D computer-aided navigation systems can significantly improve the precision and safety of implant placement surgery and reduce intraoperative X-ray fluoroscopy time [1]. Over the past years, commercially available navigation systems have been developed for various kinds of surgery, aiming at minimizing the surgical risks. For example, Behrendt et al. (2012) evaluated 2D- and 3D-navigation for iliosacral screw fixation using BrainLAB navigation systems [18]. Sun et al. (2013) conducted 85 cases of bimaxillary orthognathic surgery through BrainLab's navigation system [19]. Inui et al. (2013) implemented 82 cases of computer-assisted total knee arthroplasty with the use of Stryker navigation systems [20]. However, due to the high cost of these commercial navigation systems and the lack of software expandability, the surgeons' individual requirements cannot be met.

Therefore, 3D Slicer has been used for various studies in the community of computer-aided surgery, supporting the development of extension modules. For example, Ungi et al. (2012) developed a free, open source surgical navigation software module of "SlicerIGT" for the facet joint injections to improve the success rate and time efficiency [21]. However, the limitation of the current "SlicerIGT" module lies in that it focuses more on the execution of the US-guided intervention, while planning, calibration, and confirmation of the procedure are also important parts of the image-guided surgery as a whole. In conclusion, though some papers have been published regarding surgical navigation systems based on Slicer, applications in implant placement are rarely reported.

In this study, a new loadable module ("SNS" module) based on Slicer was developed in order to achieve computer-aided navigation, aiming at improving the precision of intraoperative drilling performance. The software module allows the calibration of surgical tools, including "Pivot calibration" and "Axis calibration of the surgical drill," high-accuracy registration (point-based and surface matching), intraoperative motion tracking, and virtual intraoperative CT imaging. The implementation and workflow of the designed Slicer module has been described in detail and validated through phantom and cadaver experiments. In addition, the "SNS" module is applicable to various surgeries such as ear, nose, throat and oral implantology, and it is open source and freely available to the global research community.

Based on the three repeated accuracy verification experiments, the mean target registration error (TRE) of point-based registration was 0.31 ± 0.06 mm, and the stable data deviations demonstrated the repeatability of our navigation module. Although the precision of the surface-based registration was slightly lower than point-based registration, the maximum distance and angle errors could still meet the precision requirement for the surgery. In addition, the precision was within the range of approximately 1 mm and 1° , which is comparable to commercially available navigation systems [1, 20, 22].

However, this is a pilot study and there are still challenges which require further research and exploration, and more clinical cases must be conducted to demonstrate the feasibility and reliability of this navigation software module. In addition, since the "SNS" module is only for the drilling performance, the calibration of surgical saw will be added for osteotomy in the near future.

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Figure 1.
The workflow and functions of the surgical navigation system based on Slicer.

Figure 2.

(a) Schematic layout of the navigation system. (b) The calibration for the surgical drill axis.

(c) The establishment of coordinate systems for real-time tracking in Slicer.

Figure 3.

(a) Using a positioning probe to collect the coordinates of the fiducial points. (b) Two paired list of fiducial points. (c) The position of the drill is tracked and rendered on the computer screen. (d) The measurement of the angular error and the distance deviations between the planned preoperative and post-operative drilling trajectory. (e) The phantom experiment of the oral implantology. (f) The phantom experiment of the pedicle screw insertion.

Figure 4.
 (a) Designing preoperative surgical planning. (b) The drilling performance for a cadaver experiment. (c) Using a positioning probe to collect the coordinates of the fiducial points.

Figure 5.

(a) The accuracy verification device. (b) The regional division for fiducial landmarks. (c) The regional division for axial holes.

The three repeated experiments of point-based registration.

Region	Distance error (mm)					Angle error (°)												
	Maximum		Minimum		Mean	Maximum		Minimum		Mean								
1	0.33	0.40	0.52	0.10	0.13	0.09	0.20	0.26	0.29	0.76	0.33	0.76	0.65	0.11	0.44	0.73	0.21	0.61
2	0.75	0.83	0.65	0.11	0.14	0.13	0.38	0.41	0.33	0.47	0.43	0.62	0.21	0.35	0.44	0.36	0.40	0.51
3	0.48	0.63	0.28	0.22	0.10	0.13	0.32	0.29	0.24	0.50	0.36	0.60	0.37	0.30	0.37	0.45	0.33	0.42
4	0.43	0.43	0.32	0.06	0.20	0.17	0.24	0.30	0.22	0.70	0.38	0.59	0.64	0.06	0.26	0.67	0.20	0.40
5	0.66	0.68	0.79	0.16	0.13	0.08	0.30	0.33	0.36	0.94	0.40	0.67	0.70	0.17	0.39	0.81	0.30	0.55
6	0.33	0.39	0.36	0.07	0.12	0.24	0.19	0.26	0.30	0.83	0.16	0.26	0.69	0.14	0.13	0.76	0.14	0.19
7	0.55	0.35	0.55	0.12	0.14	0.18	0.29	0.23	0.33	0.76	0.25	0.17	0.64	0.10	0.09	0.70	0.15	0.13
8	0.63	0.71	0.37	0.07	0.11	0.12	0.36	0.29	0.20	0.86	0.39	0.67	0.74	0.25	0.38	0.80	0.31	0.42
9	0.36	0.37	0.47	0.11	0.10	0.13	0.23	0.24	0.28	—	—	—	—	—	—	—	—	—
10	0.63	0.92	0.79	0.16	0.17	0.17	0.40	0.42	0.37	—	—	—	—	—	—	—	—	—
11	0.58	0.65	0.76	0.18	0.11	0.07	0.34	0.27	0.30	—	—	—	—	—	—	—	—	—
12	0.62	0.84	0.69	0.07	0.25	0.14	0.32	0.39	0.35	—	—	—	—	—	—	—	—	—
Total	0.75	0.92	0.79	0.06	0.10	0.07	0.30	0.31	0.30	0.94	0.43	0.76	0.21	0.06	0.09	0.66	0.26	0.40

Table 2

The three repeated experiments of surface-based registration.

Region	Distance error (mm)						Angle error (°)					
	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean
1	1.13	1.07	1.08	1.12	0.89	0.99	1.01	1.10	0.87	0.89	0.94	1.01
2	1.14	1.14	0.99	1.08	0.87	1.06	1.27	1.24	0.97	0.98	1.05	1.11
3	1.12	1.10	0.98	1.06	1.05	0.98	1.11	1.00	0.94	0.85	0.86	0.90
4	1.14	1.14	0.94	1.01	0.85	1.03	1.03	1.21	0.77	0.94	1.00	0.98
5	1.08	1.04	0.98	1.05	0.95	0.95	1.46	1.38	1.10	0.96	1.05	1.19
6	1.10	0.92	0.91	0.96	0.83	0.89	1.27	1.38	1.04	1.12	0.93	1.23
7	1.09	1.08	0.98	1.07	0.91	0.96	1.19	1.39	0.92	0.90	1.09	0.94
8	1.13	1.08	0.97	1.06	0.87	1.02	1.39	1.27	0.95	1.04	0.99	1.13
9	1.16	1.11	0.95	1.03	1.01	1.03	-	-	-	-	-	-
10	1.14	1.13	1.02	1.10	0.91	1.04	-	-	-	-	-	-
11	1.04	1.17	0.91	1.03	0.91	1.08	-	-	-	-	-	-
12	1.03	1.20	1.00	1.12	0.86	1.11	-	-	-	-	-	-
Total	1.16	1.20	0.98	1.12	0.85	1.01	1.46	1.43	0.77	0.85	0.86	1.06
												1.07
												1.09