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Surface-based registration accuracy of CT-based image-guided spine surgery

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Abstract Registration is a critical and important process in maintaining the accuracy of CT-based image-guided surgery. The aim of this study was to evaluate the effects of the area of intraoperative data sampling and number of sampling points on the accuracy of surface-based registration in a CT-based spinal-navigation system, using an optical three-dimensional localizer. A cadaveric dry-bone phantom of the lumbar spine was used. To evaluate registration accuracy, three alumina ceramic balls were attached to the anterior and lateral aspects of the vertebral body. CT images of the phantom were obtained (1-mm slice thickness, at 1-mm intervals) using a helical CT scanner. Twenty surface points were digitized from five zones defined on the basis of anatomical classification on the posterior aspects of the target vertebra. A total of 20 sets of sampling data were obtained. Evaluation of registration accuracy accounted for positional and rotational errors. Of the five zones, the area that was the largest and easiest to expose surgically and to digitize surface points was the lamina. The lamina was defined as standard zone.

On this zone, the effect of the number of sampling points on the positional and rotational accuracy of registration was evaluated. And the effects of the additional area selected for intraoperative data sampling on the registration accuracy were evaluated. Using 20 surface points on the posterior side of the lamina, positional error was $0.96 \text{ mm} \pm 0.24 \text{ mm}$ root-mean-square (RMS) and rotational error was $0.91^\circ \pm 0.38^\circ$ RMS. The use of 20 surface points on the lamina usually allows surgeons to carry out sufficiently accurate registration to conduct computer-aided spine surgery. In the case of severe spondylosis, however, it might be difficult to digitize the surface points from the lamina, due to a hypertrophic facet joint or the deformity of the lamina and noisy sampling data. In such cases, registration accuracy can be improved by combining use of the 20 surface points on the lamina with surface points on other zones, such as on the both sides of the spinous process.

Keywords Surgical navigation · Spine surgery · Computed tomography · Accuracy

Introduction

Computer navigation systems are powerful surgical tools in spinal instrumentation surgery. Advances in three-dimensional (3D) image reconstruction and

computer science have, over the past several years, allowed for the application of such image-guided systems to clinical problem solving, and surgeons performing spine surgery have found procedures involving computer navigation systems to be superior to conventional

methods in terms of improved safety and accuracy of pedicle screw insertion.

Numerous clinical trials of CT-based spinal-navigation systems have been reported [2, 7, 10, 11, 15, 16, 14, 18, 19, 20], and fluoroscopy-based navigation systems have been recently applied to computer-aided spine surgery [6, 21]. Although fluoroscopy-based navigation systems do not require preoperative CT imaging or registration, CT-based navigation systems offer advantages of precise preoperative planning and 3D visualization of patient anatomy in the operating room. CT-based navigation systems were developed to avoid misplacement of pedicle screws, and all of these systems use some type of 3D localizer, involving optical [5, 12, 17], magnetic [1], or sonic techniques [4].

Current CT-based navigation systems typically include a measurement process for sampling patient-specific medical data, a decision-making process for generating the surgical plan, a registration process for aligning the surgical plan to the patient, and an action process for accurately achieving the goals specified in the plan.

Registration is a critical and important process in maintaining the accuracy of CT-based image-guided surgery. Accuracy is affected by various conditions such as the area designated for intraoperative data sampling and number of data-sampling points used in surface-based registration. However, most previous reports have focused only on the overall accuracy of navigation systems. Nolte et al. performed an accuracy evaluation of their computer navigation system, using histological pedicle sections in a cadaveric study [17], [19] while Amiot et al. calculated overall system accuracy by measuring rectangular artificial objects [1]. Few studies have investigated registration accuracy of spinal computer-navigation systems specifically [8]. In particular, it remains unclear which sampling area should be used and how many sampling points should be selected in the clinical application of CT-based navigation systems.

The goals of this study were to evaluate the accuracy of surface-based registration when using a CT-based spinal-navigation system and to determine the clinically acceptable conditions for registration, by investigating the effect of the intraoperative sampling area selected and number of sampling points on registration accuracy.

Materials and methods

Navigation system

The Optotrak 3020 system (Northern Digital, Waterloo, Ontario, Canada) was used as the 3D optical localizer. Our navigation system consisted of an Optotrak camera, Optotrak pen probe with 24 active infrared light-emitting diodes (LEDs), custom dynamic reference frame

with four active LEDs, and a UNIX-based Sun UltraSPARK workstation (Sun Microsystems, Mountain View, CA, USA).

Phantom model and image acquisition

A cadaveric dry-bone phantom of the lumbar spine was prepared for this study. To provide the positional ground truth, three alumina ceramic balls with a 22-mm diameter (Bioceram, Kyocera, Kyoto, Japan) were attached to the anterior and lateral aspects of the vertebra body (L4) using bone cement (Fig. 1).

Continuous CT images (1-mm slice thickness at 1-mm intervals) of the phantom were obtained using a helical CT scanner (HiSpeed Advantage, GE Medical Systems, Milwaukee, WI, USA). The field of view (FOV) was 280 mm with a 512×512 matrix. A surface model of the phantom was reconstructed from acquired CT images using the marching cubes algorithm [13].

Registration technique

In surface-based registration, the iterative closest points algorithm (ICP algorithm) [3] with the least-squares method was used to match intraoperative sampling data with the computer surface model of the vertebra. Initially, five characteristic anatomic landmarks were obtained from the tip of the spinous process and the superior and inferior articular processes, for use as the starting position for surface-based registration. Additional surface points on several aspects of the vertebrae were used for surface-based registration.

Fig. 1 Dry-bone phantom model of lumbar spine. *Black arrows* indicate alumina ceramic balls

Evaluation methods

The phantom was placed in a position corresponding to a prone patient, to simulate open back surgery. The dynamic reference frame was clamped and fixed to the spinous process.

Positional ground truth was determined as follows. Sampling points ($n = 500$) were digitized at random from the entire surface of each ceramic ball using the Optotrak pen probe. The position of each ceramic ball center was calculated from these 500 sampling points, using the least-squares-method approximation for a sphere. The center of each ceramic ball in the computer surface model was estimated as the center of the best-fit sphere to the ball. Matching the three ball centers of the real object with those of the computer surface model was conducted using the ICP algorithm.

Next, the bilateral posterior aspects of the vertebra were divided into five zones according to anatomical classification (Fig. 2):

- Zone A: tip of the spinous process
- Zone B: right and left sides of spinous process
- Zone C: posterior side of the lamina
- Zone D: posterior sides of right and left transverse processes
- Zone E: posterior sides of right and left superior and inferior articular processes

From each of the five zones, 20 surface points were digitized at random, by individually touching each point, and the same numbers of sampling points were obtained from the right and left regions of each zone. Twenty data sets of surface points were collected.

Fig. 2 Photograph showing the five sampling zones of the posterior portion of the L4 vertebra. (A) tip of the spinous process; (B) right and left sides of spinous process; (C) posterior side of the lamina; (D) posterior sides of right and left transverse processes; (E) posterior sides of right and left superior and inferior articular processes

For evaluating registration accuracy, positional error was calculated as the mean distance between the ball centers of the real phantom and the computer surface model. Rotational error was defined as the mean angular difference of the vectors through two of the three ball centers between the real phantom and the computer surface model.

Of the five zones, the lamina (zone C) is the largest and the most easily accessible area under clinical conditions. The lamina (zone C) was defined as standard area. On this zone, the effect of number of sampling points on the positional and rotational accuracy of registration was evaluated. And the effects of the additional area selected for intraoperative data sampling on the positional and rotational accuracy of registration were evaluated.

Statistical analysis

Significant differences in registration accuracy based on the number of sampling points were determined by the Mann–Whitney U-test. Analysis of variance (ANOVA) followed by the Bonferroni–Dunn test were used for multigroup comparisons of all significant variables.

Results

Once the position of ground truth was determined, the mean difference between the three ball centers of the real object and those of the computer surface model was determined to be 0.06 mm.

In zone C (posterior side of the lamina), registration accuracy increased as the number of sampling points increased, and reached saturation at 20 surface points for both positional and rotational errors (Fig. 3a, b). Saturation point was determined by comparing registration accuracy using 20 surface points on zone C. Positional error using 20 surface points was found to be $0.96 \text{ mm} \pm 0.24 \text{ mm}$ root-mean-square (RMS), and rotational error was $0.91^\circ \pm 0.38^\circ$ RMS.

For the next step, we defined these 20 surface points on zone C as the baseline, and we proceeded to study changes in accuracy by combining other zone digitization (Fig. 4a, b). When 20 surface points on zone A (tip of the spinous process) were added to the baseline (20 surface points on zone C), positional and rotational errors increased. However, when the baseline was combined with 20 surface points on zone B (right and left sides of the spinous process), positional error significantly decreased ($p < 0.001$), and rotational error tended to decrease. By combining the baseline with 20 surface points on zone B, positional error was a mean of $0.74 \text{ mm} \pm 0.19 \text{ mm}$ RMS, and rotational error was $0.74^\circ \pm 0.25^\circ$ RMS.

Fig. 3 a Positional error of zone C (both sides of the lamina). (# indicates $p < 0.01$); **b** Rotational error of zone C (both sides of the lamina). (# indicates $p < 0.01$)

When we combined the baseline with 20 surface points on zone D (posterior sides of right and left transverse processes), positional and rotational errors significantly decreased ($p = 0.0025$). When the baseline was combined with 20 surface points on zone E (posterior sides of right and left superior and inferior articular processes), positional and rotational errors significantly decreased ($p < 0.001$).

When the 20 surface points on zone C were used, registration residue was 0.15 mm. When the 20 surface points on the other zones were used in combination with the 20 surface points on zone C, registration residues were less than 0.2 mm (see Table 1). There was no cor-

relation between registration accuracy and registration residue.

Discussion

Current CT-based spinal-navigation systems that use surface-based registration require intraoperative sampling data, and the quality of the data obtained—regarding, for example, the sampling area and number of sampling points—greatly influences registration accuracy, which in turn obviously affects overall system accuracy. Thus, we attempted here to evaluate the

Fig. 4 a : Mean $\pm$ SD of positional errors ($*p < 0.001$); b Mean $\pm$ SD of rotational errors ($*p < 0.001$; $**p = 0.0025$)

accuracy of surface-based registration when using a CT-based spinal-navigation system and to determine the clinically acceptable conditions for registration.

In the present study, we divided the posterior aspects of the vertebra into five zones on the basis of anatomical classification, in order to evaluate the effect of sampling area on registration accuracy. These five zones can be

easily exposed using a posterior approach in open back surgery. Our results revealed that the use of only 20 surface points on zone C afforded a mean registration accuracy of 0.96 mm and 0.91°. Zone C appears to represent a clinically useful area for registration, and as it is also easily accessible during a posterior approach, we recommend zone C (posterior side of the lamina) as the first choice for CT-based spinal-navigation systems.

To increase registration accuracy, however, data selection from other zones does appear necessary. Zone B (right and left sides of the spinous process) is another relatively accessible zone close to zone C. By the combined use of 20 surface points each on zones C and B, mean positional error was 0.74 mm, and positional error was significantly decreased. The use of zone A (tip of the spinous process) was found not to be effective for improving registration accuracy in combination with sampling points from zone C (Fig. 4a, b). In fact, the combined use of zone A resulted in increased positional and rotational error. This is in contrast to the report of Herring et al., who reported optimal registration conditions from sampling points on the lamina and tip of the spinous process. We therefore do not concur that the tip of the spinous process is an effective area for surface-based registration [8]. We believe that the lack of agreement between our results and those of Herring et al. is primarily related to the material of the phantom model used. In the present study, a dry-bone phantom model was selected to simulate clinical conditions as far as possible. The tip of the spinous process (zone A) of a dry-bone phantom, which has a rough bone surface, is likely to produce data that is noisier than that from the surface of the plastic phantom model that Herring et al. used, but it is more clinically accurate data. Furthermore, Zone A is typically covered by the thick spinous apophysis and supraspinous ligament, and it may not be easy to expose the bone surface completely. Thus, practically speaking, sampling data obtained from this zone clinically is likely to be noisier than data obtained from a dry-bone phantom model. We therefore conclude that Zone A is not an appropriate area for improving registration accuracy in combination with zone C.

Weinstein et al. reported the need to expose the transverse processes (zone D) as anatomical landmarks for safe and accurate pedicle screwing [22]. We do not recommend the use of zone D in combination with

Table 1 Registration accuracy and residue under each combined sampling data condition (pts surface points)

Digitized zones	Positional error (mm)	Rotational error (°)	Registration residue (mm)
Zone C(20 pts)	0.96 $\pm$ 0.24	0.91 $\pm$ 0.38	0.15
Zone C(20 pts) + Zone A(20 pts)	1.29 $\pm$ 0.28	0.91 $\pm$ 0.29	0.16
Zone C(20 pts) + Zone B(20 pts)	0.74 $\pm$ 0.19	0.74 $\pm$ 0.25	0.15
Zone C(20 pts) + Zone D(20 pts)	0.75 $\pm$ 0.22	0.64 $\pm$ 0.16	0.18
Zone C(20 pts) + Zone E(20 pts)	0.57 $\pm$ 0.13	0.54 $\pm$ 0.21	0.19

zone C. Zone D is covered by the paraspinal muscles. Exposure of the transverse process, therefore, carries risks of unnecessary blood loss and/or muscle damage. The tip of the pen probe is similar to a long needle, allowing sampling data to be obtained from zone D, by contact through the paravertebral muscles. The sampling data obtained from this zone without sufficiently large exposure might be noisy. Therefore, in order to minimize surgical invasiveness and enlargement of the operative field, the use of zone D is not recommended.

Zone E (posterior sides of right and left superior and inferior articular processes) was found to represent the most effective sampling zone for improving registration accuracy. However, zone E is typically covered with joint capsules, and damage to these structures can result in mechanical instability, as removing joint capsules to expose zone E may compromise the joint structure, causing instability in the upper motion segment of the spine.

The success of registration in CT-based navigation systems is usually determined by registration residue. Such residue was very small in the present study, showing essentially no difference between the combination data-sampling conditions shown in Table 1. As registration accuracy varies with the amount of sampled data captured, even if registration residue is very small, surgeons should carry out the registration process carefully and account for registration accuracy in the treatment plan, particularly in cases in which few sampling points are used.

Given the results of the present study, the use of 20 surface points on zone C should provide sufficient data to perform accurate registration in computer-aided spine surgery. Clinically, however, the lamina is often covered with a hypertrophic facet joint caused by severe degenerative spondylosis. In cases requiring revision surgery after fenestration or laminectomy, the lamina is partially removed, and in these cases digitization of the surface points from the lamina might be difficult and the sampling data noisy. Therefore, using a combination of data from surface points on both sides of the spinous process should enable surgeons to carry out accurate registration.

Conclusions

To conclude, using 20 surface points on the posterior side of lamina should provide sufficient data to perform accurate CT-based image-guided spine surgery.

In cases of severe spondylosis or revision spine surgery, when it is difficult to digitize surface points from the lamina or sampling data from the lamina might be noisy, we recommend the combined use of surface points on both sides of the spinous process.

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