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Development of a navigation system for femoral augmentation using an intraoperative C-arm reconstruction

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Introduction: Osteoporosis is one of the most widespread diseases in recent times. More than 300,000 hip fractures per year occur due to osteoporosis [1]. Femoral augmentation, also called femoroplasty, is a possible countermeasure to reduce the risk of fracture in an osteoporotic hip [2]. The technique would be especially valuable for those patients with extremely high risk of falls or with a hip that is susceptible to fractures. While the objective is to reduce fracture risk, uncontrollably or incorrectly adding augmentation material has the potential downside of creating a stress concentration [3]. Therefore, precise planning based on simulation using patient-specific mechanical bone properties and a navigation system for precise operation is required.

In this study, we propose a navigation system for femoral augmentation surgery. It employs a new type of fiducial and an algorithm for tracking the patient position with respect to the injector device. The system will assist the surgeon to plan and visualize the trajectory for injection of the augmentation material in real-time during surgery. The proposed navigation system will potentially reduce the time for the registration. In the conventional C-Arm based navigation system which optically tracks the C-Arm device, device layouts in an operating room were restricted to avoid interference of the line of sight. Whereas the proposed system tracks only reference frames within a

small area around the surgical field. Therefore it has a potential to downsize the system and increase the flexibility in terms of the device layout.

The system will encourage the use of femoroplasty as an alternative treatment for severely osteoporotic patients in a clinical setting.

Method: We built a hybrid device that combines a fluoroscope tracking fiducial [4] and an optical tracking reference frame. The body of the 18'18'72mm fluoroscope tracking fiducial is made of polycarbonate and contains stainless steel beads (9), and stainless steel wires in both line (4) and elliptical (2) shapes. The relative position between the fluoroscope tracking fiducial and the optical markers is calibrated by tracing the edge of the device using an optically-tracked pointing probe. The location of the radiopaque fiducials with respect to the C-Arm detector is calculated from a single X-ray image using a two step process. First the position is roughly estimated by extracting the centroids of the 9 beads in the image. The accuracy is then increased using an iterative 2D-3D registration algorithm, where a 3D model of the radiopaque fiducials is translated and rotated until its 2D projection matches the X-ray image.

Using the 2D-3D registration of the patient's preoperative CT data to the intraoperative X-ray image, the relative position between the patient and the hybrid tracking device is estimated and the position of the optically tracked injection device with respect to the patient is calculated. The tracked injection tool and the patient hip structure are displayed in real-time.

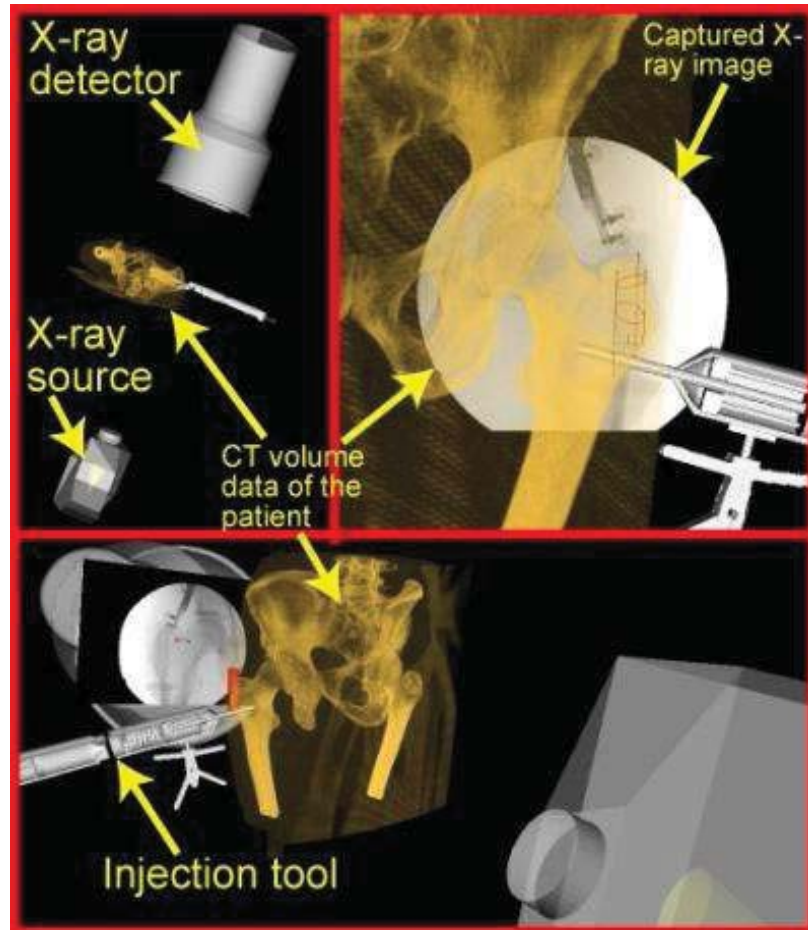
In order to evaluate the accuracy of the system, we conducted three types of experiments. We first performed a sensitivity analysis of the calibration between fluoroscope tracking fiducial and optical markers. The accuracy of the calibration was evaluated by measuring the residual error at the 9 beads. Experiments were performed under varying conditions to determine the best compromise between the required procedure time and the obtained accuracy. We then evaluated the accuracy of localizing the device pose from a single X-ray image using a 0.02 degree resolution rotational turntable as the ground truth and compared the estimated pose. In the third experiment, we evaluated the clinical feasibility by using a cadaver specimen to simulate the actual surgical setting.

Results: A simulation study was performed to determine the minimum required procedure time for accurate calibration of the tracking fiducial. This study showed that in order to achieve less than 0.1mm residual RMS error at the 9 beads, it is necessary to scan three "line features" on the fiducial for more than 120 samples per line using the pointing probe.

The experiments performed using the rotational turntable (72 poses) demonstrated that the RMS error for estimating the position of the hybrid fiducial from a single image was (0.091, 0.077, 0.643) mm in translation and (0.395, 0.235, 0.102) degrees in rotation. The X axis indicates the right direction in the image; The Y axis indicates the upper direction.

Fig.1 shows an example of the display of the proposed navigation system during the experiment using a cadaver specimen. Finally, during the preliminary cadaveric experiment, we confirmed the feasibility of the proposed navigation system with respect to surgical layout and data flow.

Discussions: We demonstrated a femoroplasty navigation system that uses a hybrid



tracking device simultaneously visible to both a C-arm and an optical tracker. The system employs a new type of fiducial for tracking the patient position relative to a navigated injection device. Combining information from optically navigated instruments and fluoroscopic images can help the surgeon precisely inject augmentation material according to the surgical plan. The system is especially advantageous in terms of simplicity of the registration process and flexibility of device layouts in the operating room. We plan to include a 3D shape reconstruction algorithm using multiple C-Arm images to evaluate the location of augmentation material during surgery. This will enable us to adapt the surgical plan intraoperatively in order to achieve an optimum bone augmentation.

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