Registration of 3D ultrasound and CT data for cervical spine surgery – first results with dorsal and lateral scans of phantom vertebrae

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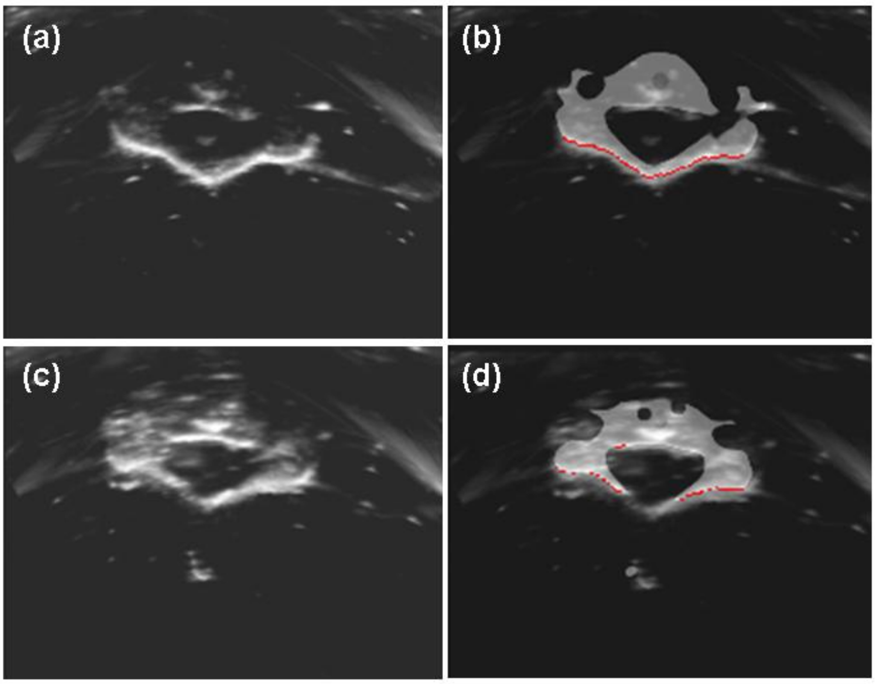
Purpose:
Hence cervical vertebrae are small and vital structures (e.g. blood vessels) lie in close proximity, high precision and reliability are important requirements for navigated cervical spine surgery. The registration of medical images offers comparatively high accuracy, especially in contrast to registration techniques using less information (e.g. landmark based registration). The registration algorithm developed by our group registers intraoperative ultrasound data with preoperative CT data and has already been tested successfully on lumbar spine vertebrae. The aim of this study was to test our fast and robust registration algorithm on phantom data of cervical vertebrae, in order to assess its suitability for clinical applications in this region. Because cervical spine surgery is performed from different entry sites we tested the registration for ultrasound data acquisition from dorsal and from lateral.

Methods:
Our algorithm uses the complete ultrasound volume for registration and thus bypasses the problematic segmentation of ultrasound data. Ultrasound is reflected on bone surfaces so any structures behind does not get depicted and a classical volume-volume registration would be pointless. By preprocessing the preoperative CT data we extract a bone surface which corresponds optimal to the surface acquired in the ultrasound volume. This three-dimensional surface can then be registered with an intraoperatively recorded ultrasound volume. The optimization is done by a state-of-the-art evolutionary algorithm (CMA-ES), which uses the sum of gray values of pixels in the ultrasound volume matching the CT surface as optimization criterion.
First we defined a reference registration for each of the phantom vertebrae. After manually preregistering as close to the optimum as possible, we did multiple local optimizations to find the optimum. The plausibility of the result was verified considering fused images of both volumes in three planes.
We compared the precision and reliability of the registration algorithm for lateral and dorsal scans of the phantom vertebrae. Every phantom vertebra was registered with 1000 different starting positions for each scanning direction. The starting positions were generated by independently displacing and rotating from the previously defined optimum, where the displacements ranged from 0 to 1 cm and the rotation from 0 to 11 degrees. To evaluate the registration results, we used the average distance between corresponding points of the registration result and the previously defined optimum. Within this metric the starting distances (which were about uniformly distributed) ranged from 0 to 16 mm.

Results:
We considered the registration successful if the average distance between corresponding points was below 1 mm. The average registration rate for dorsal scans was 99.8%, for lateral scans 96.4%. Figure 1 and 2 show a vertebra registered with dorsal and lateral ultrasound scans. Of the missing 3.6% in case of the lateral scans, 3.1% belonged to C4 registering wrongly to C5, yielding a higher optimization criterion. The mean precision of successful registrations was 0.005 mm, the variance was 0.0008 mm. 97.8% of the trials registered with a misalignment of less than 0.1 mm and 88.1% with less than 0.01 mm (see Figure 3). The computing time for one registration was less than 2 seconds on an Intel Xeon 3.06 GHz CPU.

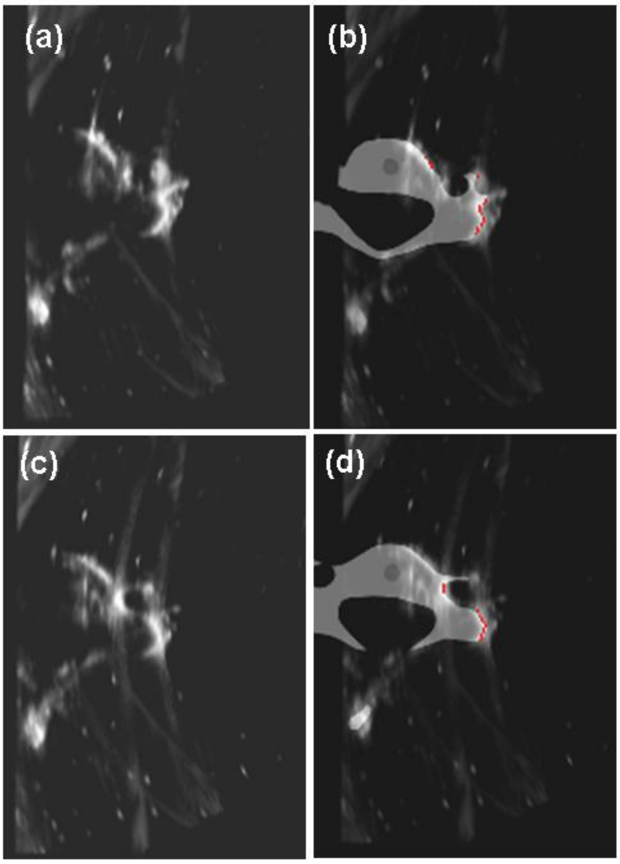
Conclusion:
Our registration algorithm showed good performance with data of a phantom cervical spine. The results confirm previous results on phantom lumbar vertebrae, where we achieved similar registration rates and precision. Those results scaled well to real world data, so we are now planning to test the registration algorithm on patient data. We believe that the algorithm is well suited for navigated surgery because of its speed, precision and reliability. Next, we plan to analyze the accuracy of our navigation system to obtain a ground truth validation.

Figure 1:



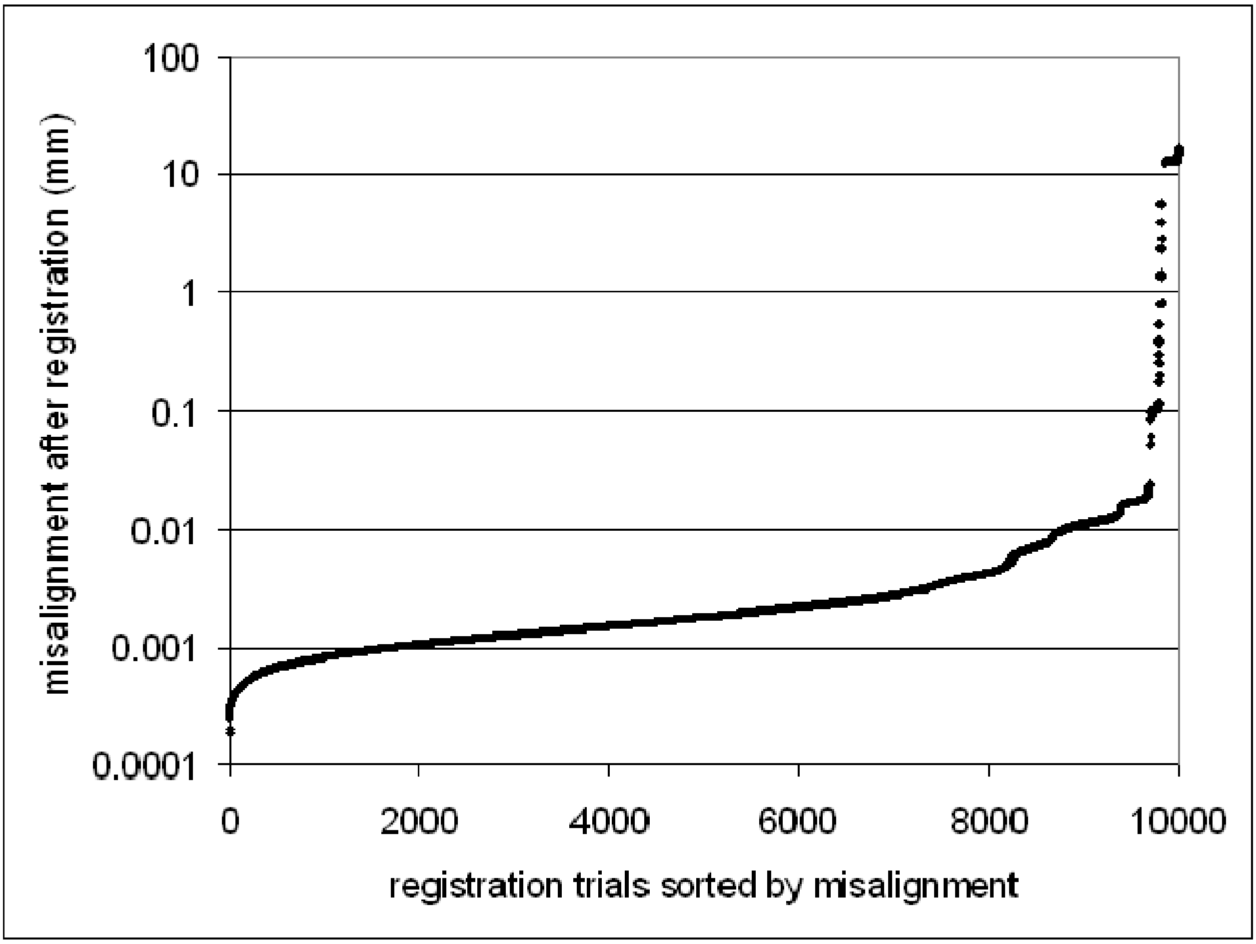
(a) and (c) are ultrasound images of a cervical vertebra, data acquisition from dorsal. In (b) and (d) the registered vertebra is projected into the ultrasound images. The red dots mark the surface points which were used for registration.

Figure 2:



(a) and (c) are ultrasound images of a cervical vertebra, data acquisition from lateral. In (b) and (d) the registered vertebra is projected into the ultrasound images. The red dots mark the surface points which were used for registration.

Figure 3:



Misalignment of 10 000 registration trials (5 vertebrae scanned from lateral and from dorsal, each registered 1000 times for each scan direction).