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Comparative Study on Methods for Scaphoid Bone Model Completion from Sonography

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Abstract

Patient-specific bone models are required for surgical planning of computer-assisted percutaneous scaphoid fracture fixation. 3D sonography may present an alternative to computed tomography (CT) or magnetic resonance imaging (MRI) for the acquisition of those bone models, but it requires a completion process to derive full models from partial sonographic surfaces. To date, methods based on statistical shape models (SSMs) represent the state-of-the-art for this completion process. However, we have shown feasibility of a deep learning (DL)-based method for scaphoid bone model completion in a previous study. In this study, we compare our DL-based approach against three SSM-based completion methods: Active shape models (ASM), least squares optimization (LSO) and general-purpose optimization (GPO). 85 scaphoid bone models were used for training the DL-based AdaPoinTr as well as for building the SSM. All completion methods were evaluated on 20 additional test models, with partial input point clouds generated using a subsampling algorithm that mimics 3D sonography. Evaluation in terms of symmetric surface distance between completed mesh and corresponding ground truth mesh showed 1.1 mm for ASM, 0.7 mm for GPO, 0.5 mm for LSO and 0.3 mm for AdaPoinTr. The assessment of suitability for screw planning showed 12 protruding screws for ASM, 4 protruding screws for GPO and LSO each, and no protrusion for AdaPoinTr. Also, AdaPoinTr was found to be at least one order of magnitude faster than all other methods. Nevertheless, SSM-based completion methods may be better suited for smaller datasets and if the generation of plausible shapes is to be ensured.

1 Introduction

Scaphoid fractures are mostly caused by a fall on the hand in extension. One of the indicated therapeutical options is a percutaneous fixation of the fracture, which is commonly conducted under fluoroscopic control (Schädel-Höpfner et al. 2023). In order to improve surgical outcome and reduce radiation exposure, several studies have proposed a navigated surgical procedure using sonography-based registration (Beek et al. 2008; Anas et al. 2016; Brößner et al. 2021a; Brößner et al. 2021b, 2023). For those computer-assisted approaches, a patient-specific bone model is required for surgical planning, which is usually still derived from preoperative computed tomography or magnetic resonance imaging. 3D sonography may present a cost-efficient and radiation-free alternative, but it requires a completion process to derive bone models from partial sonographic surface scans. In a previous study, we have already demonstrated feasibility of scaphoid bone model completion using a deep learning (DL)-based method (Brößner et al. 2024). Nevertheless, methods based on statistical shape models (SSMs) still represent the current state-of-the-art for sonography-based bone model completion (Mahfouz et al. 2021; Hohlmann et al. 2023; Hohlmann et al. 2024). In this work, we present a direct comparison of SSM-based methods with our proposed DL-based method for scaphoid bone model completion. To ensure comparability with our previous study, we used the same dataset and evaluation methods.

2 Materials and Methods

2.1 Dataset

The dataset is based on 105 carpal bone surface models provided by (Akhbari et al. 2019), which were divided along probands into 85 scaphoid models (66 probands) for training and 20 scaphoid models (10 probands) for testing. Partial input point clouds for testing were generated using a subsampling algorithm mimicking 3D sonography from a volar probe position (analog to (Brößner et al. 2024)).

2.2 Completion methods

For SSM-based completion, we used a proprietary MATLAB implementation to set up an SSM of scaphoid models consisting of 8192 points. Starting from roughly aligned training models, generalized Procrustes analysis was applied in combination with the Smooth Shells algorithm (Eisenberger et al. 2020) for registration. Finally, principal component analysis was applied for identification of modes. (This SSM is identical to the SSM used for data augmentation in (Brößner et al. 2024)). We compared three different algorithms for SSM-based reconstruction, again using proprietary MATLAB implementations: Active Shape Models (ASM) as proposed in (Cootes et al. 1995), least squares optimization (LSO) introduced in (Blanz et al. 2004), and a general purpose optimizer (GPO) for simultaneous optimization of shape and registration parameters. For all three methods, the first 65 out of 85 modes (covering 95% of morphological variance) were used, with individual mode variation limited to ± 3 standard deviations. Termination criterions for all algorithms were individually chosen according to (Hohlmann et al. 2023). For a more detailed description of the DL-based completion method AdaPoinTr refer to (Brößner et al. 2024).

2.3 Evaluation

For evaluation of the SSM-based methods, MATLAB's *pcregistericp* was used for initial registration of input point clouds to the SSM mean shape, followed by one of the three completion algorithms. To minimize the influence of initial registration on evaluation, partial input point clouds were optimally prepositioned. No initial registration was necessary for completion using the DL-based AdaPoinTr. Resulting complete meshes were evaluated against the corresponding ground truth meshes in terms of symmetric surface distance (SSD), symmetric Hausdorff distance (SHD), and in terms of directed surface distance (DSD) from partial input point clouds to completed meshes.

Additionally, we evaluated suitability of the completed meshes for surgical screw planning. For this purpose, we utilized an adapted version of (Leventhal et al. 2009) for automated screw planning based on the completed meshes and assessed these planned screws for the corresponding ground truth meshes in terms of screw protrusion and minimal safety margin to bone surface.

3 Results

A quantitative comparison of completion results for the three SSM-based methods as well as the DL-based method are given in **Table 1**. A qualitative comparison of completion results for four of the 20 test cases is shown in **Figure 1**.

Table 1: Comparison of completion results for different methods.

Completion Method	SSD / mm	SHD / mm	DSD / mm	Safety Margin / mm	Protruding Screws	Inference Time / s
SSM (ASM)	1.1 ± 0.3	7.0 ± 1.6	0.9 ± 0.3	0.3 ± 0.4	12/20	6.0
SSM (GPO)	0.7 ± 0.2	5.8 ± 1.9	0.3 ± 0.1	0.5 ± 0.3	4/20	318.9
SSM (LSO)	0.5 ± 0.2	4.4 ± 1.5	0.2 ± 0.0	0.5 ± 0.4	4/20	74.4
AdaPoinTr	**0.3 ± 0.0**	**3.1 ± 0.9**	**0.1 ± 0.0**	**0.7 ± 0.2**	**0/20**	**0.2**

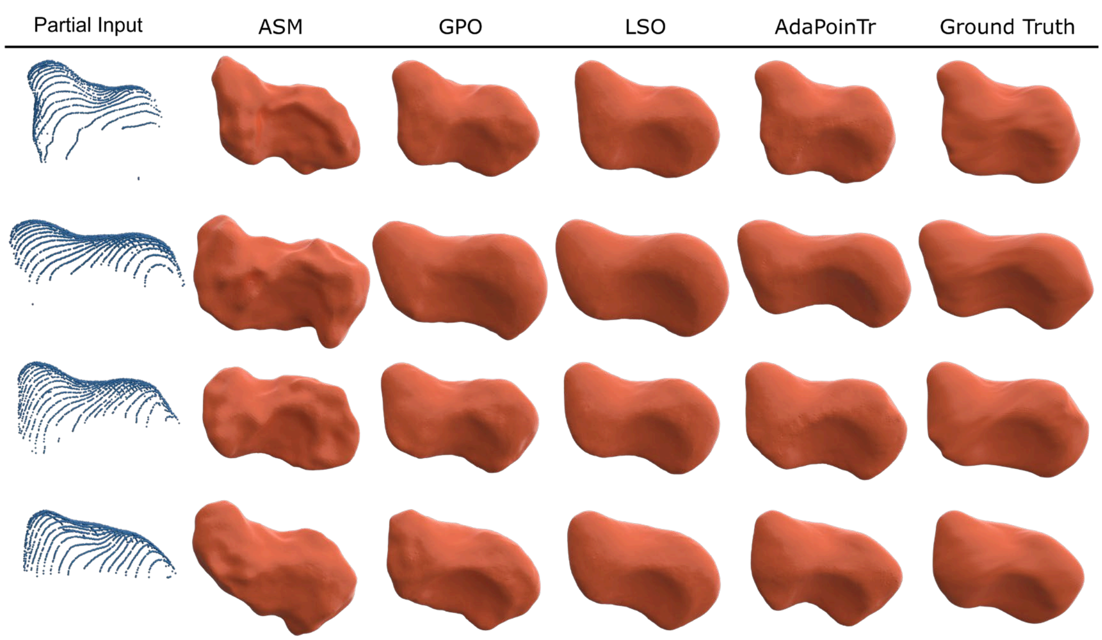

Figure 1: Comparison of completion results for SSM-based methods ASM, GPO and LSO as well as deep learning-based AdaPoinTr on four test cases. Partial input point clouds and corresponding ground truth meshes are shown in the first and last column.

4 Discussion

Of the three SSM-based methods, ASM shows the worst performance for every metric except for the computation time, which is very low compared to the other two SSM-based methods. GPO and LSO show a similar performance for screw planning, with similar margins to bone surface and 4 protruding screws found for both methods. However, LSO achieves better completion results and is significantly faster than GPO. The deep learning-based AdaPoinTr outperforms all tested SSM-based methods about every metric: It achieves the lowest surface errors and allows for screw planning without screw protrusion and with highest margin to bone surface. Furthermore, computation time is more than one order of magnitude lower than for the fastest SSM-based method ASM.

Considering our results and general characteristics, SSM-based and DL-based methods for scaphoid bone model completion from sonography are best suited for different use cases: SSM-based methods require initial registration, which makes them less robust against variance in pre-positioning. Completion performance is inferior to DL-based methods and needs to be balanced against computation times. Furthermore, the SSM setup is rather error-prone due to the need for point correspondences. However, SSM-based methods are well suited for small datasets and for shape generation (e.g. for data augmentation), with statistical boundaries ensuring plausible shapes. Training of DL-based methods on the other hand is resource-intensive and requires more data, and even so generated shapes may be implausible. In return, DL-based methods offer potentially superior completion accuracy and fast computation times. Furthermore, robustness against initial positioning can be trained.

The significance of our study is limited by the rather small test sample size of 20 scaphoids from 10 probands. Furthermore, acquisition of partial surfaces and assessment of screw planning were only conducted virtually. For future studies, we thus focus on the transfer to in-vivo scaphoid bone completion, which also allows the evaluation of robustness against segmentation errors. Moreover, the use of hybrid SSM- and DL-based completion methods may be promising to obtain complementary characteristics.

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