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Feasibility of Ultrasound-based Scaphoid Bone Model Completion for Surgical Planning

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Abstract

For computer-assisted percutaneous scaphoid fixation, a patient-specific bone model is required for surgical planning. This bone model is commonly derived from pre-operative computed tomography (CT) or magnetic resonance imaging (MRI) data. We propose an approach for bone model derivation based on intra-operative 3D ultrasound (US) imaging for the cases, where pre-operative diagnostic CT or MRI are not indicated or available. As scaphoid bone surfaces are only partially visible in sonographic images, we employ the Transformer-based AdaPoinTr architecture to incorporate statistical morphological knowledge for the completion of partial bone surfaces extracted from sonographic images. For the generation of datasets, we built a statistical shape model (SSM) based on 85 scaphoid bone models. From this SSM, we generated 12288 full scaphoid models for training. 20 additional scaphoid bone models were used for testing. Partial models for both training and testing were generated by subsampling the full models, mimicking 3D US imaging from a volar probe position. Evaluation of the final trained model on the test subset showed a mean symmetric distance of 0.3 mm between original and completed scaphoid models, with an inference time of 0.2 s per model. We furthermore planned screws based on the completed test models and evaluated their fit for the original models. We found no screw protrusion for any tested model, with a mean safety margin to bone surface of 0.7 mm. This study shows feasibility of our approach for US-based bone model generation; future work may aim at integrating dorsal surface information.

1 Introduction

The scaphoid bone is one of the eight carpal bones. Fractures are mostly caused by a fall on the hand in extension [Mehling & Sauerbier 2013]. Fracture classification is of great relevance for the success of therapy, as the scaphoid's blood supply may be compromised depending on the type of fracture [Gelberman & Menon 1980]. Computed tomography (CT) scan is recommended for fracture classification [Clementson et al. 2020]. For minimally- and moderately displaced fractures of the waist and distal pole, percutaneous screw fixation may be indicated [Arsalan-Werner et al. 2016]. This procedure has the disadvantage of exposing patient and surgeon to ionizing radiation through fluoroscopy [Singer 2005; Wang et al. 2017]. In general, percutaneous screw placement is challenging due to projective imaging [Beek et al. 2008].

To address these issues, [Beek et al. 2008] proposed a navigated approach with ultrasound (US)-based registration. [Anas et al. 2016] further developed this US-based approach by automating screw planning according to [Leventhal et al. 2009] and furthermore employing a statistical shape and pose model (SSPM) for the registration process. In previous work, our group introduced deep learning (DL)-based methods to the registration process for fast computation times and a high degree of automation [Broessner et al. 2021; Brößner et al. 2021, 2023].

All the above US-based approaches rely on preoperative CT (or MRI) for the derivation of patient-specific bone models for planning. In this work, we explore the possibility of deriving these bone models directly from US data using a DL-based approach, which represents a novelty at the time of publication.

2 Materials and Methods

Bone surfaces can be derived from sonographic images via segmentation. Limiting factors are the narrow field of view as well as the shadowing of US through bone surfaces and the resulting occlusion by adjacent carpal bones. Due to these limitations, the scaphoid bone is only partially visible in sonography. To derive a full bone model, partial scaphoid surfaces need to be completed utilizing statistical morphological knowledge. For this purpose, approaches based on statistical shape models (SSMs) have primarily been used [Hohlmann et al. 2024], e.g. for the completion of knee bone models [Hohlmann et al. 2023]. SSM-based approaches require a limited database, and their output is within realistic statistical bounds, but inference usually requires pre-alignment of input point clouds and iterative optimization, which makes it rather slow and prone to errors. These downsides may be addressed utilizing DL-based methods for completion. As the Transformer-based PoinTr [Yu et al. 2021] and the succeeding AdaPoinTr [Yu et al. 2023] showed promising results for general model completion, we employed the latter in our approach.

For the task of model completion, we assume the scanned scaphoid bones to be intact; for displaced fractures, sonographic images can either be acquired of the contra-lateral scaphoid or the fractured scaphoid needs to be reduced for image acquisition. Datasets for training and testing were based on 105 carpal models 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. For data augmentation, we built an SSM based on the 85 models assigned for training and generated 10,240 full models from it. Partial surfaces for both training and testing were generated by subsampling full models with an algorithm mimicking US image acquisition with a 3D probe from a volar position. Furthermore, partial surfaces for training and testing were randomly rotated in the range of 360°. The AdaPoinTr architecture was trained for 600 epochs. The final model was selected based on validation results in terms of L1-Chamfer Distance.

For evaluation of our proposed approach, we compared completed and ground truth models of the test subset in terms of symmetric surface distance (SSD) and symmetric Hausdorff distance (SHD), as well as partial input point clouds and completed models in terms of directed surface distance (DSD). We furthermore utilized an adapted implementation of the planning algorithm by [Leventhal et al. 2009] for screw planning based on the completed test models. Deviating from the original algorithm, the planned screws were shortened by 1 mm at the proximal end as additional safety margin. We assessed the fit of the planned screws for the corresponding ground truth models, considering protrusion and safety margin as minimum distance from screw to bone surface.

3 Results

Comparison between ground truth and completed models of our test set showed an SSD of 0.3 ± 0.0 mm and an SHD of 3.1 ± 0.9 mm (see Figure 1 for an example of the completion process and Figure 2 for a visualization of the distance between completed point cloud and corresponding ground truth model). DSD between partial input and completed model was found to be 0.1 ± 0.0 mm. No screw protrusion was found, with a distance margin between screw and bone surface of 0.7 ± 0.2 mm. Inference time for a single model was 0.2 s.

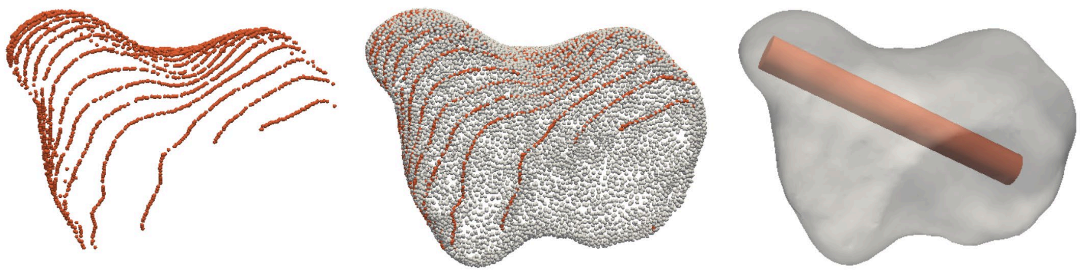

Figure 1: Example of proposed approach: partial input point cloud (left), completed point cloud (middle) and reconstructed bone model with planned screw (right).

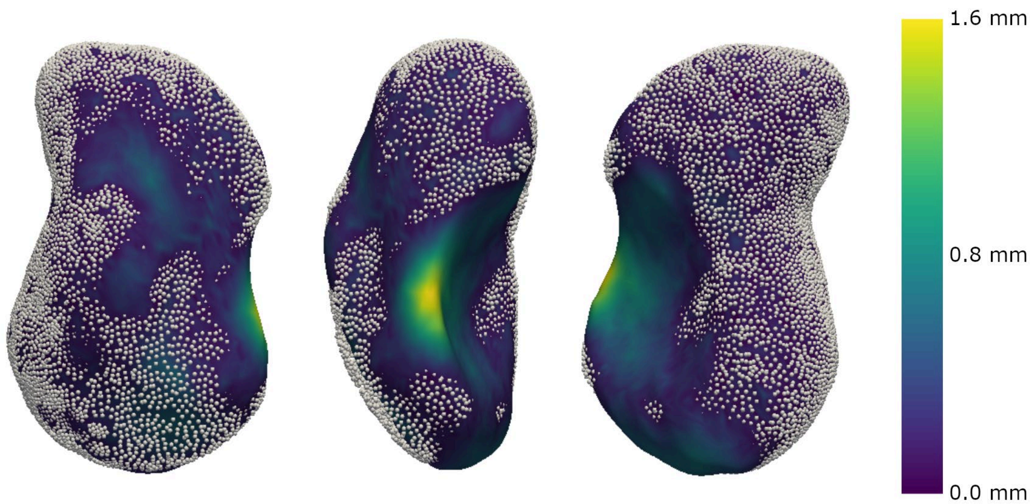

Figure 2: Visualization of distance between completed example point cloud and corresponding ground truth mesh.

4 Discussion and Conclusion

As expected, completion errors mainly occurred on the scaphoids' dorsal side, with errors at the capitate articular surface and the corresponding radial region being most relevant for screw planning, as this is the narrowest part of the scaphoid. The mean SHD indicates insufficient completion for some regions. Nevertheless, planning based on completed models was found valid for all ground truth models, as no screw protrusion occurred. The mean margin between screw and bone surface moreover exceeds the assumed cortical thickness of 0.35 mm [Leventhal et al. 2009].

In a previous in-vitro study [Brößner et al. 2023], we achieved a mean DSD of 0.2 ± 0.1 mm between partial point cloud and CT-derived bone model for intraoperative registration. [Anas et al. 2016] achieved a mean SSD error of 0.8 ± 0.2 mm over 13 cadaver scaphoid bones for their approach of fitting an SSPM to preoperative CT data and subsequent registration/adaption to intraoperative US data. In comparison to the above approaches, our approach attempts completion directly on intra-operative US data and thus eliminates the need for intra-operative registration of preoperative CT-Data, with about halved DSD and SSD for in-vitro evaluation. Employment of a DL-based method for completion in our approach required more resources for thorough training as compared to an SSM-based method but allowed for fast inference without the need for pre-alignment. This means a shift of complexity and resources from inference to training, which facilitates integration into medical workflows.

Main limitation of our study is the use of in-vitro data and subsampling: For the in-vivo application, worse surface coverage and segmentation errors will presumably further complicate the process of model completion.

We have shown feasibility of our proposed, novel approach for DL-based bone model generation from US images. Future work should focus on incorporating dorsal surfaces to the completion process to further minimize errors as well as further evaluation in ex-vivo and in-vivo experiments.

References

[Akhbari et al. 2019] AKHBARI, B; MOORE, D. C; LAIDLAW, D. H; WEISS, A.-P. C; AKELMAN, E; WOLFE, S. W; CRISCO, J. J.: Predicting Carpal Bone Kinematics Using an Expanded Digital Database of Wrist Carpal Bone Anatomy and Kinematics. In: Journal of Orthopaedic Research®, 37 (2019), 12: 2661–2670

[Anas et al. 2016] ANAS, E. M. A; SEITEL, A; RASOULIAN, A; JOHN, P. S; UNGI, T; LASSO, A; DARRAS, K; WILSON, D; LESSOWAY, V. A; FICHTINGER, G; ZEC, M; PICHORA, D; MOUSAVI, P; ROHLING, R; ABOLMAESUMI, P.: Registration of a statistical model to intraoperative ultrasound for scaphoid screw fixation. In: International Journal of Computer Assisted Radiology and Surgery, 11 (2016), 6: 957–965

[Arsalan-Werner et al. 2016] ARSALAN-WERNER, A; SAUERBIER, M; MEHLING, I. M.: Current concepts for the treatment of acute scaphoid fractures. In: European Journal of Trauma and Emergency Surgery, 42 (2016), 1: 3–10

[Beek et al. 2008] BEEK, M; ABOLMAESUMI, P; LUENAM, S; ELLIS, R. E; SELLENS, R. W; PICHORA, D. R.: Validation of a new surgical procedure for percutaneous scaphoid fixation using intra-operative ultrasound. In: Medical Image Analysis, 12 (2008), 2: 152–162

[Broessner et al. 2021] BROESSNER, P; HOHLMANN, B; RADERMACHER, K.: Ultrasound-based Navigation of Scaphoid Fracture Surgery. In: Palm, C; Deserno, T. M; Handels, H; Maier, A; Maier-Hein, K. H; Tolxdorff, T. (eds.): Bildverarbeitung für die Medizin 2021. Proceedings, German Workshop on Medical Image Computing, Regensburg, March 7-9, 2021. Wiesbaden, Heidelberg: Springer Vieweg (2021) (Informatik aktuell): 28–33

[Brößner et al. 2021] BRÖßNER, P; HOHLMANN, B; WELLE, K; RADERMACHER, K.: Validation of Automated Ultrasound-based Registration for Navigated Scaphoid Fixation. In: Current Directions in Biomedical Engineering, 7 (2021), 1: 116–120

[Brößner et al. 2023] BRÖßNER, P; HOHLMANN, B; WELLE, K; RADERMACHER, K.: Ultrasound-Based Registration for the Computer-Assisted Navigated Percutaneous Scaphoid Fixation. In: IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 70 (2023), 9: 1064–1072

[Clementson et al. 2020] CLEMENTSON, M; BJÖRKMAN, A; THOMSEN, N. O. B.: Acute scaphoid fractures: guidelines for diagnosis and treatment. In: EFORT Open Reviews, 5 (2020), 2: 96–103

[Gelberman & Menon 1980] GELBERMAN, R. H. & MENON, J.: The vascularity of the scaphoid bone. In: The Journal of Hand Surgery, 5 (1980), 5: 508–513

[Hohlmann et al. 2023] HOHLMANN, B; BROESSNER, P; PHLIPPEN, L; ROHDE, T; RADERMACHER, K.: Knee Bone Models From Ultrasound. In: IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 70 (2023), 9: 1054–1063

[Hohlmann et al. 2024] HOHLMANN, B; BROESSNER, P; RADERMACHER, K.: Ultrasound-based 3D bone modelling in computer assisted orthopedic surgery - a review and future challenges. In: Computer assisted surgery (Abingdon, England), 29 (2024), 1: 2276055

[Leventhal et al. 2009] LEVENTHAL, E. L; WOLFE, S. W; WALSH, E. F; CRISCO, J. J.: A computational approach to the "optimal" screw axis location and orientation in the scaphoid bone. In: Journal of Hand Surgery, 34 (2009), 4: 677–684

[Mehling & Sauerbier 2013] MEHLING, I. M. & SAUERBIER, M.: Skaphoidfrakturen und Skaphoidpseudarthrosen. In: Zeitschrift fur Orthopadie und Unfallchirurgie, 151 (2013), 6: 639–660

[Singer 2005] SINGER, G.: Radiation exposure to the hands from mini C-arm fluoroscopy. In: The Journal of Hand Surgery, 30 (2005), 4: 795–797

[Wang et al. 2017] WANG, M. L; HOFFLER, C. E; ILYAS, A. M; BEREDJIKLIAN, P. K; LEINBERRY, C. F.: Fluoroscopic Exposure With Use of Mini-C-Arm During Routine Hand Surgery: A Prospective Comparison of Hand Versus Eye Radiation Dosage. In: Journal of surgical orthopaedic advances, 26 (2017), 2: 102–105

[Yu et al. 2021] YU, X; RAO, Y; WANG, Z; LIU, Z; LU, J; ZHOU, J.: PoinTr: Diverse Point Cloud Completion with Geometry-Aware Transformers. In: 2021 IEEE/CVF International Conference on Computer Vision (ICCV): IEEE (2021)

[Yu et al. 2023] YU, X; RAO, Y; WANG, Z; LU, J; ZHOU, J.: AdaPoinTr: Diverse Point Cloud Completion with Adaptive Geometry-Aware Transformers (2023)