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Angaben zur Veröffentlichung / Publication details:

Gastreich de Llanes, Elina, Melina Wördehoff, Lukas Förner, Josua A. Decker, and Thomas Wendler. 2026. "Learning anatomical variability: statistical shape models for vertebral joint pose estimation [Abstract]." *Biomedical Engineering / Biomedizinische Technik* 71 (s1). https://doi.org/10.1515/bmt-2026-1001.

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Learning Anatomical Variability: Statistical Shape Models for Vertebral Joint Pose Estimation

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Introduction

Non-rigid medical image registration is essential for longitudinal analysis of spinal structures, yet standard intensity-based methods risk anatomically implausible deformations when applied to joints. Constraining such registration to biologically realistic deformations remains an open challenge, particularly for the spine, where complex intervertebral kinematics must be respected.

Methods

We present a data-driven framework combining Statistical Shape Models (SSM) and Active Shape Models (ASM) with kernel Principal Component Analysis (kPCA) to learn and encode vertebral shape variability from CT data. Using 2,627 vertebrae from 234 patients drawn from the VerSe dataset, segmentation masks were converted to surface meshes and preprocessed via Laplacian smoothing. Iterative Closest Point (ICP) registration with explicit scale normalization was applied prior to Coherent Point Drift (CPD)-based landmark correspondence, establishing 500 homologous points per vertebral group. A kPCA model with RBF kernel was trained per group to capture non-linear shape variation. New shapes are reconstructed by projecting into the learned latent space, constraining parameters to anatomically plausible ranges, and inverting the transformation back to world coordinates. Vertebral orientation was estimated via PCA-based local coordinate frames with permutation correction to ensure global consistency across the spine.

Results

Scale normalization prior to ICP yielded a statistically significant mean alignment improvement of 0.83 ± 1.75 mm across all vertebral groups (Wilcoxon, $p < 0.05$). The ASM reconstruction achieved a weighted global mean error of 7.55 ± 2.25 mm on the held-out test set, with per-vertebra errors ranging from 4.82 mm (T2) to 17.51 mm (L5). Intervertebral orientation variability was quantified at $6.77° \pm 7.94°$, $7.88° \pm 9.21°$, and $7.38° \pm 11.16°$ for the x-, y-, and z-axes respectively.

Conclusion

The proposed framework demonstrates that statistical shape priors can robustly encode vertebral morphology and joint pose distributions from routine CT data, providing a foundation for anatomically constrained non-rigid registration in longitudinal spine imaging.

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