A deformable image-based registration approach to obtain shape correspondence for statistical shape modeling of finger bones

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1 Purpose

Statistical shape models (SSMs) are a state-of-the-art approach to encode complex anatomical shape information. Here we focus on modelling finger bones to support orthopedic applications such as joint replacements and design of implants. A necessary prerequisite for the computation of a SSM is that all shape data have corresponding descriptions and are parameterized on a common reference space. In this work we present a deformable image-registration approach to obtain these shape correspondences.

2 Methods

Our approach is based on CT images of hands and segmentations of the metacarpals and phalanges. We use 200 CT data sets from clinical routine acquired at two different clinical sites. The metacarpal, proximal, intermediate, and distal bones are segmented with an nnU-Net. The ground truth segmentations for the training of the nnU-Net were created manually and the final segmentation results are reviewed by a radiology technician and corrected if necessary. From the segmentations surface meshes are generated with the Marching Cubes method and stored as Winged Edge Meshes (WEMs). All processing is done in MeVisLab (www.mevislab.de).

First, we determine a reference hand that contains all the phalanges and has a low flexion of the fingers. Since the CT images are not normalized in their orientation and bending, the next step is to perform an initial alignment of each bone. To do this, we calculate a local coordinate system for each bone. The local bone coordinate system is based on principal component analysis (PCA) and the center of gravity of each bone. For consistent axis orientation, the relation of the bones of a single finger is analyzed. We heuristically derive a right-handed, orthonormal local coordinate system including the long axis of the finger (pointing to distal) and the axis of rotation of the finger joint. The third axis is determined via cross product. We then transform all the bones into the local coordinate system of the respective reference bones to achieve a good initial alignment of the bones.

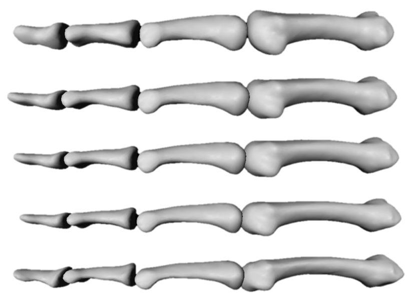
Subsequently, we perform rigid prealignment of bone masks, volumetric deformable image registration and finally non-rigid surface registration separately for each finger bone. The deformable registration is similar to the variational approach presented in [1] but we consider an enhanced objective function directly taking the surface distance between the CT images of the respective bone into account. Therefore we consider additional penalty terms measuring the distance between the segmentation masks and the distance of the deformed reference WEM to the bone segmentation surface. After the deformable registration the deformation field is used to transform the WEM of the reference bone to the template bone. To better fit the propagated WEM to the template surface we run an additional deformable registration between those. We use the Sum-of-squared differences as distance measure and a diffusive regularization for the deformable registrations.

The result of the registration pipeline is the deformed reference WEM, so all individual bones of the same structure now have (approximate) corresponding surface meshes. Now that the correspondence problem has been solved, SSMs for individual bones can be calculated using the familiar steps of Procrustes Analysis and PCA. We do not want the bending of the fingers to be included in the shape variation, so a further step is required to calculate SSMs for complete fingers. After transforming the bones back to their original coordinate system we run a position-based dynamics simulation [2] where the fingers are moved to a normalized position in which they are fully stretched. To achieve this, the simulation engine described by Walczak et al. [2] was extended with rigid body dynamics, joint constraints, and a kinematic chain mechanism. For stretching, proximal, intermediate, and distal bones are pulled in the direction of the metacarpal bone long axis (calculated during the initial alignment step described above). The individual fingers are now stored as a single WEM, and the SSMs can be computed as for a single bone.

3 Results

The figure shows the mode variation of the resulting statistical shape model, exemplified for the metacarpal of the index finger and the entire index finger with metacarpal. The SSMs were created using about 100 different fingers. Fingers with incomplete structures (due to too small a field of view or broken bones) were discarded, so the number of fingers used varies for each SSM. Shape models with significantly more data sets are in preparation, as well as a more thorough analysis and validation of the resulting shape models. The registration pipeline is fundamental for the determination of shape correspondences and thus has a major impact on the quality of SSMs. We will use the local coordinate systems of each bone to calculate cylinder coordinates to evaluate the registration results.

(a) SSM variation Index finger metacarpal



(b) SSM variation Index finger

Fig. 1: Variation of SSMs for single bone (a) and complete finger (b). The average SSM is shown in the middle, next to it the variation of the first mode, followed by the simultaneous variation of the first 5 and 10 (only a) modes.

4 Conclusion

We presented the first results of a deformable image-based registration approach to obtain shape correspondences for SSMs of phalanges and metacarpals. The use of additional objective function terms and the additional registration between deformed WEM and distance map improves the registration results and thus leads to good shape correspondences. With the help of simulation, SSMs can be generated not only from individual bones, but also from larger structures such as entire fingers with metacarpals. These SSMs can now be used to generate new realistic instances.

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References

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