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An Anatomical Atlas to Support the Virtual Planning of Hip Operations

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Abstract. Two three-dimensional digitized atlases of a female and a male pelvis were generated to support the virtual 3D-planning of hip operations. Beside the anatomical labeling of bone structures the determination of orthopedic measures, like angles, distances or sizes of contact areas, is important for the planning of hip operations. Thus, each atlas consists of labeled reference CT data sets, a set of landmarks as well as definitions of orthopedic measures and methods for their automatic computation. Furthermore, methods for the automatic transfer of anatomical labels from the atlas to an individual data set are presented resulting in three-dimensional models of the patient's bone structures. The anatomical atlases are designed to replace the interactive, time-consuming pre-processing steps for the virtual 3D operation planning.

1. Introduction

In orthopedic surgery computer assisted systems are getting more and more important. Due to the complex geometry of the pelvis the exact planning of the hip operation is essential for the operation result. The application of virtual planning procedures opens up new possibilities with regards to effort of time and costs and to an improved quality. During the computer assisted planning anatomical knowledge is required in the virtual environment. This is usually achieved by an interactive time-consuming segmentation step. The main idea of the presented approach is to represent the needed knowledge in an digital anatomical atlas and to use automatic algorithms to transfer this knowledge to the patient data.

In the past digital atlases have been used for several purposes [1-4]. Especially atlases of the brain have been designed for teaching purposes, automatic segmentation and neurosurgical planning. In the considered application, a three-dimensional atlas of the human pelvis based on the CT data of the Visible Human Data Set [5] has been built up to facilitate virtual planning procedures in hip surgery. The atlases consists of labeled CT data sets, anatomical point landmarks and computation instructions for orthopedic measures.

2. Motivation

The segmentation of different bone structures is necessary to address or analyze these structures in a virtual planning environment. Furthermore, the localization of landmarks is needed to derive orthopedic measures, like distances or angles. For instance the virtual planning of an endoprosthetic reconstruction in bone tumor surgery requires at least the segmentation of the left and right hip bone, sacrum, left and right femur as well as a series of landmarks, e.g. the center of the femoral head or points on the border of the acetabulum [6]. The segmentation of the mentioned structures requires several hours using semi-automatic volume growing algorithms and interactive post-processing tools. If further measures are needed the number of labeled structures and landmarks increases. For example measuring of the contact area between acetabulum and femoral head requires the segmentation of both structures, the computation of the antetorsion requires the localization of the centers of the femoral head and the femoral leg as well as the condyles. This may increase the needed pre-processing time essentially.

The goal of the presented approach is to avoid these time-consuming steps and to enable an automatic recognition of hip structures by using a digital atlas of the hip.

3. Digital anatomical atlas of the hip

The virtual planning of hip operations is based on bone structures extracted from CT data. Starting point to built up the two atlases are high resolution CT image sequences of a woman and a man taken from the Visible Human Data Set. In a first step, threshold based volume growing algorithms are used for a rough segmentation of the bones. In the next interactive step the different bone structures are separated and insignificant structures, like vessels or sinews, are removed. Incomplete bone contours are closed with an semi-automatic "live-wire" [7] algorithm in a post-processing step. Finally, the segmentation result was reviewed and corrected by an expert. The separated structures are hip bones, acetabuli, sacrum, os coccygis and femuri composed by femoral head and shaft.

A set of landmarks and measures for hip interventions are gathered by the surgeons. During the implementation two main problems arise: the verbal definitions of landmarks and measures are unprecise and most of them are based on x-rays. So the verbal descriptions are transformed to exact definitions of localization and computation instructions and the two-dimensional x-ray based measures are transferred into the three-dimensional space. Anatomical landmarks, e.g. promotorium or spina iliaca anterior superior, are selected interactively on the bone surface and methods for the computation of orthopedic measures, e.g. the center of femoral head, the antetorsion or the center-edge-angle, are implemented (fig. 1).

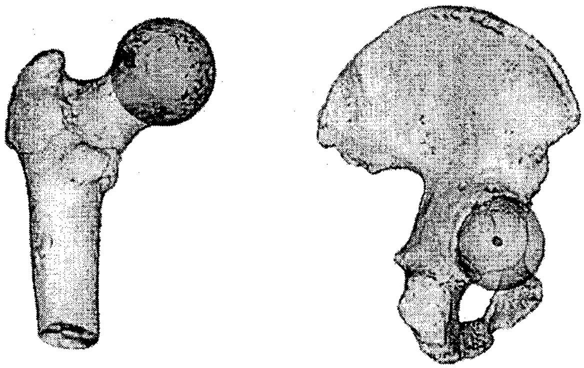

Fig. 1: The centers of the femoral head (left) and the acetabulum (right) can be determined by an approximation with a sphere. In the right figure the center of femoral head (blue) and acetabulum (red) are visualized.

4. Matching of atlas and patient data

For the transfer of the atlas information to the patient data set the non-rigid registration of atlas and patient data is necessary. In our system a totally freeform registration process based on "demons" is used as proposed in [8]. Based on the gradients in the patient image and the gray value difference between atlas and patient image each demon computes a force vector to reduce the local gray value difference iteratively. The demons are arbitrary scattered over the patient data set. If e.g. each voxel is selected as a demon, a complete 3D grid of demons acts to deform the atlas data. In order to achieve smooth deformations a gaussian filtering of the resulting force fields is performed. In an iterative process this strategy leads to a matching of reference and deformed image.

Due to the strong anatomical variations in soft tissues a correct inter-patient matching of all tissues is nearly impossible. Hence, for the planning of orthopedic interventions the atlas-matching is limited to bones and surrounding voxels. Therefore, the demons positions are determined by a threshold based bone segmentation and a following dilatation.

In our implementation we use a multi-resolution strategy to avoid a convergence of the optimization procedure in local minima and to speed up the computation. The registration process is applied from coarser to finer scales. Each final solution at one scale serves to initialize the registration at the next finer scale.

5. Recognition of anatomical structures and surface generation

After the non-rigid matching a good fit of atlas and patient data is obtained (see figure 2), but nevertheless small deviations occur. The patient's bone structures are labeled by determining the nearest neighbor in the transformed labeled atlas data set. Thus, bony patient voxels, which are not covered by an atlas label, are added to the nearest bone structure.

For every labeled bone structure a surface model is constructed applying the marching cubes algorithm to the original CT data [9]. This strategy leads to smooth surfaces with appropriate normals and gradients. The threshold of the generated isosurfaces is determined by choosing standard hounsfield units for the corticalis (~ 100 HE). A triangle decimation algorithm [10] is used to reduce the number of the generated polygons significantly. Figure 3 shows the surface models generated from the atlas data using the algorithm described above. The models consist of about 300.000 triangles due to the high resolution of $0.93\times0.93\times1$mm.

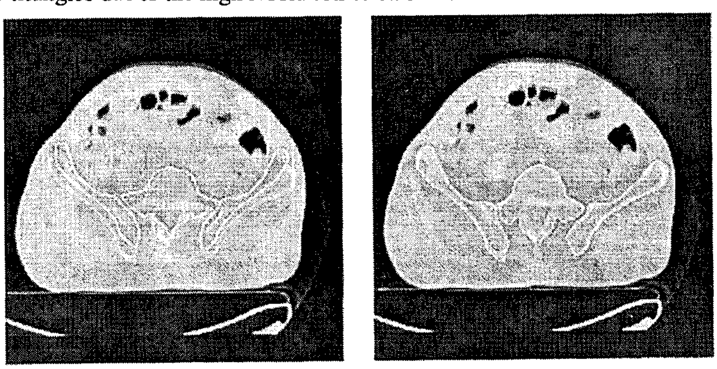

Fig. 2: CT slice of a patient's data set overlaid with the edges of the atlas bone structures (white) before (left) and after the non-rigid registration (right).

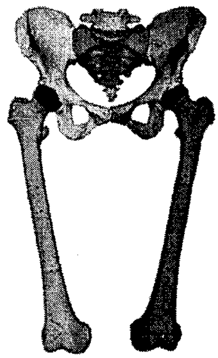

Fig. 3: Three dimensional surface model of the female atlas data. The separated structures are presented in different colours.

6. Results and Conclusion

For a first evaluation of the presented registration method, we register the two atlas data sets of the woman and the man. The image volumes are resliced to a resolution of 2×2×2mm resulting in 200×200×120 voxels. To obtain a good starting position an affine pre-registration is performed. For an automatic labeling of the female bone structures both atlas data sets are binarized using the manual segmentation results. These binary data sets are registered and the labels from the male data set are transferred to the female. In comparison to the manual segmentation results 99.5% of the bony voxels are labeled correctly. Hence, a nearly perfect automatic labeling of the regarded anatomical structures is possible.

In practice, for the patient data set only a rough threshold based segmentation is available. Therefore, a matching is performed on gray value data to evaluate the recognition accuracy in the practical application. During the registration process the CT data set of the visible female is treated as a patient data set. The female bone structures are labeled automatically by the transformed male atlas information. For 98.5% of the bony voxels the correct labels are assigned.

In figure 4 the distance from the female bone surface to the bone surface of the male after the registration is visualized. The light surface regions correspond to distances near to the voxel resolution. Inaccuracies are introduced by varying anatomical details and intensities (e.g. different calcification of bones). Furthermore, the smoothness constrain of the deformation field establishes a compromise between intensity resemblance and uniform local deformations.

The presented methods are a central step to provide the surgeon with all conditions needed for the virtual planning without interactive pre-processing steps. Beside the separated surface models orthopedic measures of the patient's hip are necessary for a successful planning. By defining point landmarks and measures in the atlas we have done the first step in this direction. Since an automatic measuring of the patient's hip needs a very precise landmark localization we are developing algorithms for an automatic correction of landmark positions in a post-processing step.

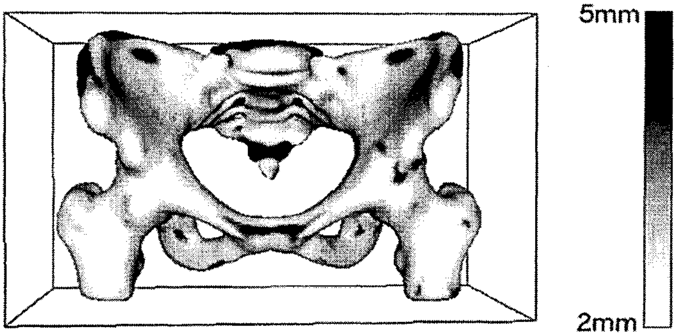

Fig. 4: Visualization of the surface fit: For every point located on the surface of the visualized bone the distance to the registered atlas surface is represented by gray scale values.

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