

Automatic 3D Reconstruction of Transfemoral Residual Limb from MRI Images

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Abstract. This work is part a new design platform for lower limb prosthesis centered on the patient's digital model and based on the integrated use of virtual prototyping tools. In particular, 3D detailed model of residual limb, that includes not only the external skin but also bones and soft tissues, is needed for socket design and finite element analysis to study the socket-residual limb interaction. In this paper, we present a procedure for 3D automatic reconstruction of the residual starting from MRI images. The output is a 3D geometric model, in a neutral format (IGES), which permits CAD information exchange among the modules composing the design platform. The reconstruction procedure consists of three different phases: image pre-processing, voxel segmentation, 3D models generation. Results have been considered promising and future activities to enhance the algorithm performance have been planned.

Keywords: Lower limb prosthesis design, MRI, 3D automatic reconstruction, segmentation.

1 Introduction

Nowadays, lower limb prosthesis design is carried out mostly following a hand-made procedure, and the final result heavily depends on the prosthetics' skills. In this context, we propose a new design platform for lower limb prosthesis design [1] whose main goal is to replace the traditional process with a virtual environment. The platform exploits several ICT tools such as 3D CAD and FEA (Finite Element Analysis) systems as well as biomechanical human models.

The platform comprehends two environments: the Prosthesis Modelling Lab and the Virtual Testing Lab. The first one allows the configuration and generation of the 3D prosthesis model, while the second permits to virtually set up the artificial leg and simulate patient's postures and gait.

The core of the new framework is the digital amputee around which the prosthesis is designed and tested. The amputee digital model is built using LifeMOD™, a biomechanical simulation package based on MSC ADAMS solver. Starting from a reference avatar, it is realized in two steps: the first concerns avatar's dimensioning and the latter residual limb linking. In this paper we focus the attention on the second step that requires the creation of a detailed model of the residual limb as well as some steps of the new design process. An example is the design of the prosthetic socket, the most important and critical component to ensure high quality prosthesis. It has to be realized in a custom way, according to the residual limb shape and patient's characteristics. To this end we have developed a virtual lab, named Virtual Socket Laboratory, which permits the prosthetics to design the socket around the digital model of the residual limb and to validate the 3D socket model by Finite Element Analysis (FEA) evaluating the interaction between the stump and the socket.

This means that a detailed digital model of the residual limb (i.e. including soft tissues and bones) is required and suitable for CAD and FEA environment. In fact, a detailed 3D model of the residual limb is fundamental to create an FE model, which allows the pressure distribution over the limb surface to be computed. The pressure is the commonly accepted that meaningful parameter to evaluate socket functionality is the contact pressure between the residual limb and socket during gait [2]. However, the final users (i.e., the prosthetics) of the platform usually have no specific skills in computer aided tools (e.g. those for medical image processing); therefore, we decided to implement a software module that automatically reconstructs, without human intervention, the 3D model of the stump.

In the following we first describe the procedure for the residual limb automatic reconstruction and adopted algorithms then, the preliminary experimentation with a case study. Finally, discussion of achieved results is reported.

2 Residual Limb Reconstruction

The detailed model of the residual limb, including external and internal (soft tissues and bones) parts is built from medical images acquired using MRI technique. Reconstruction from MRI scans is more challenging than from other medical imaging techniques [3], but we choose MRI since it is the less invasive for the patient and commonly used in considered field [4-7].

The reconstruction procedure is composed by three different phases: image pre-processing, voxel segmentation, 3D models generation. In the first one, the MRI images are pre-processed in order to reduce noise and digital artifacts. Initially, we tested a classic Gaussian smoothing but, in our case, this kind of filter did not preserve edge very well, so we decided to implement noise reduction with a 3D anisotropic diffusion filter [8]. This kind of noise reduction fits very well our purpose since it can also work in three dimensions and we can apply the filter to the whole 3D matrix of voxels. The second phase consists in segmenting the voxels belonging to the bone and those belonging to the external surface and in discarding the other voxels. The final output of this phase consists in two clusters of voxels that represent the geometry of bone and of the external surface from which we can derive the soft

tissue. In the third phase, the procedure, starting from the voxels cluster of bones and soft tissues, creates the 3D geometric models. This operation is carried out using NURBS surfaces. The control points of the NURBS are placed on the external perimeter of the cluster, in order to define the correct shape. Then, the module can export a standard IGES or an STL file after triangulating the NURBS surface. In the following we illustrate the reconstruction of the soft tissue and of the bone, considering as reference a set of MRI images acquired from a transfemoral amputee (i.e., patient with amputation above knee). The automatic procedure has been implemented using C++ languages, NURBS++ library, VTK library for polygonal conversion, and OpenCascade library for IGES exporting.

2.1 External Shape

The external surface of the residual limb is segmented in the following way. After having highly increased the contrast, edge detection by a canny filter is performed (the threshold value is 0.01) and small edges (segments with less than 50 pixels) are discarded (Figure 1). This operation is carried out slice by slice along both axial and coronal axes. The final result is a set of voxels that composes exactly the external surface of soft tissue (Figure 2).

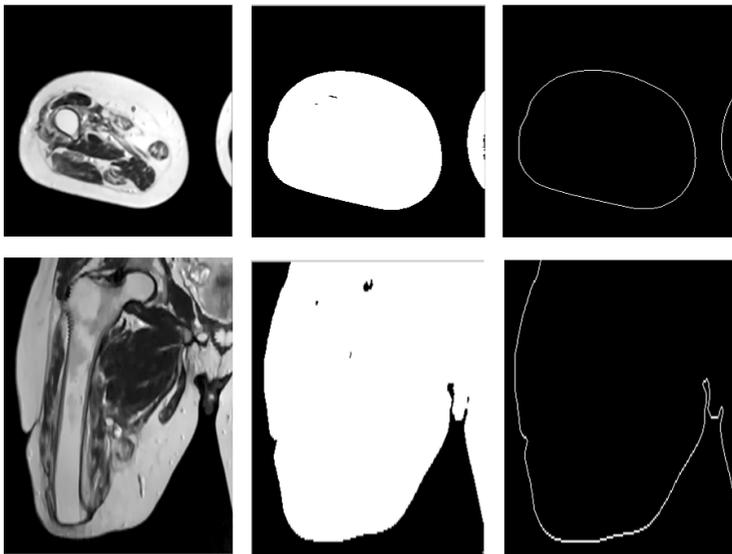


Fig. 1. External profiles detection: Axial and coronal slice (left), high contrast image (center), canny edge detection (right)

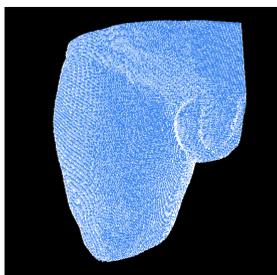


Fig. 2. Automatic segmentation of residual limb

2.2 Bone

Inner bone detection from a MRI scan is challenging because we have not a unique intensity level for every kind of tissue. Moreover, since we have to reconstruct the amputee bone, varying in size and shape, we cannot use an approach that exploits a-priori knowledge, such as ATLAS based segmentation or deformable models [9].

The MRI images can be considered as a 3D matrix of voxels, in which every single slice is part of a vertical stack. We decided to use a graph approach as proposed in [10], adapting the algorithm to a three dimensional matrix.

Initially, each voxel of the MRI volume belongs to a different cluster that has intensity mean corresponding to the voxel intensity. For performance reason, voxels with value equal to zero (intensity equal to zero means empty space) are discarded.

Then, we create a 3D graph where nodes correspond to clusters and edges (connecting clusters) have weight calculated as difference of the intensity between the two connected clusters. We use a 26 neighbors structure (all the neighbors voxels surrounding a voxel). The 3D graph is then segmented as described by the following pseudo code: (code is written in C++ language):

```
Sort edge by weights (from the lowest to the highest)
For every edge i...
  Get clusters A e B connected by edge i
  If (mean intensity difference between clusters A e B <
threshold K)
    Merge clusters A e B in a new cluster C
    Calculate features of cluster C (mean intensity)
  End
End
Final clusters analysis, discard clusters with size and
width/height ratio that doesn't fit bone shape
```

Figure 3 shows an example of the segmented cluster corresponding to the bone of the residual limb for the transfemoral amputee.

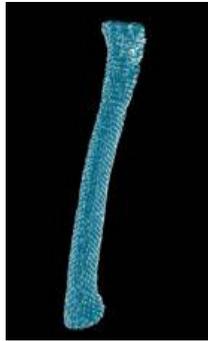


Fig. 3. Automatic segmentation of the bone

2.3 Geometric Models Generation

This phase consists in generating the 3D geometrical model of soft tissues and bone using NURBS surfaces and starting from the clustered voxels. Assuming the z-axis as the vertical axis of the clusters, we initially create a set of x-y planes intersecting the clusters from bottom to the top and with a regular step. For each plane, we create a NURBS circumference whose centre corresponds to the centre of the voxels belonging the plane. The radius of the circumference is set in such a way that the circle surrounds all the voxel belonging to the plane. Then, a convex hull operation is performed on the voxels belonging to the plane in order to obtain a closed perimeter and include any missing voxels. Afterward, for each NURBS circumference, each control point is moved toward the centre of the circumference itself until the point intersects the first voxel, which lies on the external surface of the voxel volume. Figure 4 shows the procedure.

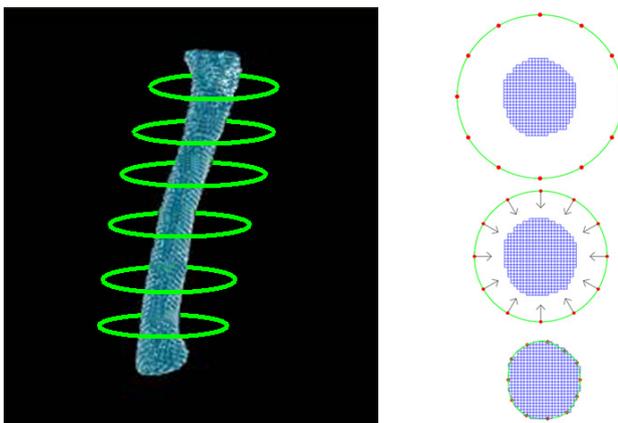


Fig. 4. NURBS perimeter voxels fitting

At this point each circumference has the shape of the external perimeter of the voxels group that the circumference surrounds. Finally the NURBS surface is generated by a lofting operation applied to the circumferences.

The NURBS surfaces can be exported in IGES format to the socket CAD system named SMA-Socket Modelling Assistant [11], specifically developed to design the prosthetic socket. It can be also easily converted by triangulation into a tessellated model and exported in STL format.

Figure 5 shows the NURBS and tessellated model of external surface while Figure 6 of the bone.

The more U and V NURBS parameters are higher, the more the NURBS surface matches the external voxels position; we figure out that $U=20$ and $V=12$ lead to a reasonable level of precision.

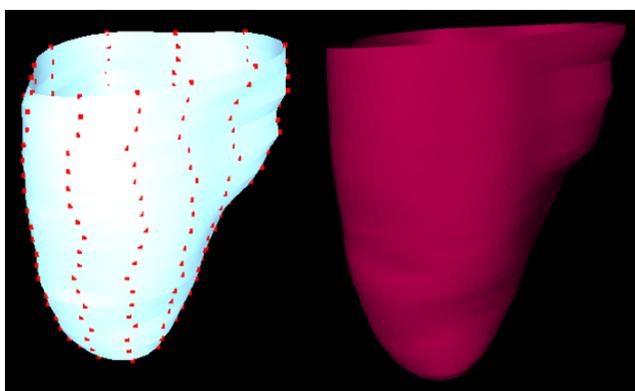


Fig. 5. NURBS (left) and tessellated (right) model of the external surface

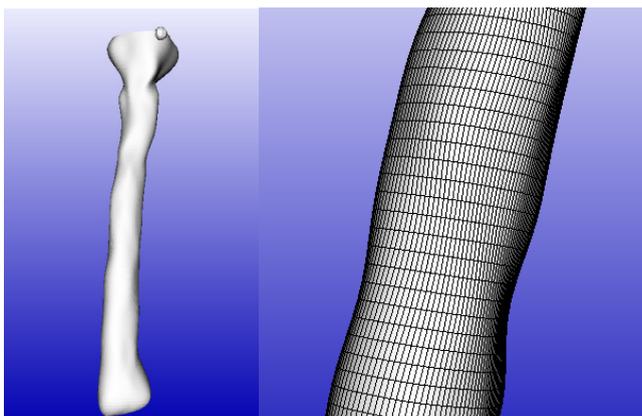


Fig. 6. NURBS (left) and tessellated (right) model of the bone

3 Preliminary Experimentation and Results

We experimented the automatic procedure with a test case of a transfemoral amputee.

We tested the algorithm on different sets of MRI scans of the same patient. External stump surface reconstruction is well performed with every set of MRI; obviously the final model accuracy depends on the resolution of the MRI images. Bone reconstruction, as previously said is more challenging. We found that the best settings of MRI scan for our purpose are the following:

- T2 weighted MRI.
- Slice thickness 2.0 mm.
- Pixel spacing 0.729 mm.
- Resolution 288x288.

In this case, the dimension of the matrix was 288 x 288 x 150 (resolution and number of slices). Based on the scanning parameters, a single voxel had size of 0.729 x 0.729 x 2.0 mm. We performed a normalization operation, so that every voxel had an intensity value between 0.0 and 1.0.

The models obtained have been used to both define a digital model of the transfemoral patient and to design the socket. Figure 7 shows the transfemoral patient's avatar with the reconstructed stump model and wearing the prosthesis.

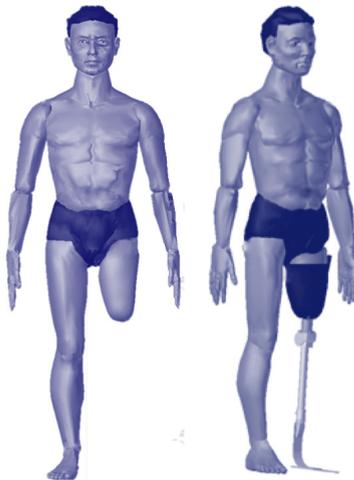


Fig. 7. Digital patient without (left) and with the prosthesis (right)

We compared the results with models reconstructed using a commercial package and following a hand-made procedure. The results have been considered promising, even if the model of the bone is less accurate. Anyway, it meets the requirements of the new prosthesis design framework consisting in an automatic reconstruction without human intervention, and geometrical models suitable for socket design and finite element analysis.

On the basis comparison, we have planned to improve the reconstruction of the bone. The segmentation graph algorithm loses some voxels belonging to the bone, due to high difference of voxel intensity. New features, such as texture characteristics [13], will be introduced during clustering. Furthermore, a shape analysis of the temporary cluster created during the segmentation will be performed to drive the segmentation toward the correct final clusters shape. In fact, a bone has a shape with a high ratio between height and width, and this information could be embedded into the algorithm to make it more effective and fast.

4 Conclusions

This paper proposes a software module that permits to reconstruct the 3D digital model of a transfemoral residual limb acquired with MRI without any human intervention. The implemented procedure runs completely in an automatic way and provides geometric models suitable for CAD and FEM phases of our new prosthesis design framework, in neutral format such as IGES files or STL.

The results compared with those obtained with a manual procedure have been considered promising and further enhancements have been planned to improve accuracy, especially of the reconstructed bone. We have also planned to extend and generalize the algorithm, firstly to transtibial residual limbs, and then to other type of applications, such as aortic aneurysm diagnosis.

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