

Surface mesh to voxel data registration for patient-specific anatomical modeling

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ABSTRACT

Virtual Physiological Human (VPH) models are frequently used for training, planning, and performing medical procedures. The Regional Anaesthesia Simulator and Assistant (RASimAs) project has the goal of increasing the application and effectiveness of regional anesthesia (RA) by combining a simulator of ultrasound-guided and electrical nerve-stimulated RA procedures and a subject-specific assistance system through an integration of image processing, physiological models, subject-specific data, and virtual reality. Individualized models enrich the virtual training tools for learning and improving regional anaesthesia (RA) skills. Therefore, we suggest patient-specific VPH models that are composed by registering the general mesh-based models with patient voxel data-based recordings. Specifically, the pelvis region has been focused for the support of the femoral nerve block. The processing pipeline is composed of different freely available toolboxes such as MatLab, the open Simulation framework (SOFA), and MeshLab. The approach of Gilles is applied for mesh-to-voxel registration. Personalized VPH models include anatomical as well as mechanical properties of the tissues. Two commercial VPH models (Zygote and Anatomium) were used together with 34 MRI data sets. Results are presented for the skin surface and pelvic bones. Future work will extend the registration procedure to cope with all model tissue (i.e., skin, muscle, bone, vessel, nerve, fascia) in a one-step procedure and extrapolating the personalized models to body regions actually being out of the captured field of view.

Keywords: Virtual Physiological Human, Image Registration, Anatomical Modelling, Patient-Specific Models

1. INTRODUCTION

Image registration is the process of aligning two or more images with the goal of finding the optimal transformation that best aligns the structures of interest in the input images. Usually, a pre-registration step positions the moving image (image that is transformed using the fixed images as references) closer to the fixed image (image that remains unchanged), and it is used as an initial solution for the registration algorithm [1]. However, most registration techniques may cope with different modalities but not with different data natures, such as mesh models and voxel recordings.

Anatomical models such as used with the Virtual Physiological Human (VPH) are frequently applied in medical simulations to improve the diagnosis and assist the physician during procedure training, therapy planning, and while performing the intervention. This requires patient-specific modeling, i.e., developing computational models of human pathophysiology that are individualized to patient-specific data [2]. In particular, our challenge is finding an existing image registration technique which considers individual patient anatomy and uses general models to general patient-specific computer models for application in regional anaesthesia (RA) procedures, for instance.

Patient-specific anatomical modelling has been subject for some works. King et al. [3] had the goal of providing anatomical information of the heart for image guided interventions by showing how 3D ultrasound images could be registered to a segmented MRI image. Uneri et al. [4] proposed a deformable registration algorithm for application in cone-beam computer tomography with the purpose of finding the targeting of small tumors in the lung during surgery.

Concerning some works on patient-specific modelling of the pelvis area, Zambrano et al. [5] used images from the pelvis for a CT image registration for radiation planning. And Zheng et al. [6] validated a statistical shape model-based technique for 3D reconstruction of patient-specific surface model from calibrated x-ray radiographs.

The Regional Anaesthesia Simulator and Assistant (RASimAs) project [7] aims at developing a training simulator and assistant prototype for RA procedures which will increase the application, the effectiveness, and the success rates of RA

and electrical nerve-stimulated RA through an integration of image processing, physiological models, subject-specific data, and virtual reality.

The femoral nerve block for RA is performed on the pelvis region and as generic VPH models may not be accurate and do not consider anatomical variations, therefore it is a challenge to create anatomical VPH models for this region.

In this paper, we aim at improving general VPH models toward personalized VPH models by registering the general mesh-based models with patient-specific voxel-based recordings.

2. MATERIAL AND METHODS

As general VPH models, two commercially available data sets were used: Zygote and Anatomium. Both yield the human anatomy in three-dimensional (3D) space and provide polygonal meshes, partly enhanced with textures. However, such data sets do not consider the subject-specific variations of anatomy.

Patient-specific information is gained from medical imaging. With respect to the RA procedure, 3D voxel recording usually are made in the diagnosis process applying magnetic resonance imaging (MRI). Within the RASimAs project so far, 34 sets of MRI of sane male and female have been recorded at Uniklinik RWTH Aachen, Germany; Research Centre Jülich, Germany; and Trondheim Hospital, Norway.

In order to be used to provide anatomical models with a focus on patient-specific modeling of the pelvis for a femoral nerve block, several libraries and software packages have been identified: (i) MatLab¹ for preparation of 3D data, image processing (filtering, segmentation, denoising), and computer graphics (3D mesh deformation, 3D mesh processing), (ii) Simulation Open Framework Architecture (SOFA)² for non-rigid registration of musculoskeletal system, nerves, and vessels, and (iii) MeshLab³ for 3D mesh processing (smoothing, slicing, splitting, re-meshing).

For patient-specific modelling in the RASimAs project, the user enters a set of Digital Imaging and Communication in Medicine (DICOM) images and the anatomical model will provide the most appropriate virtual patient. Five steps are performed to achieve the anatomical modeling: data selection, pre-registration, data conversion, registration, and data export.

1. *Data selection:* The Zygote model and the patient-specific voxel data (MRI) are selected.
2. *Pre-registration:* At first, the Zygote meshes and MRI voxels are placed in one and the same coordinate system. Thereafter, digitally reconstructed radiographs (DRR) are computed for both the virtual model and DICOM images [8]. This 2D representation allows for simple pre-registration with respect to affine movements (translation, rotation, scaling). Alternatively, coordinates from intrinsic landmarks such as *spina iliaca* (uppermost and largest bone of the pelvis) or the *trochanter* (anatomical part of the femur connecting to hip bone) are extracted.
3. *Data conversion:* A reference volume of the mesh is needed for the initialization of the algorithm of Gilles et al [9-10], which is used to set up initial intensity profiles. Therefore, we create a virtual MRI of the Zygote mesh with generic intensity values for the four most important tissues of the MRI, i.e., fat, muscle, bone, air. Although there is a certain lack of reality in this rough approach for virtual MRI generation, it turns out as sufficient for initialization purposes.
4. *Registration:* An algorithm plugin based on Gilles and using SOFA is performed. Gilles's non-rigid registration approach offers the possibility to register a 3D mesh-model/voxel-data combination on a target voxel space. The technique of Gilles focus on the application of shape matching and elastic deformation in musculoskeletal MRI images for inter-patient registration. The source input combination, can for example consist of a MRI from which a mesh was generated by manual segmentation. In the case of this work, a virtual MRI is generated based on the Zygote mesh. To set up intensity profiles, a step size s and the number of steps n that shall be taken in

1 <http://www.mathworks.com/products/matlab>

2 <http://www.sofa-framework.org>

3 <http://meshlab.sourceforge.net>

each direction is needed. For each vertex, there are n inwards and n outwards steps taken in each direction of the normal vector belonging to the vertex.

In Figure 1, each line of the image relates to a vertex. The left half of the images belongs to the inner intensity profile. That is why this part is colored white or gray, as it basically goes through the fat tissue of the virtual MRI. In the right part of the images, the pixels represent the part outside the body of the mesh and also the body in the MRI, which is the reason why they are black. From left to right it is possible to see (left) reference intensity profile of Zygote skin mesh respective to the virtual MRI in the initial setup, (middle) intensity profile of skin mesh respective to target MRI (before registration), and (right) intensity profile of skin mesh respective to target MRI (after registration).

Based on the normalized cross correlation between the reference and the target profiles, the algorithm calculates external forces for each vertex, i.e., it searches points in a certain distance d , which have the highest similarity value. Additionally, internal forces are computed with a computer animation technique [11] to reduce the effect of outliers in the external forces. To improve the performance regarding the processing time, the vertices of the source mesh are sorted in location dependent subsets (clusters) on which a combination of the two different forces is applied.

5. *Data export*: The registered and deformed meshes (skin and bone) are flattened using MeshLab and exported in one single X3D file format.

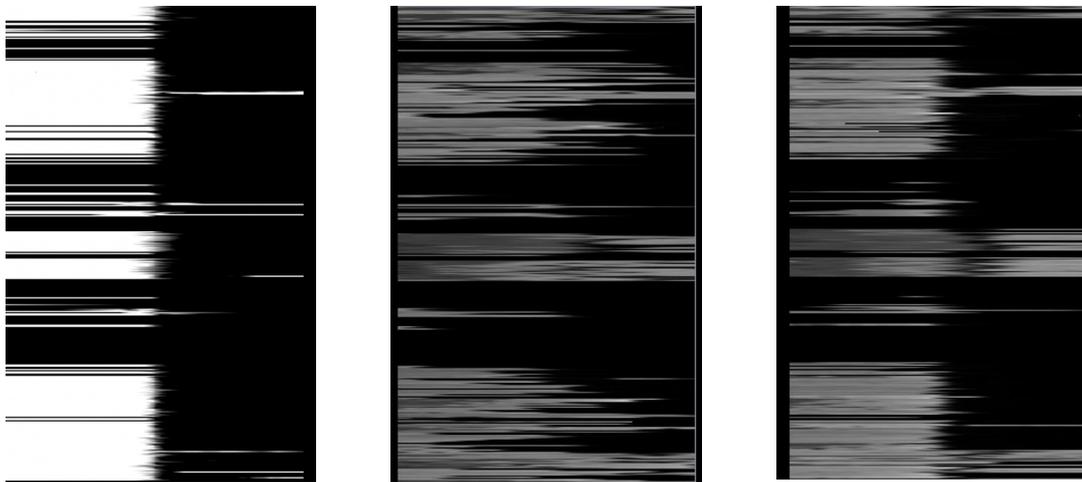


Figure 1. Reference intensity profile of skin meshes for Zygote (left) and target MRIs (middle and right).

3. RESULTS

The final results are stored at the RASimAs Information Storage System (ISS), which includes: (i) Picture Archiving and Communication System (PACS) server for medical image storage and retrieval; and (ii) data server for storage and retrieval of 3D generic and registered models.

For a female and a male subject, Figure 2 and Figure 3, respectively, show on the top the generic Zygote model and on the bottom an example of registration with different orientations regarding the skin, bones, and skin together with bones. The subject-specific data (MRI) is co-aligned with the model data (Zygote) allowing to adopt the meta-information that is stored with the model to the patient data ending up in patient-specific models. In Figure 2, the personalization of the skin for patient-specific modelling is emphasized together with larger bones, in comparison with the Zygote female model. This subject has more fat than the subject of Figure 3, where the bones on the hip are prominent and touch the skin.

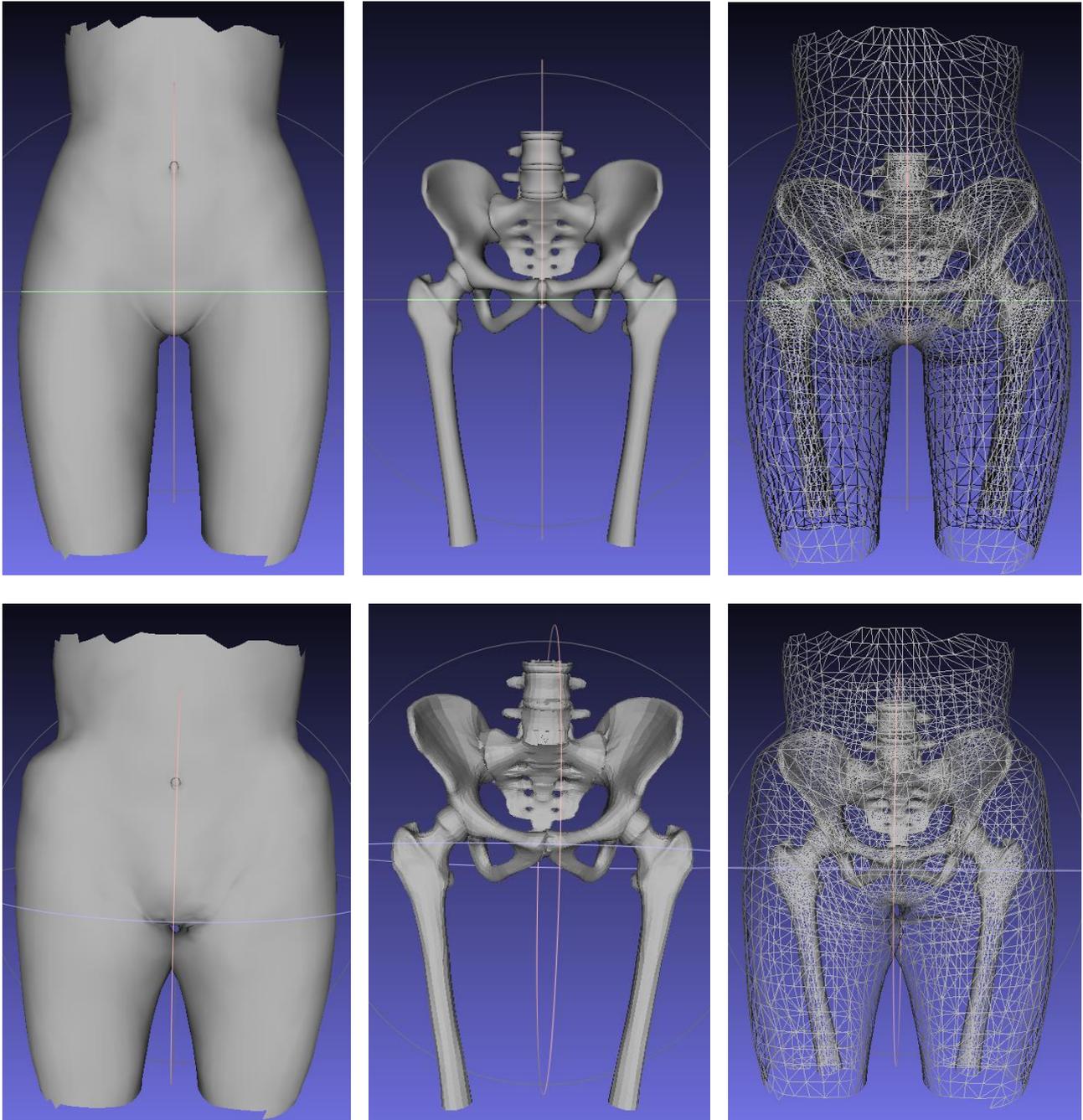


Figure 2. On the top line: Zygote female generic VPH model. From left to right: skin mesh, bones, and both surfaces together. On the bottom line: a female subject-specific model. From left to right: skin registration, bone registration, and both surfaces together.

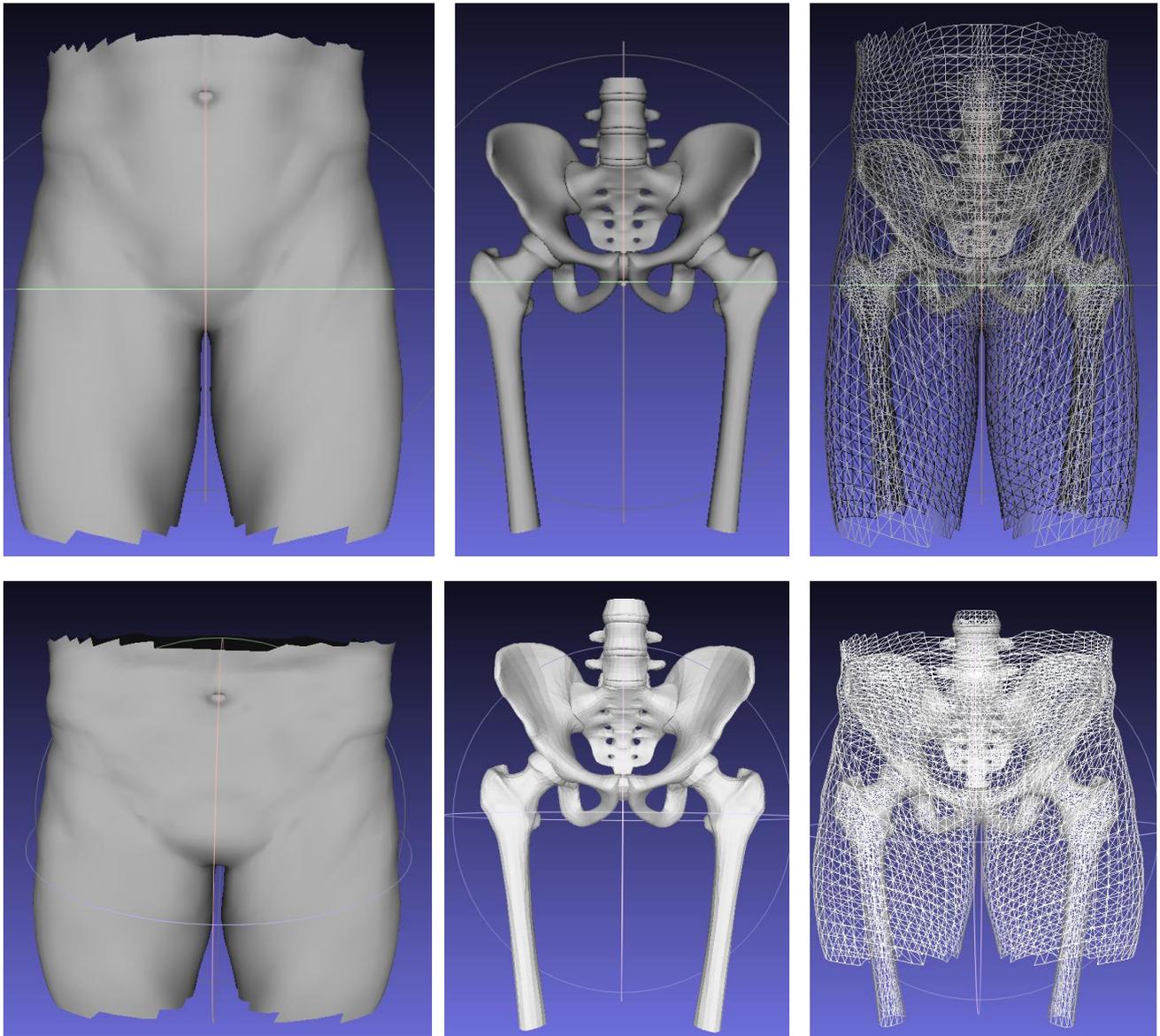


Figure 3. On the top line: Zygote male generic VPH model. From left to right: skin mesh, bones, and both surfaces together. On the bottom line: a female subject-specific model. From left to right: skin registration, bone registration, and both surfaces together

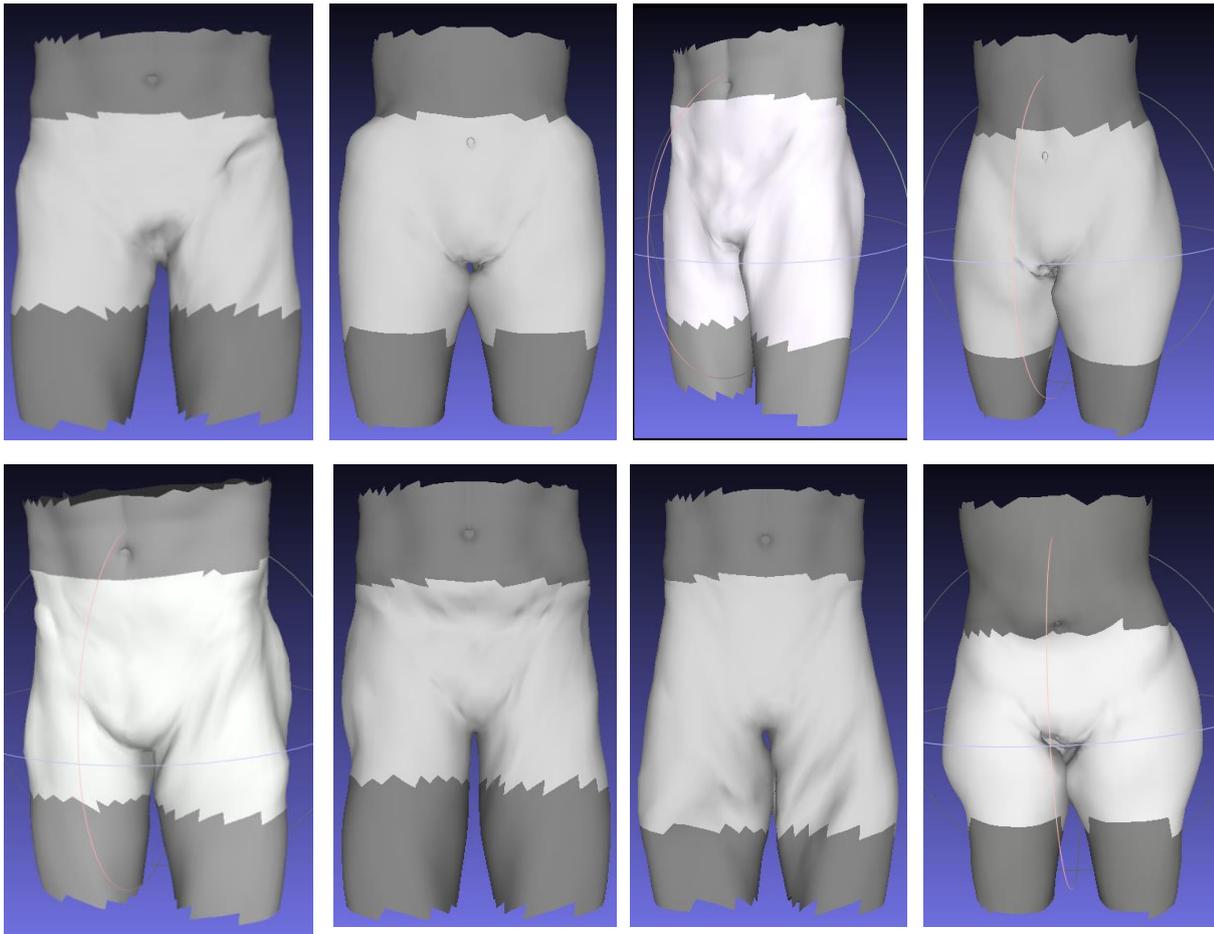


Figure 4. Examples of subject-specific image registration.

Figure 4 shows an example of skin registration (white area in the figure) for several different subjects. One can clearly see the subject-specific deformations, which are following the individual's anatomy.

4. DISCUSSION

Although there are several works of image registration of the pelvis area [12-15], as far as we know, this article presents the first study of patient-specific image registration of VPH models and MRI images. A mesh-voxel registration was applied to create subject-specific VPH models.

Especially with a focus on the pelvis area and in comparison with the use of cadavers, VPH models are rarely used for the task of patient-specific anatomical image registration. This study has adopted commercial general models, however in both models, Zygote and Anatomium, some biologically separated structures (e.g., muscles and bones) overlap, making harder the process of image registration.

The technique from Gilles et al. had to be adapted in order to work with a mesh to voxel image registration providing a new possibility for it, even though only one surface per time can be registered.

Since calculated individually, bone patient-specific image registration may overlap the skin when the subject has little fat, as shown in Figure 3, in the hip area. This demonstrates the need for joint registration with consistent meshes. So far, available VPH models do not satisfy this constrain.

In future, we will face challenges such as extrapolation of subject-specific areas without measured data, and estimating subject-specific data in different posing [16].

5. CONCLUSIONS AND FUTURE WORK

The RASimAs project uses existing libraries and algorithms for image processing to support image registration and 3D mesh processing. The project uses existing commercial VPH models and enhance them by incorporating patient data collected by MRI. The results presented are regarding the skin and bone, but the non-rigid registration for muscles is still being implemented.

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