Model-based Visualization for Medical Education and Training

Noeska Smit[1,2], Kai Lawonn[3], Annelot Kraima[4], Marco DeRuiter[4], Stefan Bruckner[1], Elmar Eisemann[5], and Anna Vilanova[5]

[1]University of Bergen, Norway, [2]Mohn Medical Imaging and Visualization Centre, Norway
[3]University of Koblenz · Landau, Germany, [4]Leiden University Medical Center, The Netherlands
[5]Delft University of Technology, The Netherlands

Abstract

Anatomy, or the study of the structure of the human body, is an essential component of medical education. Certain parts of human anatomy are considered to be more complex to understand than others, due to a multitude of closely related structures. Furthermore, there are many potential variations in anatomy, e.g., different topologies of vessels, and knowledge of these variations is critical for many in medical practice. Some aspects of individual anatomy, such as the autonomic nerves, are not visible in individuals through medical imaging techniques or even during surgery, placing these nerves at risk for damage.
3D models and interactive visualization techniques can be used to improve understanding of this complex anatomy, in combination with traditional medical education paradigms. We present a framework incorporating several advanced medical visualization techniques and applications for teaching and training purposes, which is the result of an interdisciplinary project. In contrast to previous approaches which focus on general anatomy visualization or direct visualization of medical imaging data, we employ model-based techniques to represent variational anatomy, as well as anatomy not visible from imaging. Our framework covers the complete spectrum including general anatomy, anatomical variations, and anatomy in individual patients. Applications within our framework were evaluated positively with medical users, and our educational tool for general anatomy is in use in a Massive Open Online Course (MOOC) on anatomy, which had over 17000 participants worldwide in the first run.

Categories and Subject Descriptors (according to ACM CCS): I.3.8 [Computer Graphics]: Computer Graphics—Applications

1. Introduction

Human anatomy is an essential part of the curriculum for many in the field of medicine, including doctors, radiographers, dentists, physiotherapists, nurses, paramedics, and other health professionals. A wealth of written and visual material exists to support the learning process. Additionally, an important component of the curriculum is the more practical way of learning by dissecting and inspecting human bodies. It is important to note that textbook anatomy vastly differs from what is experienced in dissection, which in turn differs from what is experienced in clinical practice through examination of patients. The link between the different representations is vital in the education of students. While books offer illustrations and medical images from scanners, they are static and cannot present a direct and consistent link between both representations. During dissection, only 3D information is available and the link to corresponding 2D information can be unclear. In the past, the interpretation of medical scans, such as MRI and CT, was mainly performed in radiology departments, but nowadays scans are available in digital form throughout the hospital and many other specialists examine the images directly. Consequently, for medical students, it is a critical yet challenging skill, to be able to mentally reconstruct a 3D model based on 2D images, as well as to relate 3D anatomy to 2D medical imaging data.

Lacking anatomical knowledge can have grave clinical consequences, for instance in the treatment of rectal cancer. Surgical resection of the rectum via a Total Mesorectal Excision (TME) procedure is the predominant surgical treatment option for rectal cancer. Due to the complex anatomy of the region, clinical studies report a high incidence of surgical complications: urinary incontinence in 34%, fecal incontinence in 39% and sexual dysfunction in up to 79% of the cases [LMM*09]. The Dutch TME trial revealed that poor functional outcome after surgery can be caused by surgical damage to the nervous system [WLB*08]. These nerves are often damaged because they cannot be seen by the surgeon in pre-operative MRI scans or during surgery due to their minuscule size. Another factor for nerve damage was the lack of anatomical knowledge and consensus on the exact location of these nerves due to the complex 3D anatomy of the region [Kra15]. Therefore, knowledge of the complicated courses and positions of the crucial nerves, i.e., hypogastric nerves, pelvic splanchnic nerves, and fascia sheets [KWT*15a, KWT*15b], are essential information in order to increase the quality of life after surgery. Excellent pelvic anatomical information is therefore instrumental to obtain high quality oncological and functional results from the TME procedure [KSJ*15].

The approach presented here is the result of a close collaboration between anatomists, surgeons, and visualization researchers [Smi16]. The aim of the project was to improve medical education and training for interventional procedures through interactive model-based visualization techniques and applications. While successful surgical training frameworks, such as SOFA [THP*15] already exist, we aimed to consider anatomical

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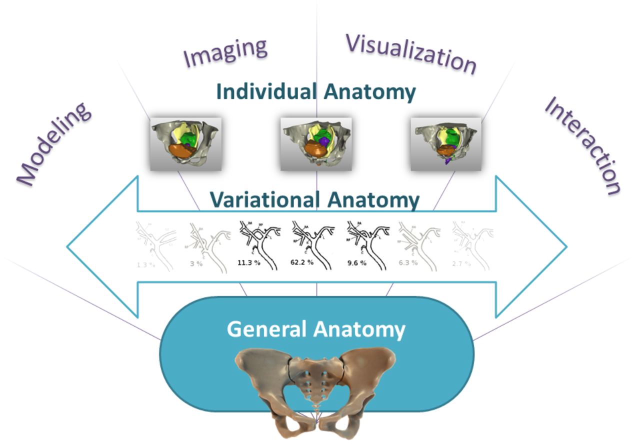

Figure 1: *Framework application overview.*

variation explicitly, and to employ models in combination with medical imaging data to visualize anatomy which is invisible in medical imaging scans. Our framework targets the full spectrum of anatomical knowledge, spanning from general anatomy, across anatomical variations, to the anatomy of the individual patients. All applications in our framework were positively evaluated by medical experts and our teaching tool for general anatomy is used by thousands of people worldwide. In the following, we describe how we addressed the challenges that arise in visualizing complex anatomy, discuss the impact of our methods on the medical field, and provide an outlook on their future potential.

2. Contributions

An overview of the application areas and methodologies involved in our framework can be seen in Figure 1. Due to the focus of our intended framework, different requirements and visualization challenges arose in anatomy visualization, anatomical variation visualization, and visualization of individual anatomy. In the following, we will present our contributions in these areas.

2.1. General Anatomy

As explained in the introduction, anatomical regions can be relatively complex, featuring many overlapping and closely related structures. The link between 2D anatomical images (typically encountered in medical imaging modalities of clinical practice) and 3D anatomy (typically explored during dissections) is considered critical information for students' understanding. To assist teaching the general anatomy of the pelvis, we have constructed a 3D atlas model of the female pelvis based on 2D anatomical data, which preserves the link between both modalities. We developed an integrated histology-based model of the pelvis, the Virtual Surgical Pelvis (VSP). It features a significantly higher level of surgically relevant detail than previous models [KSJ*13] and additionally combines spatial and non-spatial heterogeneous anatomical data [SKJ*12, SKD*12]. Our basic 3D virtual atlas of the pelvis is constructed based on manual expert segmentation of 911 high resolution cryosectional sections in the Visible Korean Female dataset, which has a spatial resolution of 5616 x 2300 pixels with

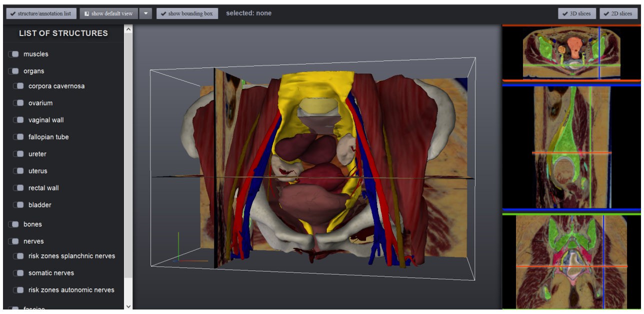

Figure 2: *Screenshot of our interactive web application, which allows users to explore linked 2D and 3D anatomy contained in the VSP atlas.*

a cross-sectional interval of 0.2 mm [PCP15]. From these segmentations, we constructed 3D surface models, which are linked to the 2D anatomical information. Furthermore, we offered the possibility to enrich the VSP with additional (non-spatial) data, e.g., hyperlinks to relevant articles, histology data, and relational information. Based on histological studies [KWT*15a], we could also indicate the zones in which the nerves at risk during surgery reside.

To share the VSP model for educational purposes worldwide, we have built an interactive web application that allows users to freely access the model from any standard modern internet browser [SHK*16]. Using our web application, users are able to interact with the 3D model and 2D slices revealing both cryosectional anatomy and segmentation labels, to improve both the understanding of pelvic anatomy, and the mental mapping between the two domains (see Figure 2). The system was successfully deployed in a Massive Open Online Course (MOOC) on pelvic anatomy to educate students worldwide in the complex 3D pelvic anatomy and the link to 2D anatomical images, and can be accessed via `anatomy.tudelft.nl`.

For scientific communication purposes, we also developed several virtual 3D anatomical models of fetal pelvic anatomy. Similar to the method used to construct the VSP, we constructed the 3D models from stacked slices of histology. We embedded these models in interactive PDF files to accompany publications on specific aspects of new anatomical discoveries, related to the pelvic lymphatic system [KDS*14, KKK*15], as well as the nerves around the ureter [KDS*16]. The availability of 3D reconstructions in addition to standard 2D immunohistochemical staining images is particularly beneficial in supporting the visual communication of anatomical findings to fellow researchers.

2.2. Variational Anatomy

In addition to generally complex anatomy, anatomical variations are important in medical education for specialists. These are deviations from typical anatomy that are considered normal and non-pathological. They are not limited to size and shape only but also include different nerve and vessel topologies. Such knowledge is critical in order to correctly diagnose and safely treat patients. Vascular topological variations, in particular, are especially important for many interventional procedures and, thus, for radiologists, vascular surgeons, transplantation surgeons, and neurosurgeons. Traditionally, knowledge on anatomical variations is presented via textual descriptions and/or simplified anatomical illustrations. Textual descriptions require the reader to construct a mental model of the

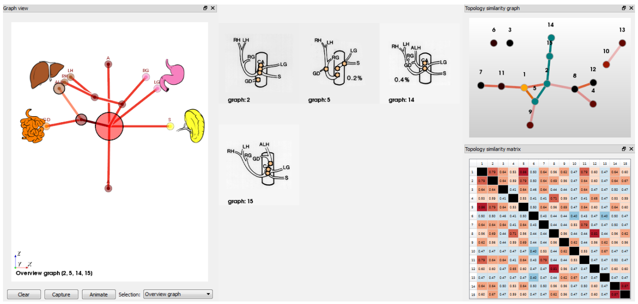

Figure 3: *Screenshot of the VarVis application, in which multiple topological anatomical variations can be analyzed.*

variations, while side by side illustrations can lead to visual overload when there are many potential variations to be described.

We provide interactive methods to visualize anatomical variability in branching structures for educational purposes [SKJ*16] within our VarVis application. The input for VarVis consists of either medical illustrations, or medical imaging acquisitions. Our method builds upon graph-matching techniques, which are used to provide an overview of similarities and dissimilarities between topological variations. The differences are presented in an interactive illustrative network visualization (Figure 3). Our solution introduces a topological distance metric to deliver insights into the similarity of variations. This metric helps answer questions that could not be easily solved by comparing traditional depictions, such as finding groups of similar variations. The resulting variation graphs can be linked to associated 3D surface representations of patient-specific CT-data or anatomical illustrations, which results in multiple views on the variations in complimentary representations. In our application, users are able to explore individual variations, compare groups of variations, and quickly discover which variations are most commonly encountered.

2.3. Individual Anatomy

In interventional training scenarios, there is a need to represent the anatomy of individuals. Due to the wide range of potential anatomical variations in size, shape, and topology, anatomy in individuals can vary greatly between patients. For some cases of interventional training, for instance in neurosurgery training, the relevant anatomy and pathology can directly be extracted from the medical imaging data. For others, however, such as TME (see introduction), medical imaging data cannot provide the anatomical detail to facilitate surgical training. In order to make this available in patient-specific models, we rely on a registration process to map relevant information from our VSP atlas to the anatomy of individual patients. Hereby, even structures that are not visible in the original scan, such as nerves, can be made visible in the context of an individual patient. Ideally, this registration process should be easy to complete. To this end, RegistrationShop [SHS*14] was designed and implemented as an interactive registration system. It applies a mixture of existing techniques such as rigid, deformable, or hybrid registration that are steered through direct visual interaction with the volumes, and it provides direct visual feedback on the registration result. We released RegistrationShop as an open source tool for the community to use and build upon.

Besides the registration process, an additional challenge lies in the anatomy related to the TME procedure. Since the complex

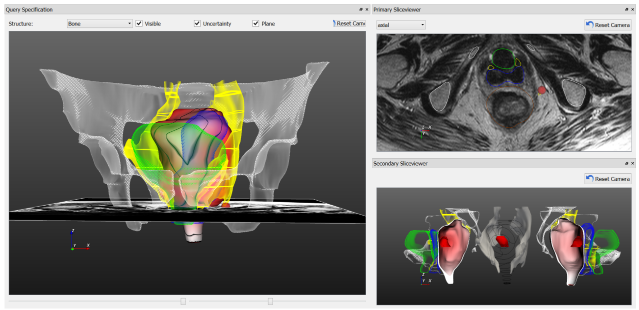

Figure 4: *Screenshot of the PelVis application in which individual anatomy of patients can be explored to train for TME procedures.*

anatomy of the pelvis hinders the view on the target structure of interest, we have developed several illustrative methods, which alleviate problems of occlusion, while maintaining an impression of the anatomical context structures. We have investigated several illustrative visualization techniques related to combined visualization of multiple modalities [LSPV15], as well as levels of illustrative abstraction in surface visualization [LSHL16]. In combination, our techniques are very useful for the surgical training procedures. Using RegistrationShop, patient-specific models can be built, which involve the real patient data. The procedure can be prepared with our surgical planning prototype application, PelVis [SLK*17]. Here, target and risk structures are visualized using illustrative techniques to convey distance information and anatomical spatial context, while limiting occlusion (see Figure 4).

After registering the VSP model atlas to a pre-operative patient-specific MRI scan using RegistrationShop, a patient-specific model of the pelvis can be constructed, which includes the regions in which the autonomic nerves reside. Surgeons in training can then prepare for procedures based on real patient anatomy using our surgical planning prototype application, PelVis [SLK*17]. In PelVis, the anatomical context, target and risk structures are visualized using illustrative techniques to convey distance information, and provide anatomical spatial context, while limiting occlusion (see Figure 4). Additionally, we visualize local registration accuracy confidence combined with the distance to the autonomic nerves zones simultaneously. Since additional patient-specific models are relatively easy to construct using our registration pipeline, it is straightforward to generate multiple training scenarios, allowing for different pathologies to be represented adequately.

3. Impact and Outlook

Every medical education and training application presented in this paper was evaluated with medical domain experts. The general pelvic anatomy web application [SHK*16] was successfully deployed in the Massive Open Online Course (MOOC) entitled 'Anatomy of the Abdomen and Pelvis; a journey from basis to clinic' (`www.coursera.org/learn/anatomy`). This MOOC attracted over 17000 participants world-wide in the first run, and we took advantage of this chance to perform a large scale user study among participants both with and without a medical background, which showed promising results. Our contribution to variational anatomy teaching, the VarVis proof of concept application, was evaluated with three domain experts involved in teaching anatomy and e-learning, and further improved after an initial evaluation. The individual anatomy visualization in the PelVis application was positively evaluated with five domain experts in the field of surgical oncology with various levels of clinical experience. They underlined the utility of the PelVis application for surgeons in training, but also indicated the potential value to experienced surgeons in difficult cases.

The components of our complete framework are not restricted to applications in the pelvic region, and can be easily applied to other medical education and training scenarios. For instance, the principle of using an atlas to visualize 'invisible' nerve regions is also valuable for radiotherapy planning, surgical simulation, or guidance applications. The visualization methods developed are generally applicable and can be extended to other anatomical regions.

4. Conclusion

We have presented a framework for medical education and training purposes, which incorporates advanced visualization techniques and applications, that covers the whole spectrum from general, to variational, to individual anatomy. While many surgical training and education applications exists, our framework is the first to address variational and 'invisible' individual anatomy explicitly. Through the use of our model-based visualization techniques, we are able to visualize nerve regions at risk for surgical damage, which are not visible from medical imaging data, in the context of individual patients.

Acknowledgments

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