The Unified Anatomical Human (Beta): Model-based Representation of Heterogeneous Anatomical Data

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Abstract Three-dimensional anatomical models can be of great clinical value in surgical and educational applications. Mostly, three-dimensional models are reconstructed from Visible Human Datasets (VHDs). In the current VHDs, problems may arise in detecting finer anatomical structures, as is the case in the complex pelvic anatomy. Other datasources, such as CT, MR or immunohistochemistry, may reveal more detailed information about specific relevant anatomical structures. At this moment, there is no way of storing, accessing and visualizing all this information in one single solution. In this work, we present The Unified Anatomical Human: a method for the integration of heterogeneous anatomical data from different sources into a single model. This model allows for storage, retrieval and interactive visualization of arbitrary anatomical data sets. It forms an ideal foundation for further surgical and educational applications in any anatomical region of interest in the human body. Furthermore, we present the foundations for a highly detailed three-dimensional model of the human pelvis. This anatomically realistic model can serve as a solid basis for surgical training, pre-operative planning and medical education.

1 Introduction

Three-dimensional modeling is of increasing interest in clinical medicine. Computer-assisted surgery refers to the collection of methods that use computer technology for surgical training and planning, often based on an anatomical three-dimensional model. Besides CT and MR images, volumetric data can also be extracted from cryosections, as is the case for Visible Human projects. We will henceforth refer to these as Visible Human Datasets (VHDs). Since the introduction of the Visible Human Project in 1994 [1], VHDs have been widely used in the creation of anatomical three-dimensional models due to their high degree of detail.

One of the most complex human anatomical regions is the pelvis. The surgical anatomy of the pelvis is known for its complicated arrangement of autonomic nerves, fascia sheaths, lymphatics and blood vessels. Pelvic surgery often comprises oncologic procedures in the case of urogenital or rectal malignancies. Oncologic outcome as well as functional outcome is of great importance. Anorectal and urogenital dysfunction occur frequently after radical pelvic tumor excision and have been shown to be mainly caused by surgical damage of the pelvic autonomic nerves [2, 3]. The complex pelvic anatomy also plays a central role in the surgical outcome. With regard to rectal cancer, pathological evaluation of surgical specimens has shown marked variability in the surgical dissection plane and incomplete mesorectal excisions in 79 percent of the cases [4]. It is clear that clinical knowledge of the pelvic anatomy should be improved.

Currently, surgical planning systems are mostly used in neurosurgery [5, 6], orthopedic surgery [7, 8, 9], hepatic surgery [10, 11, 12] and oral and maxillofacial surgery [13, 14]. In soft tissue pelvic surgery, an accurate surgical planning system representing all essential surgical structures does not yet exist. The main difficulty in the development of a three-dimensional pelvic model lies in the reconstruction of delicate anatomical structures, such as pelvic autonomic nerves, fascia sheaths and complete pelvic vasculature. A detailed anatomical model containing suitable representations all of these structures would be of enormous value to surgical planning and education. The availability of an efficient and reliable virtual pelvic model could potentially reduce uncertainties in the surgical process, ameliorate patient risk and improve surgical outcome, oncologically as well as functionally. To achieve these goals, the basic anatomical model should be as complete as possible regarding essential surgical structures.

However, current VHDs do not contain sufficient detail concerning especially the finer structures in the pelvis, as well as a number of other similar surgically important anatomical sites. The addition of other volumetric data, for instance CT imaging, MR imaging, diffusion tensor MR imaging, and especially immunohistochemistry, is required for reconstructing the more delicate anatomy. The development of a three-dimensional model for clinical implementation should be based on a number of different sources of spatial volumetric data, including accurate segmentations of all important structures. Furthermore, this should be enriched by inherently non-spatial data, such as related literature concerning for instance anatomical variations or anatomical topologies. A personalized literature database linked to a three-dimensional model will be beneficial for educational purposes, especially for medical students.

There is a need for a system that can integrate all of these heterogeneous anatomical data types, both spatially as non-spatially, in one model. Preferably, such a system would be able to process new anatomical data from any source within the same model. The quality of surgical training and planning depends strongly on accurate representation of the specific anatomy. To ensure this, model-mapping to patient-specific data is also required. Such a mapping would also enable the three-dimensional visualization of essential surgical structures in the anatomical context of a specific patient, also when such structures are not visible in the patient-specific data.

In this paper, we describe the foundations of the Unified Anatomical Human (UAH), a system that will ultimately become a repository for a great deal of heterogeneous anatomical information on the complete human body, and will be able to satisfy the requirements of storage, visualization and patient-specific mapping described above. We have designed a data representation and a proof of concept implementation with which we are able to store and efficiently query heterogeneous spatial and non-spatial anatomical data within a standardized coordinate system. As part of this proof of concept, we developed a digital dataset of a female pelvis and reconstructed a basic three-dimensional model of the pelvis. We show that this model can be mapped to CT and MRI data, and explored in The Unified Anatomical Human-viewer prototype.

2 Related Work

A great deal of work has been done on three-dimensional anatomical modeling. One of the most outstanding projects in this field is the VOXEL-MAN project, founded in 1985 by a German research group under the management of Professor Karl Heinz Höhne. The VOXEL-MAN project focused on the storage, querying and visualization of anatomical data and obtained successful results. A framework for the generation of volume based three-dimensional interactive anatomical atlases was constructed, based on a two-layer model. The spatial part of the model was realized by image volumes, which were obtained from radiological data, and congruent label volumes for different domains of knowledge like morphology or functional anatomy [15]. These volumes were linked to a semantic network containing descriptive knowledge about the objects. Up to now, several interactive three-dimensional atlases have been constructed within this framework, such as an interactive atlas of the brain and skull [16], the inner organs [17] and the hand [18]. The group succeeded to register anatomical data from the Visible Human Project to the interactive atlases. To be able to accurately segment anatomical structures, an interactive classification method that delivers realistic perspective views of the Visible Human Project was developed as well [19]. Furthermore, the group created an high-resolution spatial symbolic model of the inner organs. The spatial description was generated using color-space segmentation, graphic modeling and a matched volume visualization with subvoxel resolution [20]. This was linked to a symbolic knowledge base, providing an ontology of anatomical terms. This model offered an photorealistic presentation and level of detail, due to the high number of anatomical constituents. In 2006 Pommert et al. presented an important extension on their work on using the VOXEL-MAN model for creating surgical simulation systems [17]. Up until now, surgical simulation systems have been constructed for paranasal sinus surgery [21] and dental surgery [22].

Besides the VOXEL-MAN project, the BrainGazer project is also relevant to our research [23]. In this project Bruckner et al. introduced visual queries for neurobiological research. The BrainGazer system uses large databases of transgenic specimens and the acquisition of confocal microscope images of fruit fly brains in which distant neuronal types are highlighted together with annotated anatomical structures. In this way, neurobiologists are enabled to query this data both visually and through the database interface.

The approach we applied in the creation of The Unified Anatomical Human extends the work of the VOXEL-MAN group, and differs from the related work in several ways. The approach we applied in the creation of the UAH extends the work of the VOXEL-MAN group. First of all, the UAH allows for multiple anatomical structures to be defined at any point in model space using information from various different data sources. Thereby, the VOXEL-MAN represents a single general anatomy, while The Unified Anatomical Human is enriched by anatomical information from multiple databases, such as histological cryosections, CT images and MR images. For this reason, it is possible to describe interindividual variations, age variations, anatomical variations or 'fuzzy' anatomical boundaries. In comparison with the BrainGazer project, the UAH needs to support a number of different modalities with significantly varying sampling resolutions and strategies. It also needs to cope with the storage of pristine data sources, each packaged with a number of different task-specific spatial transformations. This last feature is in fact one of the main extensions that distinguishes the UAH from similar research.

With regard to pre-operative planning for pelvic surgery, most existing research focuses on orthopedic procedures. However, some work has been done before in order to create a three-dimensional pelvic model for surgical simulation in soft tissue as well. Up to now, three pelvic models have been constructed to this end. Stanford University was the first to develop a surgical simulation system, called "LUCY", based on their created digital dataset of a female pelvis [24]. LUCY was reported to reveal neural, fascial and lymphatic structures, but unfortunately no detailed differentiation of these incorporated structures was given. Bajka et al. focused on a surgical simulation system as well, and integrated quite sufficiently vascular structures [25]. However, no pelvis nerves, lymphatics and fascia sheaths were included. Holubar et al. developed a virtual pelvic surgery simulator, but the lack of detailed anatomical structures, such as neural, fascial and lymphatic structures renders it unsuitable for detailed surgical planning [26]. A pilot study of its usability and perceived effectiveness affirmed this observation. Fifty percent of the participants felt the module needed a higher level of anatomical detail and specifically requested inclusion of e.g. Denonvilliers' and Waldeyer's fascia, surgically important landmarks [27].

With respect to educational purposes, the most notable three-dimensional pelvic model has been constructed by Sergowich et al. [28]. They integrated successfully up-to-date volume reconstruction technologies and virtual reality techniques in one model. However, the pelvic anatomy was severely incomplete due to the absence of important delicate anatomical structures. Although this model was merely designed for educational purposes, it cannot be denied that high-quality educational training tools actually must represent delicate anatomical structures as well. Therefore, specific anatomical details essential for a surgical planning system must be reconstructed by using other data sources. Sufficient integration of all acquired anatomical information can be achieved within the Unified Anatomical Human.

While this paper focusses more on the medical context of our system, a short description of the technological contributions and a comparison to existing systems will be presented at the Eurovis 2012 conference [29].

3 Method

In this section, we discuss the theoretical representation designed for the UAH and the concepts involved in this design. Secondly, we briefly describe the anatomical datasets used for our prototype implementation.

3.1 Representation

In order to represent heterogeneous anatomical data in an integrated fashion, a model representation is needed that can handle datasets of arbitrary modalities, resolutions, spacings and sources. We developed the Unified Anatomical Human (UAH), a model-based solution for storage, querying and visualization of heterogeneous anatomical data. Using an anatomical standardized coordinate system, this model enables users to store and retrieve efficiently arbitrary numbers and types of anatomical datasets into a single unified model.

Each new anatomical dataset is enriched with at least one mapping describing the spatial relation of its complete domain to the standardized coordinate system, as well as a locator sparsely describing its location in the standardized coordinate system. Furthermore, different types of relations between the new dataset and other objects in the UAH can also be described and stored. Through the locators, datasets and their relations can be rapidly found, and through the various mappings, datasets can be transformed to different spatial domains. In the following subsections, we describe the different components of the model in more detail.

3.1.1 Overview

Figure 3.1 shows the primary concepts used in the UAH. In this approach, raw unedited anatomical data are referred to as source objects. Each of these source objects can be added to anatomical space and placed in the anatomical standardized coordinate space by adding a locator and one or more mappings. The locator describes the spatial embedding of the object and is used for spatial indexing. Each of the mappings represents a different transformation from the raw dataset space to the standardized anatomical space. Any number of relations, each of an arbitrary type, can be defined, and make use of the model object locators as operands.

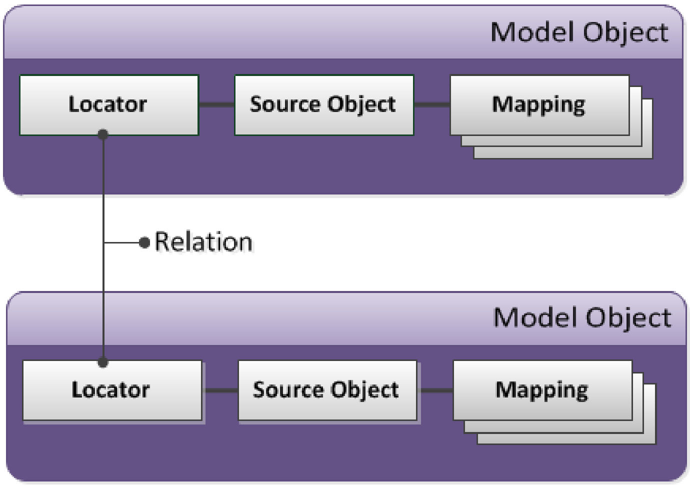


Fig. 3.1 A raw dataset, referred to as a source object, can be added to the anatomical model by enriching it with a locator, used in spatial indexing, and any number of mappings, each describing a task-specific transformation from source object space to the standardized anatomical coordinate system. Any number of arbitrary relations between datasets can be described as well.

3.1.2 Source Objects

Source objects in the UAH consist of original unprocessed data that needs to be added to model space. While there are many types of anatomical data, such as histological cryosections, CT or MR images, functional anatomical data, biomechanical data, anatomical terms and related scientific literature, these data sources can be roughly divided into two categories. The first category consists of source objects that have inherent geometry, such as acquisitions from medical imaging devices, VHDs or images derived from immunohistochemical techniques. We consider source objects in this category spatial data types. The second category consists of source objects without inherent geometry or non-spatial data types. Anatomical terms and synonyms, scientific literature that is relevant to a certain anatomical structure, statistics and bio-mechanical tissue characteristics all fall into this category. While these types of data do not have an inherent spatial component, they can still be spatially embedded in model space through their relations with structures that do have a spatial component.

It is important to store these source objects in their original state in the model, so that at any point, the user can retrieve the objects exactly as they were stored. This is especially true for patient-specific data. When for instance a CT-scan is mapped to model space, it can be deformed to fit the model, but by storing the scan ‘unmapped’ a user can also retrieve the original scan at any time.

3.1.3 Model Objects

To add source object to the UAH model, they need to be augmented with a locator, which describes their spatial extent in model space and one or more mappings to model space. The combined source object, its locator and its mappings are then called a model object. A model object is part of the standardized coordinate system and can be queried and visualized in a single space together with all other available model objects. These queries enable the user to find all model objects at a certain point or region of interest in model space.

The standardized coordinate system is defined in the anatomical position of the human body. Its origin lies in the sacral promontory, a bony easily recognizable anatomical landmark that lies near the center of gravity in the human body. The x-axis points to the left side of the body, the y-axis points forward to the anterior or front of the body and the z-axis in the cranial/superior direction. In this standardized coordinate system, any point in the human body can be intuitively defined with respect to this point.

3.1.4 Mappings

To be able to compare and view model objects in the same shared coordinate space, transformations need to be added that map the source object to model space. These transformations are called mappings, and are obtained from a registration process, that can be rigid, affine, deformable or hybrid, such as for example articulated registration [30]. Inter-modal and inter-patient registration is a challenging task, so we currently use a mix of tools such as MITK, elastix and 3DSlicer to create gold standard mappings for the source objects.

The exact type of registration chosen for the source object greatly depends on the clinical or research question. It can for instance depend on what the surgical structure of interest is. If a surgeon is interested in the nerves around the rectum, the registration needs to be near-perfect around the rectum and the correctness of the bone-to-bone mapping is of less importance. Therefore, the model allows multiple task-specific mappings to be stored. The mapping most suitable for the clinical or research question at hand can be freely chosen at all times. Since the source objects are stored ‘unmapped’, the user can also view the original data objects at any point in time.

Along with the mappings themselves, the errors made in the registration process need to be stored in order to use them to visualize uncertainty in the final representation. By storing the local error metric along with the mapping, an indication of location reliability can be given. When multiple mappings are used in succession, the successive errors made need to be combined. Any uncertainty in the exact locations of the nerves for instance, can have serious consequences for the surgical outcome and therefore need to be made apparent to the users.

3.1.5 Locators

Locators are used to define the spatial extent in model space for model objects. They are used in spatial querying to quickly locate model objects in points or regions of interest. The locator can be defined in various forms depending on the data type. It can represent a set of points, a volume or a non-geometric object. For volumes, the locator consists of its origin, extent and spacing. This meta information is then used to be able to check if a volume is available at any given point in model space. Locators consisting of a set of points are used for spatial indexing. Non-geometric locators don't store extra information, but are used to define relations that link model objects.

Since there can be several model objects that have the same spatial properties, the locators are used, so that when the spatial properties of several model objects sharing the same locator change, no changes need to be made to all of these model objects themselves. An example of this is when several differently weighted MRI scans of the same series are available. The spatial extent for all of these volumes is the same, but if a mistake was made in for instance the x-axis extent, it can be fixed by simply adjusting one locator value.

3.1.6 Relations

Relations are used to link model objects together. Relations are always defined between locators and can be free-form, i.e. one-to-many, many-to-many or one-to-one and have any semantic required. Relations are defined by a type, one or more independent and dependent variables along with optional extra parameters. Examples of relation types are associated to, lookup value, defined by, landmark or subdivision. For instance, when the user wants to link scientific literature to an anatomical structure, an associated_to relation can be used.

In the VOXELMAN-project, relations are used to describe anatomical links that are structural, functional or represent abstraction in a semantic network [15]. Our relations can be used to define all of these links, but extend this idea by allowing relations to be defined between locators of arbitrary types of model objects. For instance, the hip bone consists of three main components: the ilium, ischium and ilium, that are not connected at birth, but are fused together in adulthood [31]. Using our relations, the ilium can be defined geometrically as a subdivision where the ilium is a part of the hip bone and two splitting planes (one separating the ilium from the pubis and one separating the ilium from the ischium) define exactly how this part is defined geometrically. In this case, the dependent variable is the ilium, the independent variable is the hip bone and the parameters describe the splitting planes.

Another example of a free-form relation is defining the location of the iliac crest. It would be tedious to denote the exact location of this crest during the semiautomatic segmentation stage, as there is no clearly defined boundary between the ilium and the iliac crest. Therefore, it is preferable to define the iliac crest at a later stage based on a 3D surface model of the original segmentation using a landmark relation. The dependent variable will be the ilium, the independent variable a points locator describing the extent of the iliac crest and the parameter will describe the landmark type (a crest in this case). This landmark relation can be used to define many anatomical landmarks that cannot easily be delineated in the segmentation phase. Other examples of landmark types are holes, spinae (sharp thornlike anatomical processes) and lines.

3.2 Data

In order to create a highly-detailed three-dimensional pelvic model by integrating heterogeneous anatomical data within the UAH, we obtained the Visible Korean Human dataset, developed by the Ajou University in Suwon, South Korea [32, 33, 34]. This dataset will serve as the basic anatomical atlas to which all additional anatomical information can be added.

In addition to a number of other imaging datasets, we have developed an additional proof of concept dataset, consisting of cryosections and manual segmentations, of a different female pelvis to further enrich the model. After careful examination a defect in the levator ani muscle and scoliosis were detected. Although the specimen used for the Visible Korean Female had suffered from gastric cancer, no pathology was discovered in the pelvis. Our newly developed digital dataset was used as a proof of concept to test our method.

3.2.1 Visible Korean Female pelvis

More detailed anatomical segmentations were performed by using the Visible Korean Female dataset. This is qualitatively one of the best VHDs which is currently available, due to high resolution digital images of 4,368 x 2,912 pixels, a cross-sectional interval of 0.2 mm and the presence of corresponding CT images. Figure 3.3 shows the quality of the Visible Korean Female at this particular transversal section of the pelvis. We are currently working on detailed segmentation of all pelvic structures detectable in this dataset by using Amira software package (v5.3.3). 910 consecutive transversal sections are being manually and semi-automatically segmented. At this moment, the complete bony pelvis, surgically important pelvic musculature and the distal part of the rectum have been three-dimensionally reconstructed within the UAH (figure 3.4).

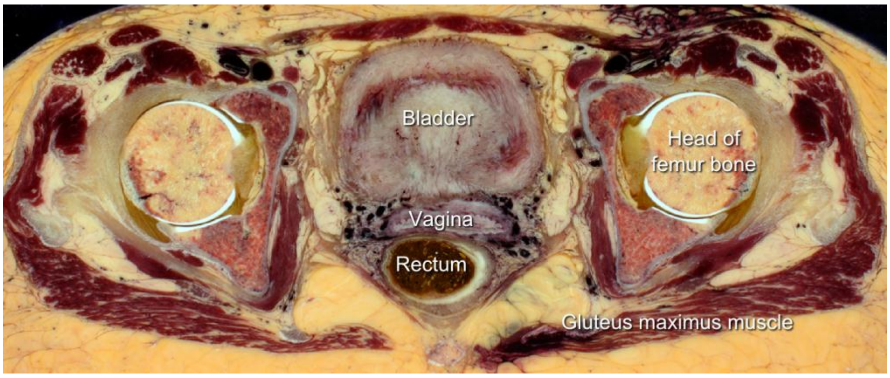


Fig. 3.3 Cross-sectional image of the Visible Korean Female dataset showing pelvic anatomy.

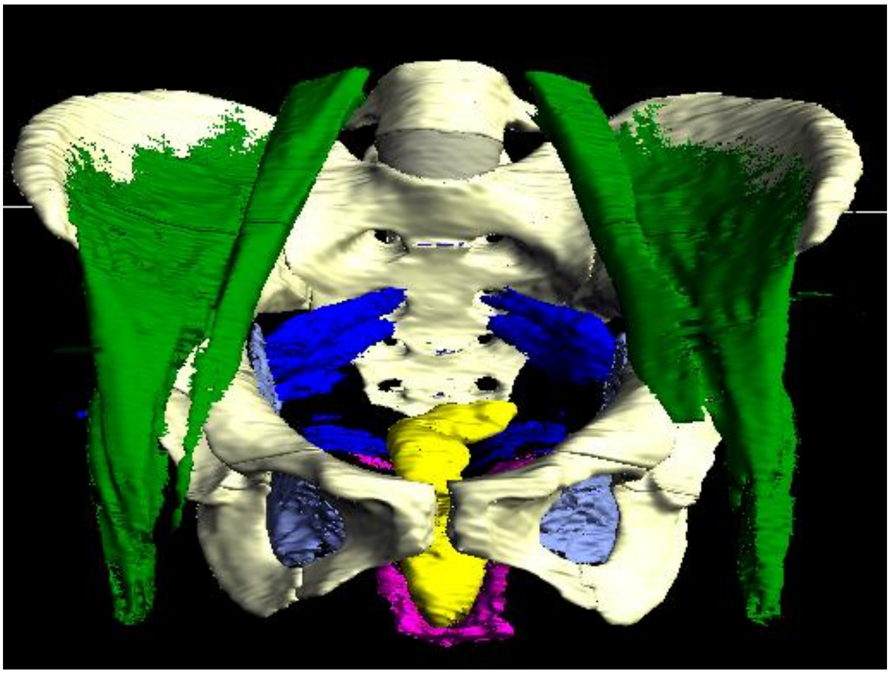


Fig. 3.4 Current three-dimensional model reconstructed from the Visible Korean Female dataset showing the bony pelvis, muscles and distal rectum.

3.2.2 Proof of concept pelvis

In collaboration with several university medical centers, a novel digital dataset of a female pelvis was developed. The description of the generation process of the digital dataset is accessible online. All images were of high quality due to cross-sectional intervals of 75 µm and a spatial resolution of 3,040 x 1,961 pixels. Figure 3.5 illustrates the pelvic anatomy in this digital dataset. Segmentation was performed by using Amira software package (v.5.3.3). To obtain reliable mapping results, anatomical structures must be segmented with accuracy. Thus, manual segmentation was performed on each structure, slide by slide. We did not focus on segmenting highly-detailed structures, which are necessary to include in a three-dimensional model applicable for a surgical simulation system, but aimed to rapidly create a basic anatomical model of the female pelvis. In total, 34 structures were segmented including the bony pelvis, all important pelvic muscles, pelvic organs, greater vessels and greater nerves.

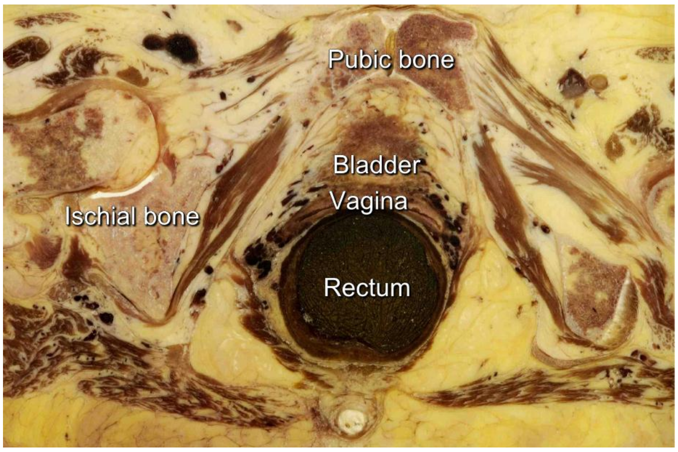


Fig.3.5 Cross-sectional image of our proof of concept pelvis showing pelvic anatomy

4 Results

In this section, the implementation of our prototype application is discussed. We first describe the software technologies that were used and conclude the section with a demonstration of our prototype application features.

4.1 Implementation

The prototype application to store, explore and query model information is implemented in Python as a DeVIDE module [6], employing the Visualization Toolkit (VTK) for its visualization functionality. DeVIDE, or the Delft Visualisation and Image processing Development Environment, is a cross-platform software framework for the rapid prototyping, testing and deployment of visualization and image processing algorithms. An important component of our system is the underlying database, which was implemented using MongoDB. MongoDB is a schema-less document-oriented database technology that is designed to be agile and scalable. Since there is no fixed schema design required in the initial stages of the project, a benefit of using this technology is that it is easy to further extend our model as new information is provided to us by the anatomists, without any changes required to the existing database. Furthermore, MongoDB's GridFS enables us to store large volume data and rapidly retrieve it from the database. The prototype model is based on a manual segmentation in Amira of cryosectional images of a Dutch female pelvis. Based on this segmentation, an iso-surface was rendered using the Marching Cubes algorithm [35]. The registration of an MRI of the same specimen and a CT-scan of a male patient to the cryosectional images was done using the 3DSlicer software package.

A schema-less database differs from a traditional relational database in that there is no predefined data model or schema. Instead of tables and rows it has collections and documents. The documents store BSON (binary-serialized JSON-like data) fields as key-value pairs and can embed other documents. The key-value pairs consist of a name as the key and the value can contain any basic type (such as a string, integer, timestamp, binary, etc.), document or array of values. In a document-oriented database technology such as MongoDB, there are no joins, but the ability to embed documents reduces the need for join-operations. The effect of these design decisions is that a high performance can be attained making read and write operations fast. The collections that form the database are consistent with the method described in the previous section. There is a collection for the model objects and locators. The source objects are stored embedded in the Modelobjects collection (keep in mind that source objects become model objects when a locator and mappings(s) are added). The mapping(s) associated with a volume are also stored as embedded documents within the Modelobjects collection. Relations are stored in the database in the Modelobjects collection of the relation type. The parameter, dependent and independent components are then stored as fields of the relation type model object. Additionally, there are two collections in the database design not described in the previous chapter. A k-d tree, used for fast spatial indexing, is stored in the points collection. The second extra collection is the prototypes collection. This stores the prototype description of current types of model objects available in the Modelobjects collection. The fields of those model object types that are compulsory for that type are stored as a prototype. The prototypes collection can then be used for instance to format query output per type.

4.2 Prototype application: UAHViewer

To evaluate the practical applicability of the UAH, a prototype application was built: the UAHViewer. This prototype application offers several visualization functionalities and demonstrates the usefulness of our model. The user interface consists of three render windows that represent the surface model along with two linked slice viewers, that can display arbitrary volume data. The user is not only able to query anatomical structures topically (by subject), by selecting an anatomical term from a drop-down list or clicking on a structure in any view, but can also query the model spatially. In this section we demonstrate the utility of our model-based anatomy visualization prototype using three examples.

4.2.1 Generic Multi-modal Data Querying

By mapping volumes to anatomical model coordinates, it becomes possible to simultaneously slice through volumes of different modalities and different subjects. The linked volume representations enable the user to compare arbitrary multi-modal volumes side-by-side in an interactive and intuitive way.

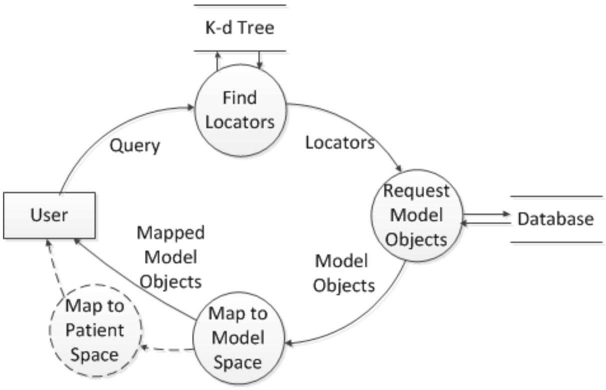
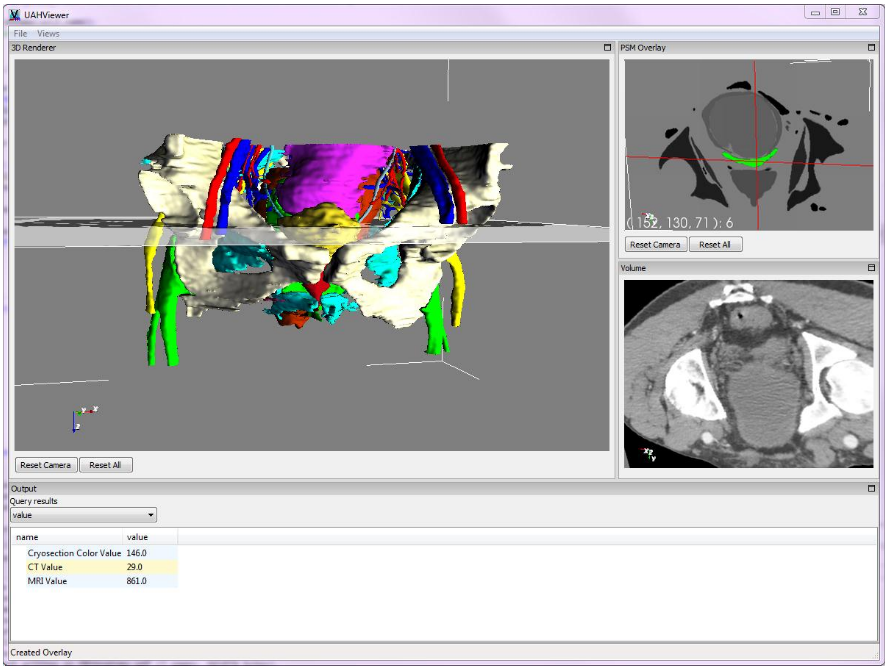


Fig. 4.1 The high-level data flow diagram for querying in the Unified Anatomical Human.

It is also possible to query a specific voxel value in all available volumes at a selected point. This type of spatial querying is done by either clicking on a structure in the surface rendering or in one of the slice viewers. A high-level data flow diagram of this process is shown in figure 4.1. When the user selects 'value' from the query results, the coordinates of the point last clicked by the user are acquired. These coordinates are then used to find all available volumes in that point using the volumes' locators. Since the locators for volumes store the spatial extent, spacing and origin for every volume, it is straightforward to check if a coordinate in standardized anatomical space is available in that specific volume. When the available volumes are returned from the database, the value at the query-coordinate can be acquired and returned to the user. For example, in figure 4.2 a point is queried in the segmentation label volume. This query returns the voxel values for all volumes available in that point. The linked representations make it easy to locate points of interest in any view preferred by the user. The CT Hounsfield value can then be used for instance to calculate the Young's modulus (compressive stiffness) of bone [36].



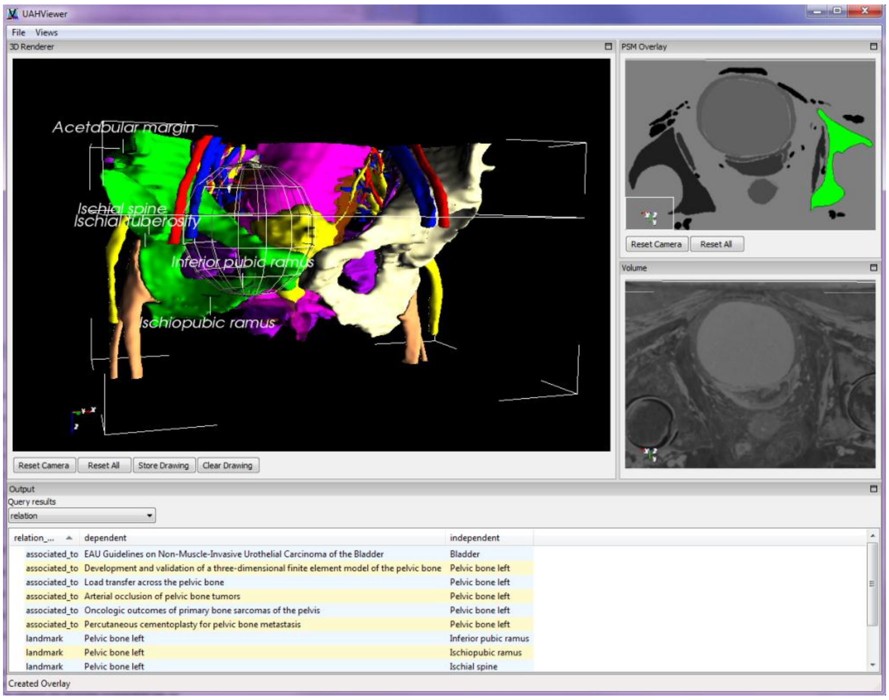
name	value
Cryosection Color Value	146.0
CT Value	29.0
MRI Value	861.0

Created Overlay

Fig. 4.2 Value querying in arbitrary views presents query results for all available volumes in that point. The surface render shows an MRI slice while the top right render window displays the linked segmentation label volume slice and the lower right render window displays the mapped CT slice

4.2.2 Distance Querying

Besides topical queries, spatial queries are also possible. The user can query a specific subvolume of the model space by using a selection query sphere. In this way, users can select an area of interest and perform a distance query in this area. The application then returns the query results of the point that was selected as well as all locators in the region encompassed in the selection sphere. The query process is similar to the one shown in figure 4.1, but the locators are found by specifying a coordinate and range of interest. As an example, when a user is interested in all information on anatomical structures within a region of interest surrounding the bladder, a query sphere can be placed to define that region. Figure 4.3 shows how the sphere selection returns query results based on the locators found inside the sphere. In this figure, a distance query presents the relations of all structures found inside the selection sphere and literature associations within the sphere are revealed. In this case, the user has drawn anatomical landmarks on the bone in the three-dimensional surface reconstruction and stored these in the database. Also the user has associated relevant literature to this structure. Since the literature and landmarks are stored as relations in the database, the related model objects are easily found and added to the query results. The query results therefore consists of all available information for this structures themselves, for instance the names and segmentation values, as well as the literature and anatomical landmarks related to these structures.



relation_...	dependent	independent
associated_to	EAU Guidelines on Non-Muscle-Invasive Urothelial Carcinoma of the Bladder	Bladder
associated_to	Development and validation of a three-dimensional finite element model of the pelvic bone	Pelvic bone left
associated_to	Load transfer across the pelvic bone	Pelvic bone left
associated_to	Arterial occlusion of pelvic bone tumors	Pelvic bone left
associated_to	Oncologic outcomes of primary bone sarcomas of the pelvis	Pelvic bone left
associated_to	Percutaneous cementoplasty for pelvic bone metastasis	Pelvic bone left
landmark	Pelvic bone left	Inferior pubic ramus
landmark	Pelvic bone left	Ischiopubic ramus
landmark	Pelvic bone left	Ischial spine

Fig. 4.3 A distance query returns all information related to the structures inside the sphere.

As mentioned in the implementation section, the segmentation of anatomical structures is stored by building a k-d tree from a sparse point sampling of each structure. The locator for an anatomical structure thus consists of a set of points that represent the spatial extent in model space. When a query is sent to the database, specifying a coordinate and the range, the k-d tree is rapidly traversed to find all points within the area of interest. Having found the locators representing these points, the associated model objects can be found by querying the model objects collection for objects that use these locators. Using the database implementation of a k-d tree as a spatial index of the point sets, spatial query results can be updated dynamically in real time. This means that when the sphere is moved in the three-dimensional view, the query results update in real time to reflect the model objects that are at that time present in the sphere of interest. This provides the users with the ability to rapidly explore all model objects within a region of interest in an intuitive way.

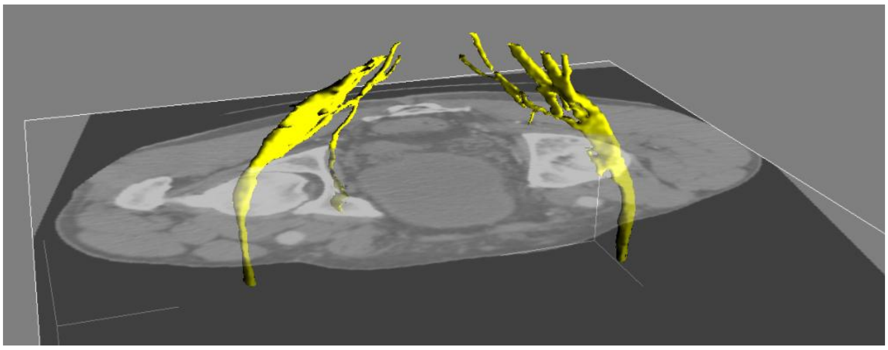


Fig. 4.4 Using our approach, the nerves that were segmented in the cryosectional images can be mapped to unseen patient specific CT-scan data. The location of these pelvic nerves is not as clearly visible in the original CT-scan.

4.2.3 Mapping Model Information to Patient Data

A third example of the prototype functionality is enriching unseen patient scan data with the information provided by model objects. By registering a patient-specific scan, of an arbitrary modality, and deriving from this registration a mapping between patient and model space, it becomes possible to reveal structures that cannot be denoted in that modality by default. For instance, because there is not enough contrast between nerves and surrounding soft tissues in CT-scans, the location of nerves is therefore not visible in a CT-scan. In histological and cryosectional images, however, the nerves can be seen and segmented. In figure 4.4, a CT-scan added to model space is enriched with an isosurface render of the nerves segmented based on cryosectional images.

In general, figure x shows the process of making arbitrary structures stored in the UAH patient-specific. By selecting a structure of interest and an arbitrary modality mapped to model space, the stored mapping is used to map the structure of interest to patient space. This process can be used to map the cryosectional volume that forms the basis of the model space and standardized coordinate system back to a patient-specific scan. This does of course require the transformation stored in the mapping to be invertible. By selecting the mapping that is most appropriate for the task at hand, for instance a mapping based on a structure-specific registration process, it becomes possible to map structures of interest to patient-specific scans in the most suitable way given the structure of interest. Using this same mapping principle, it is also possible to map the entire segmentation label volume to patient-specific data. If the registration is done correctly, this creates an automatic segmentation of the unseen patient-specific scan. This mapped segmentation can be used to make a three-dimensional patient-specific model by rendering the isosurfaces.

Our system enables the efficient storage, retrieval and application of different structure- and task-specific mappings. So far, we have used a number of interactive imaging tools to derive different mappings for the structures and datasets in our model, in each case evaluating the mapping's quality through expert visual inspection and the relevant similarity metric. For each new dataset added to the model, this process has to be performed at once for each new structure- or task-specific mapping. In the future, we plan to streamline this important process, both for adding new datasets to the model, and for mapping model objects to patient-specific datasets. We expect that visual inspection and interaction will remain an important component, especially in more complex mappings, for example derivatives of articulated registration

5 Conclusion

The Unified Anatomical Human (UAH) forms a solid foundation for the comprehensive integration of heterogeneous anatomical data of spatial and non-spatial origin into a single, unified model. The unique design, based on source objects, model objects, locators and mappings within a standardized coordinate system, allows users to store, query and visualize arbitrary heterogeneous anatomical data. Due to the schema-less database design, new anatomical datasets can be added to the UAH incrementally.

Datasets within the UAH can be mapped from model space to patient-specific data, such as CT and/ or MR images. In this way, patient-specific data can be complemented with anatomical information obtained from the UAH, which was originally not detectable. In clinical practice, pre-operative planning for radical pelvic surgery will be strongly facilitated as detailed anatomical structures, such as pelvic autonomic nerves, can be mapped in patient-specific data. Furthermore, multi-atlas segmentation of unseen patient-specific scans has become possible, because of the stored mappings within the UAH.

Highly-detailed three-dimensional pelvic modeling has become feasible by integrating heterogeneous anatomical data in the UAH. Volumetric spatial data of detailed anatomical pelvic structures can be extracted from different image modalities. Therefore, it is possible to reconstruct much more anatomical detail then by segmentation of a VHD alone. Non-spatial data can be added to the UAH as well, which enables clinicians and medical students to explore three-dimensional pelvic anatomy with, for example, specific related literature in one unified database. Finally, the generic concept of the UAH can be applied to other anatomical regions. As such, the UAH provides an excellent basis for further clinical and educational applications.

6 Future Work

We are presently working on the creation of a highly-detailed three-dimensional model of the female pelvis applicable for surgical training and planning and medical education. To this end, we are segmenting histological cryosections from the Visible Korean Female, CT images and MR images. Accurate immunohistochemical studies on the pelvic autonomic nerves and fascia sheaths will be performed. All segmentation results will be reconstructed in the UAH. As discussed before, the proof of concept model has shown that this is feasible.

We envision surgical and medical educational applications being developed by using anatomical information unified in the UAH. For surgical training, various surgical procedures and scenarios can be created for different anatomical and pathological situations. Surgical residents would then be able to rehearse their future daily clinical practice in a virtual environment. Visualization of anatomical details in the extent of a patient-specific situation within the UAH, forms the basis for patient-specific pre-operative planning. For pelvic surgery, this surgical planning tool will be very beneficial in view of surgical and functional outcome. The development and validation of such surgical simulation systems must be based on a multidisciplinary approach including clinicians, educationalists and industrial designers.

The design of the UAH model is generic. Therefore, the same method of three-dimensional anatomical modeling can be applied to any other anatomical regions. In the future, we strive to develop a highly-accurate anatomical atlas of the human body, based on this principle. Clinicians already have shown their interest in creating an anatomical atlas of the thoracic cavity including the heart within the UAH. However, extension as such will bring along new challenges, for example storing of enormous amounts of data and including time-varying data sets in the UAH.

Moreover, a web-application is being constructed that represents a simplified version of the UAHViewer prototype. Clinicians, researchers and medical students will be able to explore the model and its information from any computer with internet access within the hospital. With emerging technologies such as WebGL, hardware-accelerated three-dimensional graphics become feasible. This would allow users to interact with information in the UAH without the need to install additional software or a specialized workstation.

Other standard coordinate systems, such as the Talairach or MNI space used in the neuroscience community [9], will be investigated for possible integration with the UAH. At first glance, it seems that mappings between these coordinate systems and our standardized anatomical coordinate systems are feasible. The source objects can then be stored in their original coordinate system and the mappings specify how this relates to our standardized coordinate system.

Furthermore, we plan to create richer visualization options for model objects. Currently, only isosurface rendering and volume slicing are available, but we would like to extend the visualization possibilities with direct volume rendering techniques. With the information available from the model objects and their relations, it will be possible to create composite custom visualizations for different clinical questions. It might even prove beneficial to allow our system to create composite visualization suggestions based on the structures of interest and the optimization of a cost function.

References

[1] Ackerman MJ (1999) The Visible Human Project: a resource for education. Acad Med 74:667-670

[2] Wallner C, Lange MM, Bonsing BA, Maas CP, Wallace CN, Dabhoiwala NF, Rutten HJ, Lamers BH, DeRuiter MC, van de Velde CJH (2000) Causes of fecal and urinary incontinence after total mesorectal excision for rectal cancer based on cadaveric surgery: A study from the cooperative clinical investigators of the dutch total mesorectal excision trial. J Clinic Oncol 26(27):4466 –4472

[3] Lange MM, Marijnen CAM, Maas CP, Putter H, Rutten HJ, Stiggelbout AM, Meershoek-Klein Kranenbarg E, van de Velde CJH (2009) Risk factors for sexual dysfunction after rectal cancer treatment. Eur J Cancer, 45(9):1578–1588

[4] Leonard D, Penninckx F, Fieuws S, Jouret-Mourin A, Sempoux C, Jehaes C, van Eycken E (2010) Factors predicting the quality of total mesorectal excision for rectal cancer. Ann Surg 252:982-988

[5] Beriault S, Al Subaie F, Mok K, Sadikot AF, Pike GB (2011) Automatic trajectory planning of DBS neurosurgery from multi-modal MRI datasets. Med Image Comput Comput Assist Interv 14:259-266

[6] Robison RA, Liu CY, Apuzzo ML (2011) Man, mind, and machine: the past and future of virtual reality simulation in neurologic surgery. World Neurosurg 76:419-430

[7] Cimerman M, Kristan A (2007) Preoperative planning in pelvic and acetabular surgery: the value of advanced computerised planning modules. Injury 38:442-449

[8] Heng PA, Cheng CY, Wong TT, Wu W, Xu Y, Xie Y, Chui YP, Chan KM, Leung KS (2006) Virtual reality techniques. Application to anatomic visualization and orthopaedics training. Clin Orthop Relat Res 442:5-12

[9] Muller W, Bockholt U, Lahmer A, Voss G, Borner M (2000) VRATS--Virtual Reality Arthroscopy Training Simulator. Radiologe 40:290-294

[10] Numminen K, Sipila O, Makisalo H (2005) Preoperative hepatic 3D models: virtual l iver resection using three-dimensional imaging technique. Eur J Radiol 56:179-184

[11] Reitinger B, Bornik A, Beichel R, Schmalstieg D (2006) Liver surgery planning using virtual reality. IEEE Comput Graph Appl 26:36-47

[12] Debarba HG, Zanchet DJ, Fracaro D, Maciel A, Kalil AN (2010) Efficient liver surgery planning in 3D based on functional segment classification and volumetric information. Conf Proc IEEE Eng Med Biol Soc 2010:4797-4800

[13] Tolsdorff B, Pommert A, Hohne KH, Petersik A, Pflesser B, Tiede U, Leuwer R (2010) Virtual reality: a new paranasal sinus surgery simulator. Laryngoscope 120:420-426

[14] Pohlenz P, Grobe A, Petersik A, von SN, Pflesser B, Pommert A, Höhne KH, Tiede U, Springer I, Heiland M (2010) Virtual dental surgery as a new educational tool in dental school. J Craniomaxillofac Surg 38:560-564

[15] Höhne KH, Pflesser B, Pommert A, Riemer M, Schiemann T, Schubert R, Tiede U (1995) A new representation of knowledge concerning human anatomy and function. Nature Med 1(6):506–511

[16] Tiede U, Bomans M, Höhne KH, Pommert A, Riemer M, Schiemann T, Schubert R, Lierse W (1993) A computerized three-dimensional atlas of the human skull and brain. Am J Neuroradiol 14(3):551-559

[17] Pommert A (2001) Creating a high-resolution spatial/symbolic model of the inner organs based on the visible human. Med Image Anal 5:221–228

[18] Gehrmann S, Höhne KH, Linhart W, Pflesser B, Pommert A, Riemer M, Tiede U, Windolf J, Schumacher U, Rueger JM (2006) A novel interactive anatomic atlas of the hand. Clinic Anat 19(3):258–266

[19] Höhne KH, Pflesser B, Pommert A, Riemer M, Schubert R, Schiemann T, Tiede U,Schumacher U (2001) A realistic model of human structure from the visible human data.Methods Inf Med, 40(2):83–89

[20] Tiede U, Schiemann T, Höhne KH (1998) High quality rendering of attributed volume data. Visualization '98 Proceedings 255-266

[21] Tolsdorff B, Pommert A, Höhne KH, Petersik A, Pflesser B, Tiede U, Leuwer R (2010) Virtual reality: a new paranasal sinus surgery simulator. Laryngoscope 120(2):420-6

[22] Pohlenz P, Gröbe A, Petersik A, von Sternberg N, Pflesser B, Pommert A, Höhne KH, Tiede U, Springer I, Heiland M (2010) Virtual dental surgery as a new educational tool in dental school. J Craniomaxillofac Surg 38(8):560-564

[23] Bruckner S, Soltészová V, Gröller E, Hladůvka J, Bühler K, Yu JY, Dickson BJ (2009) BrainGazer- visualqueries for neurobiology research. IEEE Trans Vis Comput Graph 15(6):1497–1504

[24] Heinrichs WL, Srivastava S, Dev P, Chase RA (2004) LUCY: a 3-D pelvic model for surgical simulation. J Am Assoc Gynecol Laparosc 11:326-331

[25] Bajka M, Manestar M, Hug J, Szekely G, Haller U, Groscurth P (2004) Detailed anatomy of the abdomen and pelvis of the visible human female. Clin Anat 17:252-260

[26] Holubar SD, Hassinger JP, Dozois EJ, Camp JC, Farley DR, Fidler JL, Pawlina W, Robb RA (2009) Virtual pelvic anatomy and surgery simulator: an innovative tool for teaching pelvic surgical anatomy. Stud Health Technol Inform 142:122-124

[27] Hassinger JP, Dozois EJ, Holubar SD, Camp JC, Farley DR, Fidler JL, Pawlina W, Robb RA, Larson DW (2010) Virtual pelvic anatomy simulator: a pilot study of usability and perceived effectiveness. J Surg Res 161:23-27

[28] Sergovich A, Johnson M, Wilson TD (2010) Explorable three-dimensional digital model of the female pelvis, pelvic contents, and perineum for anatomical education. Anat Sci Educ 3:127-133

[29] Smit NN, Kraima AC, Jansma D, de Ruiter MC, Botha CP (2012) A Unified Representation for the Model-based Visualization of Heterogeneous Anatomy Data. Accepted, to appear.

[30] Baiker M, Milles J, Dijkstra J, Henning TD, Weber AW, Que I, Kaijzel EL, Löwik CWGM, . Reiber JHC, Lelieveldt BPF (2010) Atlas-based whole-body segmentation of mice from low-contrast Micro-CT data. Med Image Anal 14(6):723-737

[31] Gray H (1918) Anatomy of the human body. Ann Surg 68(5):564

[32] Park JS, Chung MS, Hwang SB, Lee YS, Har DH, Park HS (2005) Visible Korean human: improved serially sectioned images of the entire body. IEEE Trans Med Imaging 24:352-360

[33] Park JS, Chung MS, Hwang SB, Shin BS, Park HS (2006) Visible Korean Human: its techniques and applications. Clin Anat 19:216-224

[34] Park JS, Jung YW, Lee JW, Shin DS, Chung MS, Riemer M, Handels H (2008) Generating useful images for medical applications from the Visible Korean Human. Comput Methods Programs Biomed 92:257-266

[35] Lorensen WE, Cline HE (1987) Marching cubes: A high resolution 3D surface construction algorithm. Comput Graph 21(4):163-169

[36] Keller TS (1994) Predicting the compressive mechanical behavior of bone. J Biomech 27(9):1159-1168