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VISIBLE HUMAN PROJECTS - A STEP TOWARDS THE VIRTUAL PATIENT: MODELS AND SIMULATIONS

This paper reports on our experiences using datasets from the Visible Human Project in different biomedical applications. Introduced 1994 by the US National Library of Medicine the digitized multimodal anatomical datasets of the Visible Man have challenged the worldwide scientific community. A significant response to this challenge from several interdisciplinary research teams has emerged as a new area of research. This area requires close interaction and collaboration among anatomists, radiologists, computer scientists, mathematicians, engineers and physicians. The digitized volumetric images of the human body have been applied not only for the computer-aided exploration of the human gross anatomy, but also as structural input for the therapy planning and simulation systems. The importance of such virtual patient model is becoming increasingly recognized in modern medicine. To effectively use these specific datasets a sophisticated framework consisting of image processing, computer graphics and mathematical modelling methods is required. In this work various aspects of the developed framework are presented and discussed. Some preliminary results of our biomedical simulations are presented.

1. INTRODUCTION

In 1989, the US National Library of Medicine (NLM) has initiated the Visible Human Project (VHP). The aim of the VHP was to create a digital image dataset of a complete human male and female cadaver in CT and MR modalities as well as digital photographs of the axial cryosections. Beside of high resolution CT and MR datasets over 1800 24-bit RGB images 2048 by 1216 were created. In November 1994, the complete set of MR, CT and RGB data occupying about 15 Gbytes has been made available for public use [1][2]. One year later the NLM completed the Visible Female dataset with better voxel spacing characteristics as the male dataset and 43 Gbytes in size. The initial aim of the Visible Human Project has been achieved. The NLM through this project has provided the medical research and computer science community with a rich set of high-resolution anatomical data. The free accessible archive of digitized anatomical data contributed plentifully to the

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development of digital anatomy. A lot of computer based applications has been implemented, which enabled to explore the anatomical information of both datasets. The majority of them has focused on medical education. More of less sophisticated software applications enable students to render, animate and interact with the three-dimensional human gross anatomy. For those, who must learn the human anatomy without access to cadaver dissection, it complements effectively the large collection of standard anatomical atlases [3] and conventional anatomical models.

The importance of the high resolution anatomical datasets in various health-related areas has been widely recognized. In 2000 a network of several scientific institutions in Korea has launched the Visible Korean Human project [4]. The first Chinese visible human was created in October 2002. Till up to now the physicians and scientists working in the Chinese Visible Human project [5] have acquired four very high resolution anatomical datasets. There exists a variety of applications where the digitized Visible Human datasets are being used. Apart of the medical education, some of them are: testing of the segmentation, registration and visualization algorithms, virtual crash dummies, virtual reality actors, biomechanical modelling and many others. The excellent resolution of the physical cross-section images was the first main obstacle to the researchers. The huge size of the whole dataset made its processing practically impossible, even on high-end computers. Data reduction and simplification of the high quality anatomical information was the first step towards the processing of the Visible Human data. In this work we present a methodology for conducting health-related biomechanical simulations based on the high resolution multimodal anatomical datasets. In the first part, the generation of high quality virtual human model using registration, segmentation and visualization procedures has been described. The second part includes the biomechanical modelling and simulation of the virtual human taking into account the physics of the compounding tissues.

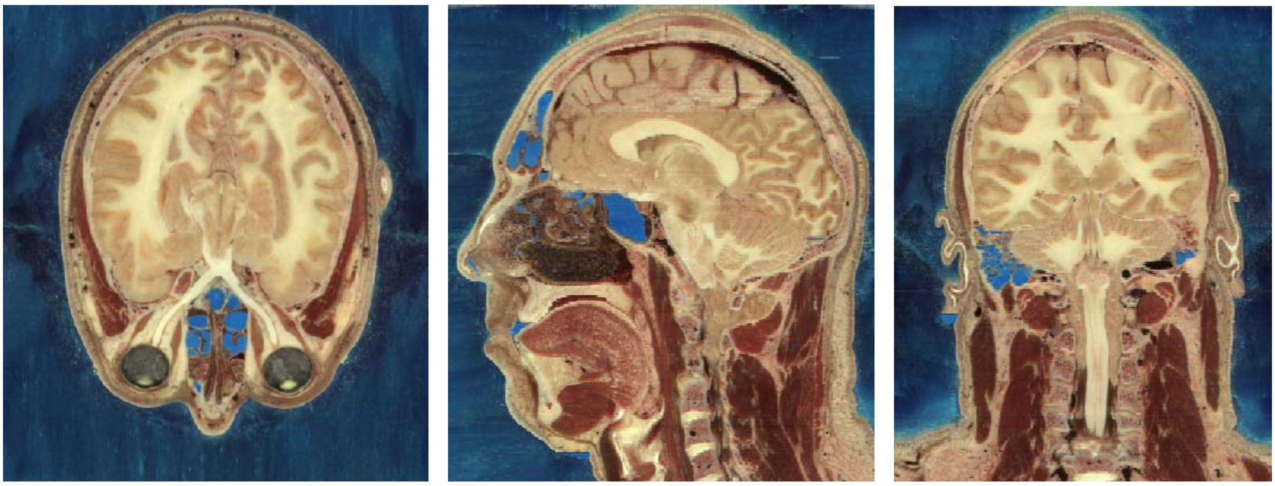


Fig. 1. Transversal, sagittal and coronal cryosections (from left to right) of head from the anatomical VHP male dataset. The VHP male dataset consists of 1878 anatomical cross-sections with the 2048x2048 scanning resolution and 1 mm axial spacing.

2. SEGMENTATION AND REGISTRATION OF THE VISIBLE HUMAN DATA

Segmentation and registration play a crucial role in the patient-specific anatomical model generation process [6] [7]. The quality and the usefulness of the created virtual anatomical model strongly depends on the quality of the applied segmentation and registration procedures. There are many alternative ways that enable the quality improvement of the segmentation process. In this work, we present a new segmentation approach based on the registration paradigm. This method can be applied if there are available volumetric datasets of the same patient acquired in different modalities. Usually, such multi-modality datasets have different resolutions and they differ in the degree of diagnostic significance. We classify the data into quality classes according to the resolution and the contents of the relevant diagnostic information. Lower quality datasets are used in the early stage of the proposed method and the highest quality datasets in the final segmentation step. The method consists of three main steps. In the first step we perform the registration of all acquired datasets. At this and the next registration stages we use the affine matching transformation, the normalized mutual information as the similarity criterion and the Powell's method as the optimization algorithm. The registered MR, CT and RGB datasets have been shown in Figure 2a. The second step is the preliminary segmentation of the low quality datasets. Its main goal is to create binary masks corresponding to anatomical structures in these datasets (in our case MRI and CT). Various segmentation methods can be used in this step, depending on the data modality. Threshold based segmentation, region growing and scan line algorithms together with morphological operations may be successfully applied at this stage. The segmentation accuracy in this step is not the main goal, the most important is the creation of the mask that fully covers the segmented structures. Such masks are going to be used in the next stage. The third and the final step is the segmentation of the dataset with the highest spatial resolution and the most relevant diagnostic information. In our case (data originated from the Visual Human Project) the best dataset available is that one, which consists of a large stack of high-resolution RGB photographs. Such photographs, in contrast to data obtained from CT or MRI scanners, reveal the anatomical details with a superior resolution. The standard segmentation algorithms applied to the RGB data would fail to delineate these structures properly, because the colours corresponding to adjacent anatomical structures are much more tough to distinguish than the grey-values in the CT and MRI datasets. To make this segmentation process possible we use masks that come from the previous step. These masks have to be transformed by the optimal transformation parameters estimated in the first step. The transformed masks from the lower quality datasets (MR and CT) are used now as constraints for the segmentation algorithms applied to the higher quality dataset (RGB) and allow the delineation of the structures of interest only. The region-growing algorithm with different decision criteria can be used for obtaining the most satisfying results. For example, the border of the mask can be used as a sharp stopping criterion, or we may define some probability distribution function that enables to classify more accurate the voxels situated near the border of the mask (the closer to the boundary, the lower probability of the voxel association with the structure of interest). This final segmentation stage yields high quality masks that can be used to create high quality patient-specific virtual anatomical model. The same procedure can be applied as well to segment different soft tissue types in the MR data based on the segmented (with reduced quality) corresponding or complementary regions in the CT data. The usability of the complex virtual patient models depends strongly on efficient visualization methods that enable understanding, exploration and effective use of such huge amount of data. There are many visualization and data exploration methods. Some of them have been shown in Figure 2.

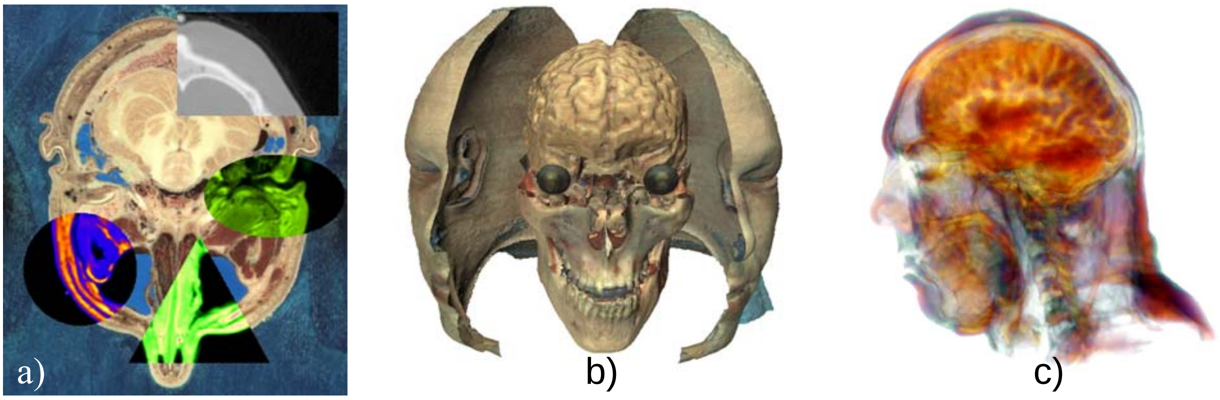


Fig. 2. Different instances of the virtual anatomical model. Various inspection windows in the cross-section view of the registered MR, CT and RGB VHP datasets (a). Exploration of the model can be done using different visualization and manipulation tools, like surface rendering and cutting tools (b) or volume rendering (c).

3. STRUCTURAL INPUT FOR SURGICAL AND BIOMECHANICAL SIMULATION

Different stages of the surgical or biomechanical simulation require the virtual anatomical model as structural input. The segmentation method for multimodal datasets described in the previous chapter is the first step in the anatomical model based biomedical simulation pipeline. The generation process of the virtual anatomical models is not a trivial task. The complexity of the whole process depends on the purpose of the target anatomical model. For the most basic applications i.e. 3D visualization, exploration, manipulation or simple surgical planning procedures the final virtual models can be represented as triangle mesh surfaces of anatomical structures. The whole model generation process in such cases consists of three steps: filtering (noise removal, quality improvement), segmentation and triangulation. The generated tissue surfaces are sufficient for the simple preoperative planning and simulation. If the virtual anatomical model is to be used for the biomechanical simulation taking into account the physics of tissues, the model generation process becomes more difficult task. To perform the biomechanical modelling and simulation we have to obtain volumetric meshes which represents not only the surfaces but also the interior of anatomical structures. The first three phases are identical as in the described above simple case. But after the triangulation phase it is important now to process further the triangle mesh. The rest of the virtual model generation process can be divided into following steps: mesh hole closing (to obtain closed triangle mesh), mesh simplification (decimation, smoothing – to obtain lower number of triangles), tetrahedral meshing (to create volumetric meshes). Mesh closing procedures are highly dependent on the geometrical properties of individual holes. Filling a hole algorithms have to be properly selected and applied to obtain closed oriented manifold meshes. In the simplification step the main goal is to reduce the number of triangles of the surface. Because the biomechanical simulations based on the finite element modelling (FEM) are computationally highly demanding it is important to reduce significantly the number of triangles. In this process it is very important to avoid generation of triangles with long edges and sharp angles. Such triangles have unsuitable properties for the whole process and may lead to failure at the next stage. After the good quality mesh with low number of triangles is prepared, we can apply the tetrahedral meshing algorithm. It is the most sophisticated part of the whole process and even the highly expensive commercial software can often fail to create the tetrahedral mesh of good quality and suitable number of elements. This step gives us the final 3D mesh which can be used for the simulation procedures (see Figure 3). After the structural input for the biomechanical simulation has been created, the physical properties of the involved tissues, its behaviour, boundary conditions and the numerical solvers have to be defined. Each element of the above described whole data processing pipeline plays an important role in the assertion of the highest quality simulation of biomechanical phenomena.

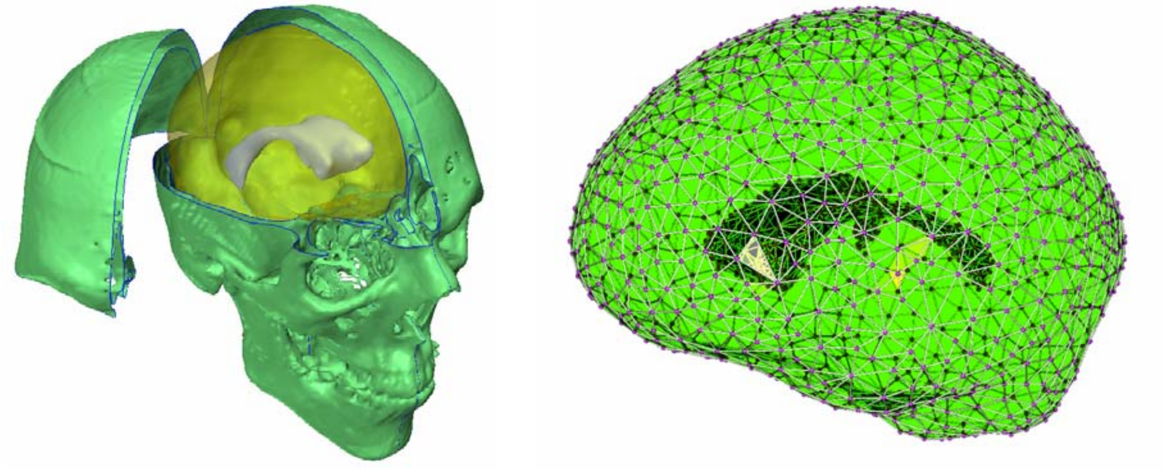
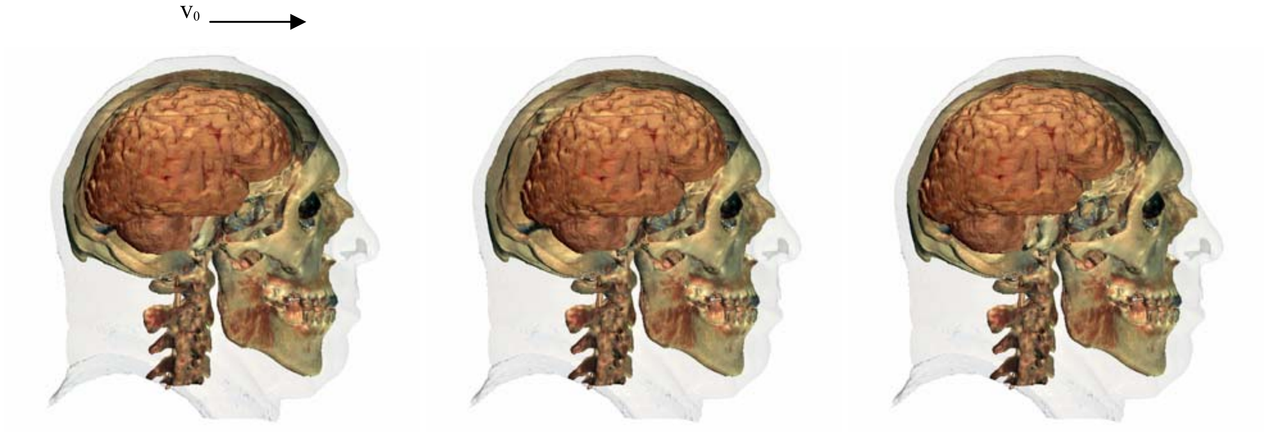


Fig. 3. 3D visualization of the whole anatomical model (left) and the brain tetrahedral mesh (right) used in the whiplash simulation. The ventricles are visible inside the brain. The tetrahedral mesh for the whole model (brain + skull) consists of 16075 elements and 20034 nodes.

4. WHIPLASH SIMULATION

In our work with the VHP datasets we have simulated different biomechanical health-related phenomena like tumor growth, retraction of soft tissues after cutting or various injury mechanisms resulting from car accidents. In this paper we would like to present the simulation of the whiplash injury (called also coup-contra-coup injury) occurring in the fall and traffic accidents (see Figure 4). Whiplash is the most common brain injury resulting from car accidents. Direct trauma to the brain can occur when the skull strikes a steering wheel or a windshield in car accidents after high-speed stops. Although the skull may not be penetrated or fractured in these types of accidents, the forces imparted to the brain can cause the brain to collide against the inside of the hard skull. When a moving head comes to a quick stop, the brain continues in its movement, striking the interior of the skull. This can cause bruising of the brain (a contusion) and bleeding (hemorrhage). Injury in these types of accidents occurs in parts of the brain closest to the point of impact, quite often the tips of the frontal and occipital lobes. In cases of blunt head trauma the brain can also be injured directly opposite the site of trauma - on the other side of the brain, an injury known as contra-coup. This injury typically occurs when a moving head strikes a stationary object like the windshield. At impact the brain opposite the site of impact is pulled away from the skull, injuring the brain there. In serious whiplash injuries, the nerve axons are stretched so much that they are damaged.



a) b) c)

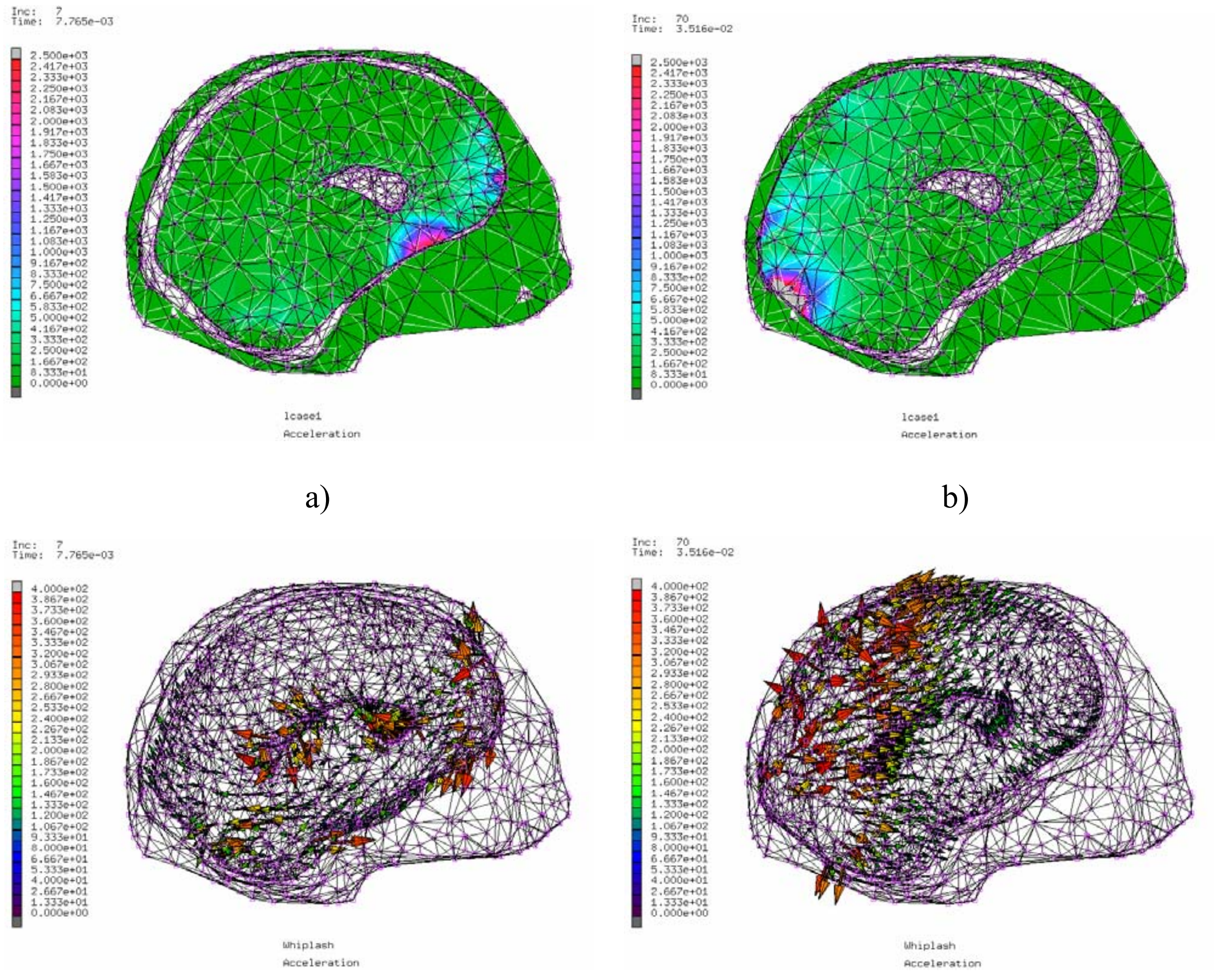
Fig. 4. Whiplash or "coup-contra-coup" injury mechanism common to many traumatic brain. When a moving head (a) with some velocity v_0 comes to a quick stop, the brain continues in its movement, striking the interior of the skull. The next two image illustrations show coup caused by the primary impact (b) and the secondary impact or contra-coup injury (c).

5. RESULTS

The generation of the virtual anatomical models has been done using our own developed software. The simulation of the tissue biomechanical behaviour during the whiplash has been computed by the commercial finite element analysis system MSC.Marc Mentat [8].

The finite element model used in the whiplash simulation consists of two objects: the brain and the skull. The skull is composed of 4608 tetrahedral elements and modelled as isotropic material. The material properties are defined by the Young’s modulus $E = 6.5\times10^9$ N/m^2, Poisson’s ratio $\nu = 0.22$ and mass density $\rho = 1420$ kg/m^3. The brain tissue consists of 11467 elements and has been modelled as hyperelastic material using the Mooney-Rivlin model ($C_{10} = 50000$, $C_{01} = 27000$, mass density $\rho = 1020$ kg/m^3). The tetrahedral mesh of the brain used in our simulation has been shown in Figure 5. The Young's modulus, Poisson's ratio, mass densities, C_{10} and C_{01} material constants were obtained from the literature [9][10]. The boundary conditions are given by the fixed zero displacement for the bottom brain (fixation of the spinal cord area) and the gravity load. The initial condition in this problem is given by the brain velocity $v_0 = -1.4$ m/s at time $t = 0$.

Presented in Figure 5 selected results of our whiplash simulation give us a deep insight into the dynamical brain behaviour in this biomechanical phenomenon. The brain acceleration values and vectors in the region of interest confirm fully the post-accident observations. The acceleration vectors of the brain finite elements for the two impact cases show that the temporal lobes (see Figure 5a and c) and the occipital lobes (see Figure 5b and d) are subjected to 200-400 g's. It causes the nerve axons are stretched so much that they are damaged.



a) b)

c) d)

Fig. 5. The simulation of the "coup-contra-coup" injury mechanism. The acceleration of the brain during the primary impact (a) and the secondary impact (b) (compare with Fig. 5). The acceleration vectors of the brain finite elements for the two impact cases show that the temporal lobes (c) and the occipital lobes (d) are subjected to 200-400 g's. It causes the nerve axons are stretched so much that they are damaged.

6. CONCLUSIONS

In this work different issues related to generation of the virtual anatomical patient models and its biomechanical simulation based on the anatomical high resolution Visual Human Project datasets have been presented and discussed. A new segmentation method of the anatomical data combined with the registration approach has been described. The correlated volumetric datasets found the base for the construction of the virtual patient-specific anatomical model. After the segmentation step the presented variety of visualization methods enables efficient exploration and utilization of the virtual patient model. Further step in the utilization of such high quality digital anatomical models is the possibility to simulate different biomechanical phenomena related to human health. Such advanced numerical models of the human body enable to perform realistic, physically based simulations and parametric studies. They give access to the mechanisms of injuries, enable pre-, intra- and post-operative analysis, and help to design optimal prostheses. If we look into the future, we can imagine a new generation of Visible Human datasets acquired at the cellular resolution. It will open new possibilities for medical or generally human biology related simulation.

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