3D anatomical functional models for the human musculoskeletal system

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Abstract. This paper presents the main research achievements of the EU Marie Curie RTN project titled 3D Anatomical Human (3DAH) (http://3dah.miralab.ch/). The objective of 3DAH research network is to increase, by scientific exchange, the development of realistic functional 3D models of the human musculoskeletal system, with the methodology demonstrated on the human neuromusculoskeletal system of the lower limb. The core aim of the 3DAH is in the development of high-level models and thus improves the accessibility and usability of such simulation models by the clinicians. The network is naturally pluri-disciplinary and pluri-institutional and it strives to bridge complementary approaches for modeling and simulating the musculoskeletal system with methods spanning multiple levels of anatomy and physiological processes. With the project nearing completion (01/10/2006 – 30/09/2010), there has been a wide range of research outcomes and innovations discovered (12 journals, 41 conferences, 5 book chapters and 1 book). Highlights of this research are presented in this paper.

Introduction

Human body representations have been used for centuries to help in understanding and documenting the shape and function of its compounding parts. Since the Da Vinci drawings, human body atlases have evolved significantly and can nowadays describe the human anatomy with great precision, using multi-level biological scales spanning multiple dimensions. In parallel, the body physiology, its systems and their functions, the mechanics of human motion, the pathological and healing processes are among the many topics being studied and described in different domains of science. However, while the greatest anatomy atlases provide static images of the body, existent functional models of human physiology, biomechanics and motion are rarely associated to the shape of the corresponding anatomical structures. Analogue to anatomical models, functional models of the human neuromusculoskeletal system, bringing together the various facets of human modeling, will be of significant value. Such functional human musculoskeletal models will help to improve our understanding of normal and pathological physiology and will allow applications in both normal and extreme conditions.

The 3DAH network, consisting of 8 partners from 5 countries (lead by MIRALab, University of Geneva, Switzerland), works around this theme. The development of such models and applications requires joint work of various expert domains, fomenting huge collaboration and training in a very multi-disciplinary environment. Researchers of different expertise identified overlapping problems, exchanged ideas and solutions, and finally collaborated to derive solutions to multi-disciplinary research challenges. Expert domains in the network include Medical Imaging and Processing, Biomechanics, Computer Graphics and Knowledge Management.

Main Achievements

The main goal of the project is to achieve a neuromusculoskeletal analysis and simulation performed on patient-specific data. The structure of interest is the lower limbs and more specifically the knee, selected due to its being a major weight-bearing joint and its important relevance to the research community. All steps must be patient-specific in order to provide a consistent analysis across the different scales (functional, organ, tissue, etc.). In cases where this requirement cannot be fulfilled (e.g., soft-tissue measurements on volunteers being prohibited due to ethical reasons), 3DAH consortium devised optimal contingency plans to estimate at best the missing information.
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Figure 1. Overview of the 3DAH research framework. First, patient-specific data is acquired from multiple modalities such as multi-scale and dynamic MRI (e.g., a) high-resolution knee MRI), b) optical motion capture, force plates and EMG. Then, image processing and segmentation are performed on images to produce high quality anatomical models of the lower limbs (bones, muscles-tendons and ligaments with attachments, cartilages, etc.) which can be inspected with interactive and illustrative visualization techniques as in c). Subsequently, models are simulated at various scales, such as d) in silico soft tissue simulation at joint level or f) in silico dynamic neuromuscular simulation. In parallel, e) in vitro validation and modeling are carried out to refine and improve the numerical models. Finally, collected information is centralized and analyzed to establish links across models and levels, aiming at presenting a consistent physiological and anatomical lower limb model.

3DAH research is divided into 5 areas: acquisition, modeling, simulation, evaluation and exploitation. Figure 1 illustrates some of the main components of the research framework - from acquisition to simulation and testing. Multi-modal acquisition faces the challenge to acquire data at various scales and with heterogeneous modalities. In case of medical images for instance, the full lower limbs are acquired in 3-4 slabs with a low image resolution while joints are scanned with high-resolution image protocols [1] (See Fig. 1a). A continuous feedback was established between acquisition and processing partners in order to design the best acquisition protocols. Attention was particularly paid towards the reduction of image artifacts and on the design of image alignment strategies (e.g., overlap between image slabs, addition of alignment cues such as radio-opaque markers on subject skin).

The reconstruction of anatomical models starts with image segmentation based on deformable models, which deform models in the image according to shape (robust multi-level statistical shape models [2]) and appearance (multi-modal clustering of intensity profiles [3]) priors. These priors, built from training data, regulate models evolution and effectively attract them toward the boundaries of the structures to segment. The lower limb being composed of multiple organs in contact (Fig. 1c), appropriate collisions detection/response techniques were implemented and GPU-based approaches were explored to speed-up the process. Subsequently, the resulting models were coupled with kinematical and dynamic information obtained from test motions (e.g., sit-to-crouch). Protocols for motion analysis (MoCap, force plates, etc.) were carefully designed to yield the necessary information to set up simulations for the knee joint and full limb. In particular, various novel non-idealized knee models were proposed and compared in neuromuscular simulations [4][5], as well as a new 3D finite element model of the knee soft tissues [6]. This model, able to integrate local anisotropy of oriented connective tissues and non-linear stress-strain responses, will be compared with a human cadaver knee based on validated in vitro testing protocols [7].

Major research outcomes were also produced in the domain of interactive visualization. Real-time inspection of heterogenous volumetric datasets (massive (up to many Gb), raw or segmented datasets as shown in Fig. 1c) was...
made possible with a dynamic GPU-based multi-resolution approach. Its efficiency was demonstrated on conventional and advanced 3D displays [8]. Moreover, new interaction and illustrative rendering tools were explored by exploiting the view-dependent perceptual cues delivered by advanced 3D displays [9]. Evaluation with physicians highlighted the better understanding of 3D anatomical structures on these 3D displays.

The 3DAH being multi-disciplinary, the collected knowledge is highly diversified and requires appropriate knowledge-management solutions. As a result, we built a knowledge management system (based on DOGMA [10]) which allows detailed searching of the 3DAH ontology to retrieve, filter and present semantic information [10]. Our developed DOGMA framework that consists of an ontology base with sets of conceptual relations and a layer of ontological commitments with the domain rules, has been successfully applied to model organs relationships.

The scientific success and impact to the research community from this project can be measured by the number of leading international publications resulting from 3DAH consisting of over 60 publications (12 journals, 42 conferences, 5 book chapters and 1 book). In addition, a large number of media publications (newspaper, magazine, news broadcast, etc.) was also produced.

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References