technische universität
dortmund

Department of
Computer Science

Computer Graphics Group

Prof. Dr. Mario Botsch
Otto-Hahn-Straße 16
D-44227 Dortmund
phone +49 231 755-6324
mario.botsch@cs.tu-dortmund.de
https://graphics.cs.tu-dortmund.de

Technische Universität Dortmund | D-44221 Dortmund

doc. RNDr. Mirko Rokyta, CSc.
Faculty of Mathematics and Physics
Charles University

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Report for the dissertation
"Inverse Anatomical Modeling and Simulation of Virtual Humans"
submitted by RNDr. Petr Kadleček

The doctoral thesis of Petr Kadleček is concerned with the modeling and simulation of virtual humans, which is a very timely topic with high potential impact. In contrast to most previous works in the field of Computer Graphics, he not only considers the outer surface of the human, which can nowadays be acquired easily through 3D surface scanning. Instead, he models the virtual humans as a volumetric mesh with interior anatomical details like skeletal bones, muscles, and adipose soft tissue. Since data on a human's interior are typical inaccessible, reconstructing these anatomical details is a severely underdetermined problem, which Petr Kadleček addresses through the use of a volumetric template model and anatomically-motivated heuristic constraints. The thesis proposes methods to reconstruct anatomical virtual models for both the full body and the head from a set of surface scans of a person in either several body poses or several facial expressions. This is achieved by fitting the volumetric template model to these observations, i.e., determining all model parameters, such as rest shape, material properties, skeletal articulation, or muscle activation.

The required mathematical machinery consists of forward simulation (determine skin from bone articulation and muscle activation) and, more importantly, inverse simulation (determine model parameters from skin observations). After a short introduction, Chapter 2 therefore introduces the required background in forward modeling, in particular spatial discretization through tetrahedral meshes and the finite element method, elasticity models from continuum mechanics, and forward time integration or quasi-static equilibrium. Chapter 3 introduces the process of inverse physical modeling, using both inverse kinematics and inverse dynamics, which is a numerically much harder problem.

Chapter 4 then proposes the forward and inverse modeling of the full human body. The forward model starts by user-defined articulation of the skeletal bones, to which muscles and soft tissue are attached through penalty forces. An elasticity simulation of the flesh (i.e., muscles and bones) eventually yields the skin surface. The inverse modeling then determines the parameters of the forward

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model in order to closely fit to 3D body scans of several poses. The whole pipeline is demonstrated to work robustly on a set of various body shapes and poses, which is a highly remarkable result and was the first approach to achieve anatomical human modeling from 3D scans. Minor drawbacks are that global collisions are not resolved (for performance reasons) and that interpenetrations of bones and muscle/skin can occur (due to non-conforming tetrahedral meshing), which is also clearly discussed in the thesis.

Chapter 5 transfers the computational machinery of forward and inverse physical simulation from full-body shapes in several poses to humans heads in several facial expressions. Previous approaches to physics-based face simulation modelled facial muscles explicitly and computed facial expressions through user-controlled muscle contractions, which, however, is rather unintuitive and hard to control. The approach proposed in the thesis instead follows the intuitive and well-established blendshape paradigm for controlling facial expressions. Starting from 3D surface scans of a human head in neutral pose and several facial expressions, a volumetric template is fitted to the neutral scan and volumetric blendshapes are determined by inverse fitting to the expressions. The strain of muscle tetrahedra in the individual volumetric blendshapes is then considered as muscle activations, which are linearly blended based on user-defined weights, followed by a forward simulation to compute the skin surface. This approach nicely combines the intuitive blendshape paradigm with the high fidelity of a physics simulation (e.g., collision handling, gravity, inertia). Although the approach is conceptually similar to the body modeling of Chapter 4, many face-specific details are different, such that the method in this chapter can also be clearly considered a novel scientific contribution. Furthermore, in Section 5.4 an anatomically more accurate approach to muscle contraction is described, which leads to even more faithful reconstruction of a person's face. This is also confirmed by the fact that the detetermined material parameters are in line with in-vivo stiffness measurements, which is an impressive result. A drawback is that the latter model is evaluated on a single person only.

The research described in this thesis can without doubt be considered as novel, very interesting, and high-impact contributions to the scientific state of the art, not only in computer graphics but also in related fields like medical physics and biomechanical engineering, where the proposed virtual human models can be useful in many applications. The presented approaches have been published in ACM Transactions of Graphics (2016 and 2017) and the Symposium on Computer Animation (2019), which are the most prestigious publication venues in Computer Graphics and Computer Animation. The thesis convincingly demonstrates Petr Kadleček's ability to work at a very high scientific level.

The thesis is very well written, and despite the high mathematical complexity the approaches are nicely explained and well understandable. The images and figures are of high quality and foster understanding. Chapters 4 and 5 are rather literate copies of the respective scientific papers, which is fine and typically done. However, some changes caused by re-formatting have not been performed with sufficient due dilligence. For instance, Section 4.4 refers to a non-existing appendix for mathematical justifications, Section 5.3.4 to a non-existing inset figure. The fitting term in Equation (5.4) is wrong, the matrix $\mathbf{T}$ has not been defined, and the regularization term from original paper has been removed, which could be explained. The function $\mathcal{S}(\vec{\mathbf{a}})$ in Section 5.3.2 should be explicitly defined, and the statement $\mathcal{S}(\vec{\mathbf{a}}_{j,i}) = \mathbf{I}$ in Section 5.3.4 was not clear to me. The objective function in Equation (5.7) is stated to simultaneously optimize over all facial expressions/deformations $\vec{\mathbf{x}}_k$, which in this form it clearly does not. The most important limitation of the presented thesis is that the related work sec-

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tions of Chapters 4 and 5 have not been updated from the original papers. As a consequence, the most recent related papers discussed in the thesis are from 2018, and for the body modeling of Chapter 4 they even are from 2016. Hence the thesis clearly fails to describe the *current* state of the art and to position the presented approach with respect to the state of the art, which in my opinion is not adequate for a doctoral dissertation.

I recommend the PhD committee to accept the submitted doctoral thesis of Petr Kadleček due to the high scientific value of his work. However, I also recommend the committee to ensure that the above-mentioned errors are fixed and that the state of the art is updated before the final publication of the thesis.

Sparkasse Dortmund
IBAN DE09 4405 0199 0001 1813 27
BIC DORTDE33
Ust-ID-Nr. DE 811258273