Interactive Biomechanical Modeling and Simulation of Realistic Human Musculature in Virtual Environments

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Abstract. We present an approach to interactive modeling, biomechanical simulation and realistic visualization of human musculature. Our aim is to facilitate the use of these techniques in virtual environments; therefore special attention has been paid to the optimization of real-time approaches yielding results with a high degree of realism. Our system allows for immersive modeling of musculature and a real-time simulation of muscle forces based on biomechanical models.

1 Introduction

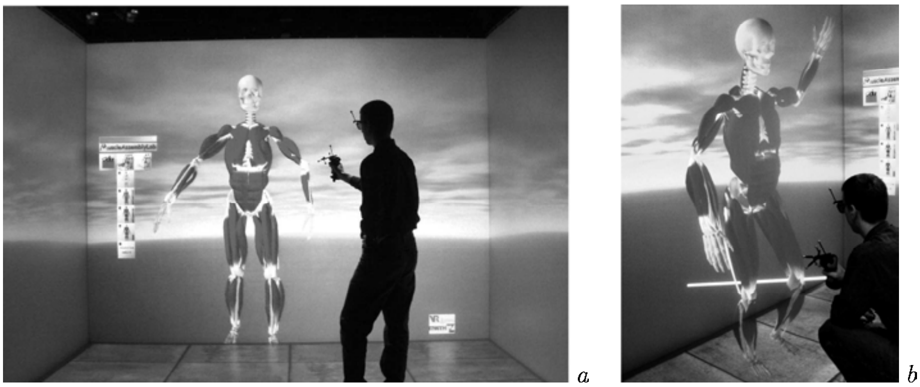
Virtual humanoids play a central role in medical applications. They can be used as communication partners for generic interaction or as virtual patients. Other areas of medical application lie in ergonomics or presentations of anatomy and physiology. Realistic virtual humanoids are required for these purposes, able to simulate and represent anatomical structures and physiological processes. Common approaches towards virtual humanoids make use of multi-layered models, containing skeleton, soft tissue and skin data, with each layer representing anatomical or functional structures.

Kinematics simulation and realistic visualization of virtual humanoids remain the subject of extensive research. In particular, much attention has been given to soft tissue visualization, based on medical imaging data, in the last decade. Surprisingly, soft tissue simulation has been researched only with regard to certain selected areas. In addition, these approaches often suffer from time consuming algorithms. An extensive approach to whole body simulation has not yet been developed.

Human musculature is of great interest in the research areas of anatomy, physiology, ergonomics and biomechanics. However, interactive biomechanical modeling in combination with realistic visualization of musculature remains a problem for large body parts, not to mention whole human bodies.

We have created a tool for biomechanical modeling of human musculature in virtual environments (cp. Fig. 1). It combines the high degree of realism found

Fig. 1. *a*, *b* Modeling, simulation and visualization of musculature in a large projection virtual environment.



in straightforward visualization systems with an interactive biomechanical simulation approach, whilst paying special attention to the volume-preserving nature of musculature. Our algorithms allow for visualizations of arbitrary musculature geometries, that are interactively modified in order to preserve the enclosed volume with respect to the current skeletal posture. This results in a real-time whole body simulation and an interactive representation of musculature with a high degree of realism.

This paper is structured as follows. Section 2 presents related work. Section 3 describes algorithms used in our system. Section 4 presents some performance data and a discussion of our system.

2 Related Work

There are numerous modeling systems designed for immersive virtual environments. The 3dm system by Butterworth et al. [1] was among the first tools in this area. Further examples are HoloSketch [2], LEMAN [3] or FreeDrawer [4]. These tools are capable of handling 6-DOF input devices and support stereoscopic visualizations. However, they focus on geometric modeling and their use cannot be extended to support the specific tasks of modeling and simulation of musculature.

Several approaches to soft tissue visualization of whole humanoid bodies have been published. Visualizations are mostly created on the basis of medical imaging data. The voxel data is segmented and converted to mesh representations of specific organs that can be visualized. A popular data source for these algorithms is the Visible Human Project [5]. Visualizations based on this data have, for instance, been used in the VOXEL-MAN system [6]. This approach allows for highly realistic visualizations, but lacks support of interactive modification of the models, e. g., kinematics or further physiological simulations.

The simulation of musculature mainly focuses on biomechanics. In biomechanical simulation trajectories and forces are computed for a given musculature and skeleton configuration. Muscles are usually represented by lines of action that connect the origin and the insertion of the particular muscle. Hill proposed the first widely accepted muscle model with a combination of parallel and serial springs and a contractile element [7]. Muscle forces can be approximated by using simplified spring-mass models for time efficient computations.

First methods for muscle visualization were developed in the area of biomechanics by Delp [8]. This particular study used simplified action lines. More geometrically advanced approaches use basic volume-preserving shapes in order to represent musculature, e. g., ellipsoids [9] or cylinders [10]. Another technique utilizes merged, implicit spheres, the so-called metaballs [11]. Further approaches depend on parametric representations through NURBS [12] or B-splines [13]. Other solutions have been proposed that utilize volume-rendering techniques and dynamics simulation through classical FE methods [14]. The above-mentioned techniques have a roughly ascending degree of realism that also means greater computational complexity. These methods either utilize highly detailed and realistically deforming geometries, with an aim to visualize musculature and accept non-interactive frame rates, or they employ simplified geometries and basic shapes with a low resolution, in order to achieve real-time visualizations.

3 Modeling, Simulation, and Visualization of Musculature

The base of our system is the Virtual Reality toolkit ViSTA and its multimedia extension [15]. The **modeling** component allows for the creation of musculoskeletal models of virtual humanoids. New muscles can be added interactively by attaching their insertion, origin, and control points to a virtual skeleton. Furthermore, it is possible to manipulate the posture of the articulated figure. The system has been designed for a variety of working environments. We have evaluated the system on several platforms [16].

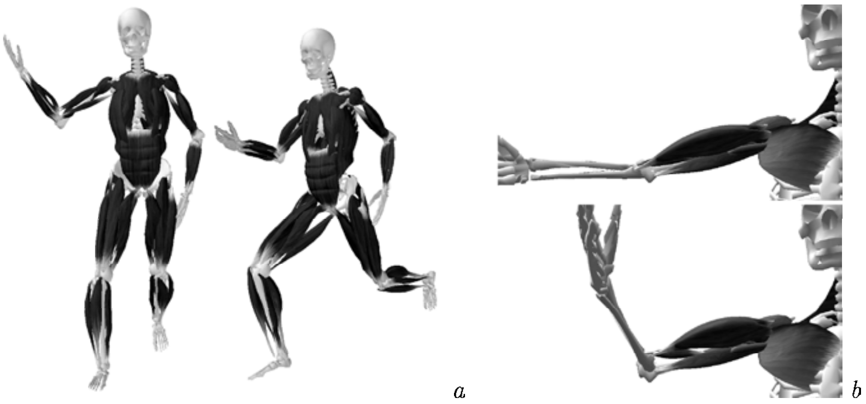
The biomechanical **simulation** is solved through inverse dynamics. Our system takes the previous and current skeletal configuration and computes the forces of each muscle affected by the motion. The actual length of each muscle is taken as a parameter for the volume-preserving deformation of the musculature geometries. In our **visualization** approach we compute the new spatial distribution for each muscle based on scaling factors derived from the bounding box of its geometry.

Given the original size $\mathbf{l} = (l_x, l_y, l_z)^T$ of the bounding box, its volume $V = l_x \cdot l_y \cdot l_z$, and the modified length l'_x, then l'_y and l'_z are computed as follows

$$l'_y = 1/\rho \cdot \sqrt{V/l'_x} \qquad l'_z = \rho \cdot \sqrt{V/l'_x} = \rho^2 \cdot l'_y \tag{1}$$

The control factor $\rho = \sqrt{l_z/l_y}$ is dependent on the initial ratio between width and height. It can be easily verified that $l'_x \cdot l'_y \cdot l'_z = V$, i. e., both volumes of the original and the scaled bounding box are equal. The resulting volume-preserving scaling factors are given as $s_x = l'_x/l_x$, $s_y = l'_y/l_y$, and $s_z = l'_z/l_z$. By application of the Divergence Theorem it can also be shown that scaling with s_x, s_y, and s_z preserves the volume of each enclosed geometry.

Fig. 2. *a* Musculature data. *b* Volume-preserving deformation based on scaling factors.



The degree of realism mainly depends on the geometries representing the muscle. Our approach allows for the use of arbitrary geometries for each muscle with varying detail resolutions.

4 Results & Discussion

The system we have described is capable of visualizing and simulating realistic musculature for whole human bodies in virtual environments. The underlying algorithm supports user-defined geometries for each muscle. We have modeled and configured a human skeleton with 56 principal muscles (cp. Fig. 2 *a*). In our first approach we have created musculature geometries from a visual reference, based on an interactive anatomy atlas [17].

We have evaluated the performance on a typical desktop-VR system, equipped with a 1.8 GHz AMD Athlon64, a GeForce 6600 GT graphics adapter and running Windows XP. We have used ellipsoid visualization in a low-detail (5,412 vertices) and a high-detail (16,892 vertices) configuration. The mean frame rates were 44 fps and 19 fps respectively. The customized musculature geometries with 18,720 vertices yielded a mean frame rate of 42 fps, whereas a more detailed model consisting of 37,440 vertices was represented at 22 fps.

Fastest results are achieved through action line visualization. The geometry complexity is quite low and no volume computations need to be done in this case. Nevertheless, the quality of visualization is quite abstract and of a technical nature. Our approach is comparable to or even faster than the commonly used ellipsoid technique. Moreover, our technique is capable of creating realistic results (cp. Fig. 2 *b*).

5 Conclusions

Our system has proven to be capable of interactive modeling and simulation of musculature for whole human bodies. By using our simulation algorithms we achieve a realistic visualization of musculature without time-consuming computations. In fact, the employed techniques are comparable to or even faster than existing approaches. The system is used for interactive modeling of musculature in virtual environments and for anatomical presentations.

In our future research we intend to incorporate musculature based on medical imaging data. Furthermore, we plan to include collision handling for adjacent muscles in our scaling factors approach.

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