The Simulation of Humans and Lower Animals

Demetri Terzopoulos

Computer Science Department
University of California, Los Angeles, CA, 90095, USA

ABSTRACT

This paper presents a brief review of our ongoing work on the biomechanical simulation of the human body. Our comprehensive musculoskeletal model, which includes more or less all of the relevant articular bones and muscle actuators, plus soft tissue deformations, raises the challenge of simulating natural body movements by controlling hundreds of contractile muscles. We have begun to confront this problem by developing a trainable neuromuscular controller for the important special case of the neck-head-face complex. Additionally, I briefly review our relevant earlier work on the motor control of anthropomorphically articulated dynamic models, as well as the biomechanical modeling of lower animals such as fish, including motor control algorithms that enable these simulated animals to learn natural, muscle-actuated locomotion.

Keywords: Biomechanical Modeling and Simulation, Human Simulation, Musculoskeletal Modeling, Neuromuscular Control, Motor Control Learning

1. INTRODUCTION

The simulation of humans and lower animals is a "grand challenge" that confronts us with many difficult open problems spanning a breadth of topics from biomechanics to artificial intelligence.[1] I have been engaged in this broad scientific endeavor for most of the past two decades. This paper reviews our current research on biomechanical human simulation plus some relevant highlights from our earlier work.

Because of the complexity of the human body, its detailed biomechanical modeling has not received adequate attention. I will first describe a comprehensive biomechanical model that addresses the long-term challenge of modeling, simulating, and controlling more or less all of the relevant articular bones and muscle actuators, plus the physics-based deformations of the soft tissues. I will also review a more focused effort in modeling the vitally important head-neck-face complex and successfully controlling it with a biologically inspired, neuromuscular controller. Using machine learning techniques, the neural networks of the controller are trained offline to efficiently generate the online control signals necessary to synthesize autonomous movements for the behavioral animation of the human head and face.

In the latter half of the paper, I will also briefly review our related earlier work on the motor control of anthropomorphically articulated dynamic models, and on the biomechanical modeling of lower animals such as fish, including motor control algorithms that enable these simulated animals to learn natural, muscle-actuated locomotion from first principles.

2. BIOMECHANICAL SIMULATION OF THE HUMAN BODY

We have been developing a comprehensive biomechanical model of the human body,[2] undertaking the combined challenge of modeling and controlling more or less all of the relevant articular bones and muscles, as well as simulating the physics-based deformations of the soft tissues, including muscle bulging (Fig. 1).

In particular, we have created a jointed physics-based skeletal model that consists of *75 bones* and *165 DOFs* (degrees of freedom), with each vertebral bone and most ribs having independent DOFs. To be properly actuated and controlled, our detailed bone model requires a comparable level of detail with respect to muscle modeling. We incorporate a staggering *846 muscles*, which are modeled as piecewise line segment Hill-type force actuators. We have also developed an associated physics-based animation controller that computes accelerations to drive the

Further author information: www.cs.ucla.edu/∼dt

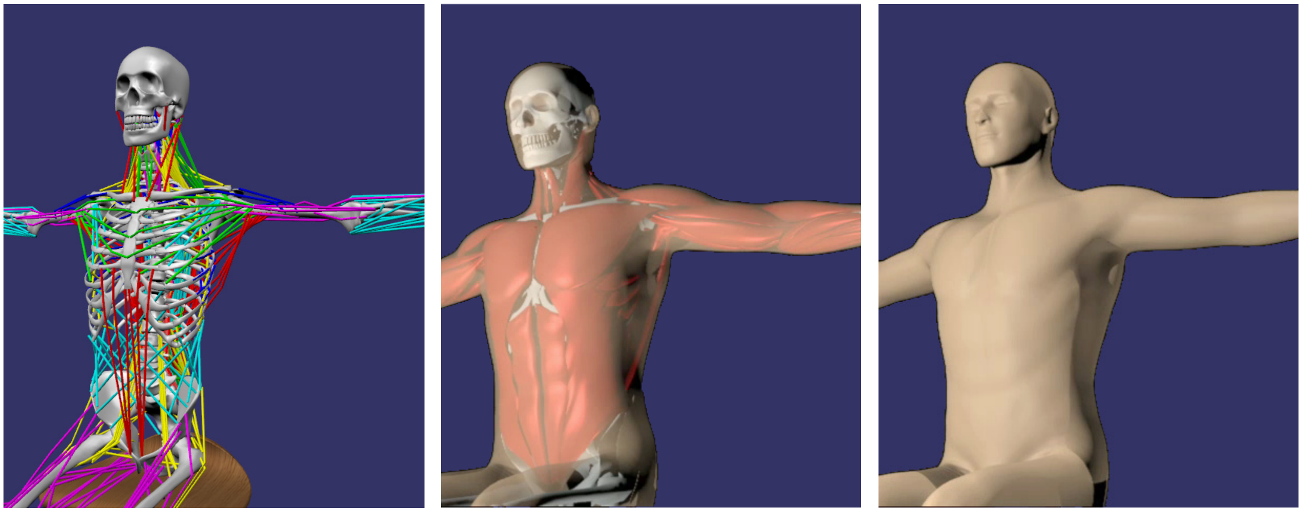


Figure 1. Our comprehensive human body simulation is characterized by the biomechanical modeling of the relevant musculoskeletal tissues. The skeleton with 75 bones is actuated by 846 muscles (left). The motion of the skeleton and the activation level of each muscle deforms the inner soft tissue (center) and, hence, the outer skin (right).

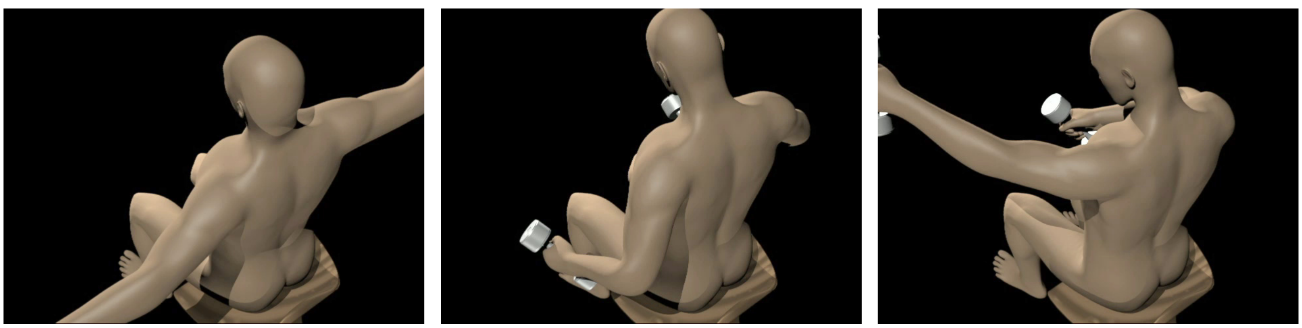


Figure 2. An inverse dynamics motor controller drives the musculoskeletal system to track a sequence of target poses.

musculoskeletal system toward a sequence of preset target key poses, and then computes the required activation signal for each muscle through inverse dynamics.

Our volumetric human body model incorporates detailed skin geometry, as well as the active muscle tissues, passive soft tissues, and skeletal substructure. Driven by the muscle activation inputs and resulting skeletal motion, a companion simulation of a volumetric, finite element model of the soft tissue introduces the visual richness of more detailed 3D models of the musculature. Specifically, we achieve robust and efficient simulation of soft tissue deformation within the finite element framework by decoupling the visualization geometry from the simulation geometry. A total of *354,000 Body-Centered-Cubic (BCC) tetrahedra* are simulated to animate the detailed deformation of the embedded high-resolution surfaces of the skin and each of the muscles.

Figure 2 demonstrates biomechanically simulated arm flexing motions with dumbbell loads.

3. SIMULATION AND CONTROL OF THE NECK-HEAD-FACE COMPLEX

The neck has a complex anatomical structure in and of itself, and it plays an important role in supporting the head atop the cervical spine, while generating the controlled head movements that are essential to so many aspects of human behavior. We have developed a biomechanical model of the human head-neck system that emulates the relevant anatomy[3] (Fig. 3). Characterized by appropriate kinematic redundancy (7 cervical vertebrae coupled by 3-DOF joints) and muscle actuator redundancy (72 neck muscles arranged in 3 muscle layers), our model presents us with a challenging motor control problem, even for the relatively simple task of balancing the mass of the head atop the cervical column in gravity.

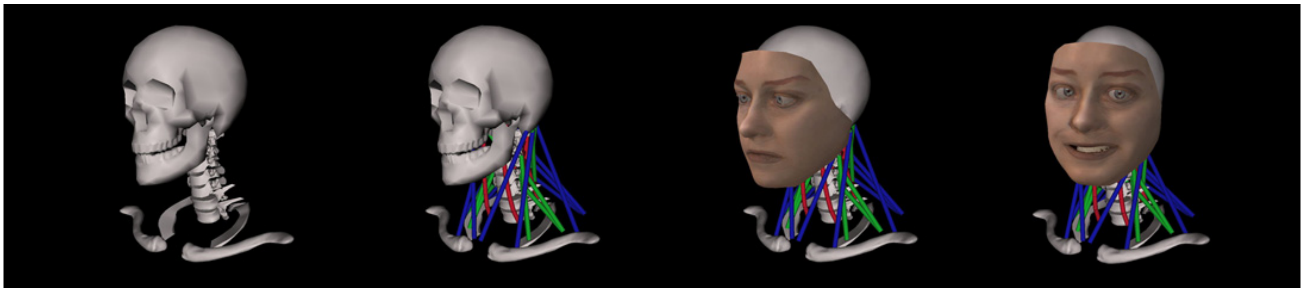


Figure 3. Musculoskeletal neck-head-face model with 72 Hill-type muscle actuators and a neuromuscular controller.

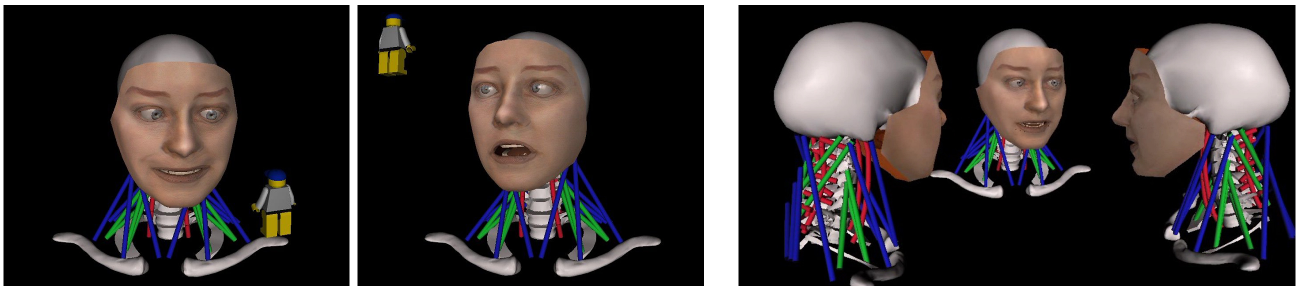


Figure 4. Head-Eye gaze behavior (left); the model gazing at a visual target in different directions. Autonomous behavior-based interaction between three face-head-neck systems (right).

We have developed a neuromuscular control model for the neck that emulates the relevant biological motor control mechanisms. Incorporating low-level reflex and high-level voluntary sub-controllers, our hierarchical controller provides input motor signals to the numerous muscle actuators. In addition to head pose and movement, it controls the coactivation of mutually opposed neck muscles to regulate the stiffness of the head-neck multibody system. Taking a machine learning approach, the neural networks within our neuromuscular controller are trained offline to efficiently generate the online pose and tone control signals necessary to synthesize a variety of autonomous movements for the behavioral animation of the human head and face (Fig. 4).

Biomechanically simulating the human face presents its own deep challenges, and I have been interested in this problem for approximately 20 years. We employ an improved version of the biomechanical face model described in.[4] Conceptually, the face model decomposes hierarchically into several levels of abstraction related to the behavioral control of facial expression, the anatomy of facial muscle structures, the histology and biomechanics of facial tissues, as well as facial geometry and appearance. Like our biomechanical model of the neck, the face model is muscle-driven. Its 44 facial muscles are arranged in an anatomically consistent manner within the bottom layer of a synthetic facial soft tissue. The tissue is modeled as a lattice of uniaxial viscoelastic units assembled into multilayered prismatic elements with epidermal, dermal, sub-cutaneous fatty tissue, fascia, and muscle layers. The elements enforce volume preservation constraints and model contact response against the skull substrate. Expressive facial tissue deformations result from numerically simulating the physical response of the element assembly to the stresses induced by appropriately coordinated facial muscle contractions. The face simulation runs at real-time, interactive rates on a PC.

4. CONTROLLING DYNAMIC ANTHROPOMORPHIC MODELS

An ambitious goal in the area of physics-based computer animation is the creation of virtual agents that autonomously synthesize realistic human motions and possess a broad repertoire of lifelike motor skills. To this end, the control of dynamic, anthropomorphic figures subject to gravity and contact forces remains a difficult open problem. We have developed a *virtual stuntman*, a dynamic graphical character that possesses a nontrivial repertoire of lifelike motor skills.[5] The repertoire includes basic actions such as balance, protective stepping when balance is disturbed, protective arm reactions when falling, multiple ways of rising upright after a fall (Fig. 5), and several more vigorously dynamic motor skills.

Figure 5. A supine dynamic "virtual stuntman" rolls and rises to an erect position, balancing in gravity.

Our virtual stuntman is the product of a framework for integrating motor controllers, which among other ingredients includes an explicit model of preconditions; i.e., those regions of a dynamic figure's state space within which a given motor controller is applicable and expected to work properly. We have demonstrated controller composition with preconditions determined not only manually, but also automatically based on support vector machine (SVM) learning theory.

5. SIMULATING LOWER ANIMALS

We have also developed biomechanical models of several lower animals, among them artificial fishes (Fig. 6(a)).[6] Each fish is an autonomous agent with a deformable body actuated by internal muscles. The body includes eyes and a brain with motor, perception, behavior, and learning centers (Fig. 6(b)). The simulated fish have a perceptual awareness of their virtual world. The ethological model supports a repertoire of piscine behaviors, including collision avoidance, foraging, preying, schooling, and mating.

To synthesize realistic fish locomotion we have designed a simple, biomechanical fish model (Fig. 7) consisting of 23 nodal point masses and 91 damped springs, each of which is a Voigt uniaxial viscoelastic element comprising an ideal spring and an ideal damper connected in parallel. The damped spring arrangement maintains the structural stability of the body while allowing it to flex. Twelve of the damped springs running the length of the body are actively contractile, thus serving as muscles. Through controlled muscle actions, the artificial fishes swim through virtual water in accordance with hydrodynamic principles. Their caudal and articulate pectoral fins enable them to locomote and freely maneuver underwater. Forward caudal locomotion normally uses the posterior muscles on either side of the body, while normal turning uses the anterior muscles.

Though rudimentary compared to those in real animals, the brains of artificial fishes are nonetheless capable of learning how to swim in accordance with biomechanical first principles, by appropriately coordinating muscle actions, and they can also learn to carry out basic perceptually-guided navigation tasks.[6,7]

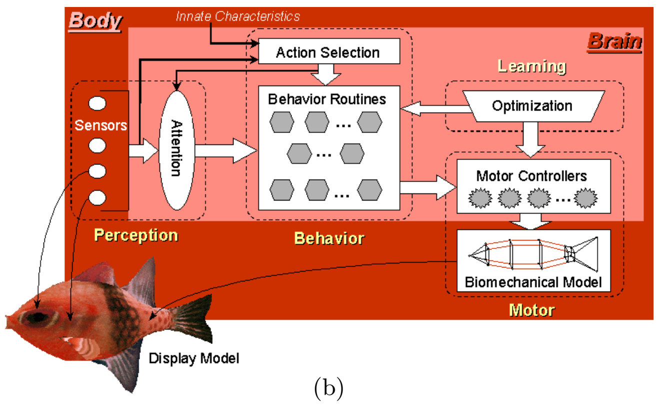
6. CONCLUSION AND FUTURE WORK

The work reviewed in this paper was motivated by applications in advanced computer graphics animation for the motion picture and interactive game industries. However, its repercussions are significantly broader, extending across biomechanics, adaptive control, machine learning, and other domains.

In view of the complexity of human simulation, our work is inevitably incomplete. For example, our biomimetic modeling approach heightens the need to model skeletal joints more accurately. To this end, since the elementary joints conventionally used in physics simulation cannot produce the complex movement patterns of biological joints, we have introduced a new joint model, called *spline joints*, that can better emulate biological joints.[8] Beyond such low-level technical issues, among the biggest high-level challenges for us going forward is to tackle the neuromuscular control problem for the comprehensive biomechanical body model and, subsequently, to integrate the model within our overarching artificial life framework,[1,9] leading to biomechanically-simulated autonomous pedestrians.

My long-term vision is the creation of a computer simulated world that approaches the complexity and realism of the real world, inhabited by artificial humans and animals that look, move, and behave like their natural counterparts. Such a *Reality Emulator* could be used in revolutionary ways with profound impact across multiple scientific disciplines.[10]

(a)



(b)

Figure 6. Artificial fishes in their physics-based virtual world (a); the 3 reddish fish are engaged in mating behavior, the greenish fish is a predator hunting prey, the remaining 3 fishes are feeding on plankton (white particles). Functional diagram (b) of the artificial fish model illustrating the body (biomechanical model, sensors) and brain (motor control, perception, behavior, learning) submodels.

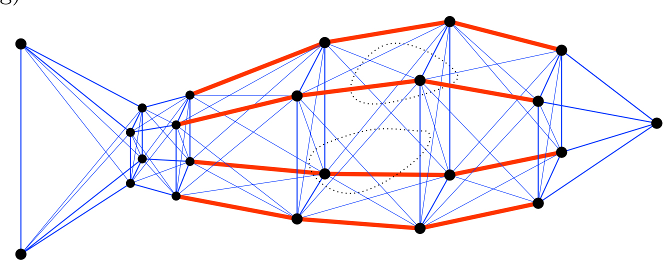


Figure 7. Biomechanical fish model. Nodes are lumped masses. Lines are damped springs (shown at their natural lengths). Bold red lines are actively contractile damped springs, representing muscles. Dashed curves indicate caudal fins.

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