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Modeling and Simulation of Skeletal Muscle for Computer Graphics: A Survey

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Abstract

Muscles provide physiological functions to drive body movement and anatomically characterize body shape, making them a crucial component of modeling animated human figures. Substantial effort has been devoted to developing computational models of muscles for the purpose of increasing realism and accuracy in computer graphics and biomechanics. We survey various approaches to model and simulate muscles both morphologically and functionally. Modeling the realistic morphology of muscle requires that muscle deformation be accurately depicted. To this end, several methodologies are presented, including geometrically-based, physically-based, and data-driven approaches. On the other hand, the simulation of physiological muscle functions aims to identify the biomechanical controls responsible for realistic human motion. Estimating these muscle controls has been pursued through static and dynamic simulations. We review and discuss all these approaches, and conclude with suggestions for future research.

Contents

1
Introduction

Computational human modeling has been an important research topic in many domains: from films and video games, to augmented and virtual reality, in which virtual humans play vital roles. As the value of virtual human models extends to new areas, such as ergonomics, medicine, and biomechanics, there is a rapidly growing need for and interest in modeling humans stemming from these new applications. Different approaches to modeling humans address different performance requirements. For example, while greater interactivity is required for real-time applications, greater visual realism is more desirable in film production. Moreover, physiological and biomechanical accuracy are the most crucial in designing medical applications. Despite considerable effort, the immense complexity of the human body continues to make modeling it computationally extremely challenging. Furthermore, our keen perception of human bodies and their movement can make us very critical of even small deviations from expected behavior.

The human body is composed of an intricate and complex anatomical structure which is made up of a variety of interacting tissues. Computational human modeling requires accurate reconstruction of this anatomical structure, the relevant biological and physiological functions, and their mathematical formulation into practical physical and mechanical models. Among the various tissues composing the body, those that form muscles carry out diverse physiological functions and collectively perform body movement. This survey focuses specifically on skeletal muscles because they impart two important features essential for computational human modeling. First, skeletal muscles serve as major body components which make up nearly 50% of total body weight, characterizing the shape of a body and its tone. Second, they provide physiological functions to stabilize body posture and drive body movement. While the former is a key feature for realistic representation of the body which demands accurate modeling of muscle morphology, the latter is crucial for realistic animation of body movement which needs accurate simulation of muscle functions.

Early approaches [11, 52] proposed human models based on rigid skeletons. While they have been widely used in various biomechanical studies, such as biped locomotion analysis, their capacity is fairly limited to represent the human body realistically and they have difficulties in modeling soft tissues. Later, muscle and fatty tissue were introduced as additional layers to represent elastic deformation of soft bodies [17]. However, this muscle model is physically unrealistic and its application is limited to expressing bulging effects over joints. Various researchers thus devoted significant effort to developing realistic muscle models, focusing on accurate representation of muscle shape and its deformable behaviors. For example, anatomical knowledge has been integrated into constructing muscle geometry [10, 57, 69, 89] and medical imaging techniques have been employed to enhance visual quality [59]. Once muscle geometry is constructed, its deformable behaviors during muscle contraction need to be described. To this end, a variety of approaches have been proposed: geometrically-based, physically-based, and data-driven approaches. In the biomechanics community, skeletal muscles have also been extensively studied, but most of this review has focused on understanding their mechanical properties and physiological functions for human locomotion. As biomechanical models have been validated through rigorous experiments [34, 95], they have begun to draw the attention of graphics researchers, who study simulation of human motions based on computed muscle controls [41, 43, 44, 84], in the hope of producing realistic human animation. In this survey, we examine and discuss these approaches with respect to two principal features of muscle: muscle deformation and muscle simulation.

This review is organized as follows. Section 2 gives a brief introduction to anatomical and biomechanical descriptions of muscle, which have been considered in most applications. In Section 3, we examine various approaches proposed to model muscle deformation. In Section 4, we address muscle control problems and present related simulation models to solve them. Section 5 concludes with a discussion of possible approaches to bridge the efforts of the biomechanical and graphics research communities, working toward a unified model.

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