Anatomy-Based Modeling of the Human Musculature

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"Anatomy increases the sensitivity of the artist's eye and makes the skin transparent; it allows the artist to grasp the true form of the surface contours of the body because he knows the parts that lie hidden beneath a veil of flesh." *Gerdy*

Abstract

Artists study anatomy to understand the relationship between exterior form and the structures responsible for creating it. In this paper we follow a similar approach in developing anatomy-based models of muscles. We consider the influence of the musculature on surface form and develop muscle models which react automatically to changes in the posture of an underlying articulated skeleton. The models are implemented in a procedural language that provides convenient facilities for defining and manipulating articulated models. To illustrate their operation, the models are applied to the torso and arm of a human figure. However, they are sufficiently general to be applied in other contexts where articulated skeletons provide the basis of modeling.

CR Categories and Subject Descriptors: I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling *Surfaces and Object Representations*; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism.

Additional Keywords: Articulated Models, Procedural Modeling, Deformations, Muscles, Tendons, Bones, Human Figure Animation

1 INTRODUCTION

Human figure modeling and animation has been one of the primary areas of research in computer graphics since the early 1970's. The complexity of simulating the human body and its behavior is directly proportional to the complexity of the human body itself, and is compounded by the vast number of movements it is capable of. Although articulated structures containing rigid segments is a reasonable approximation of the human skeleton, most researchers use articulated structures that are too simple to be deemed anatomically appropriate. The shoulder, spine, forearm, and hand are typical examples where accuracy is sacrificed for simplicity. The more difficult problem of fleshing-out a skeleton is currently an active area of research [6][9][23][28][29]. In several of these cases, oversimplification causes undesirable or distracting results. Using flexible surfaces at or near joints is a poor approximation because many deformations (like bulging muscles) occur far away from joints. Also, producing intricate joint-dependent changes in the shape of the skin without considering the motivators for those shape changes seems implausible.

In this paper we present an approach to human figure modeling similar to the one taken in artistic anatomy—by analyzing the relationship between exterior form and the underlying structures responsible for creating it, surface form and shape change may be understood and represented best. We focus on the musculature by developing anatomy-based models of skeletal muscles, but many of the principles apply equally well to the modeling of other anatomical structures that create surface form, such as bones and fatty tissue.

1.1 Related Work

Because of demands for rapid feedback and the limitations of present-day technology, human figures are often represented with stick figures, curves, or simple geometric primitives. This approach sacrifices realism of representation for display efficiency. Recently, a layered approach to the representation of human figures has been adopted [2][20][23][28] in which skeletons support one or more layers, typically muscle, fatty tissue, skin, and clothing layers. The additional layers serve to flesh-out the skeleton and to enhance the realism of the representation.

Anatomy-based skeletal models

Most human figure models use a simplified articulated skeleton consisting of relatively few jointed segments. Magnenat-Thalmann and Thalmann [11] challenged researchers to develop more accurate articulated models for the skeletal support of human figures. They observe that complex motion control algorithms which have been developed for primitive articulated models better suit robot-like characters than they do human figures. To address this issue, researchers have revisited the skeletal layer of human figure models to solve some specific problems. In Jack [1], the shoulder is modeled accurately as a clavicle and shoulder pair. The spatial relationship between the clavicle and shoulder is adjusted based on the position and orientation of the upper arm. In another treatment of the shoulder-arm complex, the Thalmanns [11] use a moving joint based on lengthening the clavicle which produces good results. Monheit and Badler [14] developed a kinematic model of the human spine that improves on the realism with which the torso can be bent or twisted. Scheepers *et al*. [21] developed a skeleton model which supports anatomically accurate pronation and supination of the two forearm bones. Gourret *et al*. [9] use realistic bones in their hand skeleton to assist in producing appropriate deformations of the fingers in a grasping task.

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Modeling deformable tissues

Ignoring the effects that gravity and other external forces may have on tissue, some researchers have concentrated on the deformations that occur in the vicinity of joints. One simplifying assumption considers the human body as consisting of rigid body parts connected with flexible surfaces at joints. Chadwick *et al*. [2] use free-form deformations [22] (FFDs) to deform skin surfaces that surround the underlying skeleton. By using abstract muscle operators, a relationship between skeletal parameters (such as joint angles) and the control points of the FFDs is established. For example, tendon muscle operators are used to control deformations near joints. The Thalmanns[12] use joint-dependent local deformation operators to control the changes that surfaces undergo near flexing joints. Singh [23] models the skin surfaces near joints with polyhedral objects embedded in implicit functions. As the joints move, the implicit functions deform the polyhedral definition, and therefore the skin surface in the vicinity of the joint.

Surfaces may also be deformed in areas other than near joints. Chadwick *et al*. [2] use flexor muscle operators based on FFDs to simulate the visible result of muscle contraction, while Nahas *et al*. [15] manipulate the control points of a B-spline model to mimic deformations. Henne [10] and Singh [23] both use implicit function primitives to model muscles and pseudo-physical models to cause these muscles to bulge. None of these methods model individual muscles in an anatomically appropriate way, nor do any of them attempt to account for all muscles that create or influence the visible surfaces surrounding the underlying skeleton.

Early physically-based techniques for modeling facial expressions consider the face to be sufficiently representable by its skin, applying abstract muscle actions to the skin to produce facial expressions [17]. The work of Waters [26] in this regard is particularly noteworthy. More recent physically-based techniques are anatomically more appropriate [25]. Pieper [16] developed a model of soft tissue which accounts for the 3D structure and mechanical properties of human facial tissue, allowing accurate simulation of the interaction between soft tissue, muscles, and bony structures in the face. Waters [27] extended his earlier work by using a physical model of the epidermis, subcutaneous fatty tissues, and bone to model facial expressions more realistically.

Chen and Zeltzer [3] developed a finite element model of muscle to simulate muscle forces and to visualize the deformations that muscles undergo during contraction. They used polygonal data derived from MRI scans or data digitized from anatomically accurate plastic models to represent muscles. Their model accounts for shape changes due to external forces, such as gravity, or due to internal muscle forces which produce movement.

In her approach to modeling and animating animals, Wilhelms [28] uses ellipsoids to model bones, muscles, and fatty tissue. She uses an iso-surface extraction program to generate polygonal skin surfaces around the ellipsoids in some rest posture of the body, and anchors the skin to the underlying body components, allowing the skin to be adjusted automatically when the body moves. Her research concentrates on the generation of models that may be developed at least semi-automatically.

1.2 Overview

The remainder of this paper is organized as follows. In Section 2 we identify the anatomical structures that influence surface form and discuss the musculature and its influence in some detail. In Section 3 we briefly describe a procedural model for skeletons. Section 4 presents anatomy-based muscle models for simulating the deformable nature of skeletal muscles. We illustrate the operation of each muscle model and show how the muscle models may be used in conjunction with the skeleton model presented in Section 3. Concluding remarks are given in Section 5 where we discuss possibilities for future research.

2 ARTISTIC ANATOMY

Anatomy is a biological science concerned with the form, position, function, and relationship of structures in the human body. *Artistic anatomy* [8][19][30] is a specialized discipline concerned only with those structures that create and influence surface form. Whereas medical anatomies consider the human body in an erect and motionless stance, artistic anatomy is also concerned with changes that occur when the body moves into different stances.

Three general anatomical structures create surface form:

1. *The skeleton*, consisting of bones and joints organized into an articulated structure;
2. *The musculature*, consisting of contractile muscles and nonelastic tendons; and
3. *The panniculus adiposus* (or fat layer), consisting of fatty tissue located beneath the skin.

Before discussing the musculature and its effect on surface form, we briefly mention the influence of the skeleton. Interested readers should consult reference [20] for more detail.

2.1 The skeleton

The *skeleton* is the basis of all surface form [30]. It determines the general shape of the body and each of its constituent parts. The skeleton also affects surface form more directly: bones create surface form where skin abuts to bones, such as at the elbows and knees. Bones are attached at *joints* which allow the bones to move relative to one another. Parts of bones that appear not to create surface form in some postures do so in others. For example, the heads of the metacarpal bones cannot be seen unless the hand is clenched into a fist.

2.2 The musculature

Of the anatomical systems that determine surface form, the musculature is the most complex. Muscles are arranged side by side and in layers on top of bones and other muscles [8]. They often span multiple joints. Muscles typically consist of different kinds of tissue, allowing some portions to be contractile and others not. Depending on their state of contraction, muscles have different shapes and they influence surface form in different ways.

Muscles

Skeletal muscles are voluntary muscles which contract in order to move the bones they connect. Located throughout the body, these muscles form a layer between the bones of the skeleton and subcutaneous fatty tissue.

Structurally, skeletal muscles consist of a contractile *belly* and two extremities, often tendinous, called the *origin* and the *insertion*. The origin is usually the more stationary end of a contracting muscle, and the insertion the more movable. Skeletal muscles consist of elongated muscle fibers and fibrous connective tissue which anchors the muscles to the underlying skeleton. The composition of muscle fibers in a muscle determines the potential strength of muscle contraction and the possible range of motion due to contraction. The shapes of muscles often reveal their function.

Anatomists distinguish between two types of muscle contraction. In *isotonic contraction*, the length of a muscle changes and the muscle produces movement, while in *isometric contraction*, the muscle contracts or tenses without producing movement or undergoing a change in length.

Skeletal muscles act across one or more movable joints, working together in groups to produce movement or to modify the actions of other muscles. Depending on the types of joints involved and the points of attachment of the muscle [4], a standard name can be given to any movement so produced, for example flexion/extension or protraction/retraction [7].

Tendons

Skeletal muscles attach to other structures directly or by means of tendons. A *tendon* is a dense band of white connective tissue that connects the belly of a muscle to its attachment on the skeleton. Tendons are nonelastic, flexible, and extremely strong. They concentrate the force produced by the contractile muscle belly, transmitting it to the structure to be moved. Tendons decrease the bulk of tissue around certain joints, obviating the need for long fibers in the belly portion of the muscle. For example, in the forearm and lower leg, long tendons shift the weight away from the hand and foot, making the ends of the arm and leg lighter.

Influence on surface form

Skeletal muscles can be thought of as independent convex forms [8] placed in layers on top of the underlying skeleton. Although the forms of adjacent muscles tend to blend with each other, furrows or grooves are present between some muscles and muscle groups, especially between those that have different or opposing actions. This arrangement of muscles is visible on the surface as a series of convexities [8], especially when the muscles are put into action. In their relaxed state, however, muscles are soft and appear less defined, even hanging loosely because of the pull of gravity [19]. Upon contraction, the belly of muscles become shorter and thicker. In superficial muscles, this change in shape can be observed on the surface where the muscle's relief becomes increasingly defined.

When muscles with narrow tendons contract, the tendons often stand out prominently on the surface of the skin. For example, some of the tendons of the forearm muscles can be seen on the wrist when the fingers are clenched into a fist. In superficial muscles, the area of attachment of a tendon and its muscle belly is often apparent on the surface.

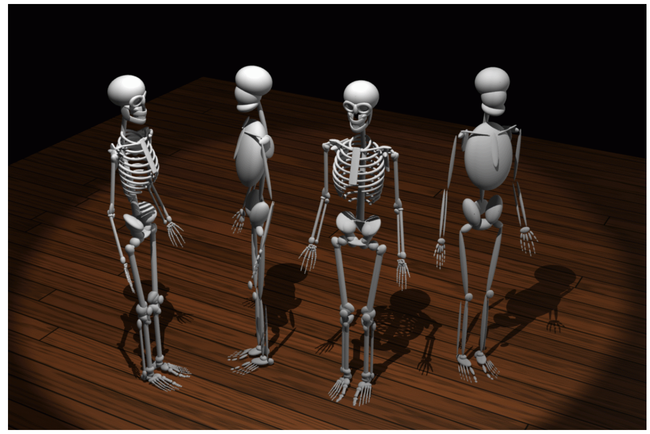

Figure 1: *Stage-fright*—stylized representations of a human skeleton assembled from spheres, cylinders, tori, hyperboloids, and bilinear patches.

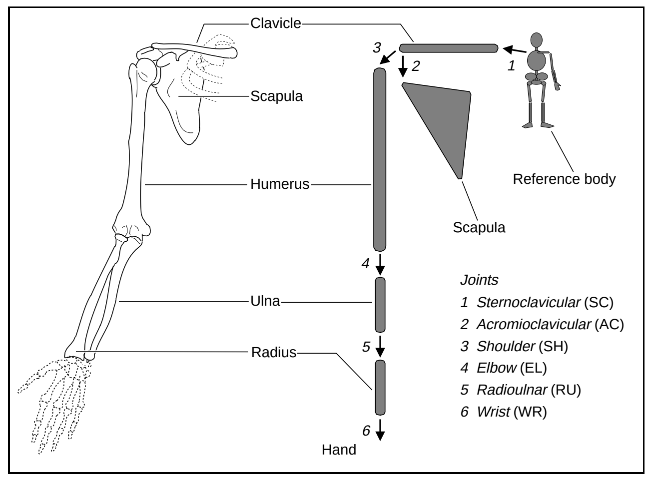

Figure 2: Conceptual model of the arm skeleton.

3 SKELETAL SUPPORT

In this section we give a brief overview of a procedural model for skeletal support [21]. The model is implemented in AL [13], a procedural modeling and animation language with facilities for defining and manipulating articulated models. We introduce articulation variables (or *avars* [18]) to the model and use them to provide animation and interaction controls. The model is applied to the arm skeleton to illustrate its operation. This example will be extended in the next section when the modeling of muscles is considered.

3.1 Bones and joints

Since bones are hard relative to other anatomical structures in the human body, a rigid model for individual bones is appropriate. We model bones with functions that select one representation out of a number of alternatives based on a complexity parameter. Two of these alternatives, constructed in piecewise fashion from predefined *geometric primitives* (*g-prims*), are shown in Figure 1. If necessary, arbitrarily complex boundary representations could be included as alternatives, but for our purposes the *g-prims* representations suffice.

The different types of movable joints in the human skeleton can also be modeled with functions. Conceptually, each function applies the required transformations to locate and orient the joint. Joint motions may be restricted to predetermined excursion ranges, one for each of the degrees of freedom of the joint. We use an object-oriented style of programming in AL to encapsulate the implementation details into a joints class. This abstraction allows the instantiation of joint types to be stated succinctly, which, in turn, simplifies the arrangement of bones and joints into hierarchies.

3.2 The arm skeleton

The upper limb of the human body is supported by a complex and intricate skeleton which provides an excellent testbed for developing articulated models. To simplify interaction, we introduce 'anatomically appropriate' simplifications to the arm skeleton. For example, since the acromioclavicular joint is capable of very little motion in itself [24], we separate the scapula from the arm skeleton (see Figure 2) and define its motion functionally in terms of *avars*.

Figure 3 shows a hierarchical definition of the arm skeleton. We place the rooted reference skeleton first, and use nested blocking constructs to specify the kinematic chain from the sternoclavicular joint and the clavicle bone down to the wrist joint and the hand

```
(define (the-arm-skeleton)
 (lambda
  (reference-skeleton)
  (model "clavicle" (ElevateDepress ProtractRetract)
   (SC-joint (ElevateDepress) (ProtractRetract))
   (clavicle)
   (separator
    (AC-joint (ElevateDepress) (ProtractRetract))
    (scapula))
   (model "humerus" (AbductAdduct FlexExtend Rotate)
    (SH-joint (AbductAdduct) (FlexExtend) (Rotate))
    (humerus)
    (model "ulna" (ElbowFlexExtend)
     (EL-joint (ElbowFlexExtend))
     (ulna)
     (model "radius" (PronateSupinate)
      (RU-joint (PronateSupinate))
      (radius)
      (model "hand" (FlexDorsiflex RabductUabduct)
       (WR-joint (FlexDorsiflex) (RabductUabduct))
       (hand)
)))))))
```

Figure 3: AL function defining the arm skeleton (*avars* associated with each model appear in *italics* and are named for joint movements).

skeleton. Low-level motion control is provided by binding *avars* to joint angles. High-level motion control is also possible. For example, by relating a normalized *avar clench* to the flexion angles of interphalangeal joints, the fingers of the hand can be clenched into a fist simply by setting *clench* equal to one.

4 THE MUSCULATURE

In this section we present three anatomy-based muscle models for simulating the behavior of skeletal muscles. Before doing so, however, we discuss the representation of muscle bellies.

4.1 Muscle bellies

We use ellipsoids to represent muscle bellies. As Wilhelms argues [28], the ellipsoid is a natural and convenient primitive for representing muscle bellies because it can be scaled along its three major axes to simulate bulging. We automatically adjust the dimensions of the muscle belly when its extremities are moved further apart or when they are brought closer together. These adjustments not only preserve the ratio of the belly's height to its width, but also the volume of the muscle belly—an approach justified by considering the anatomical structure of muscles and their behavior during isotonic contraction.

Let E be an ellipsoid whose principal axes have lengths $2a$, $2b$, and $2c$, respectively, and let $l = 2c$ denote the length of a muscle belly to be represented. Given the required volume $v = \frac{4\pi abc}{3}$ and the ratio of the width and height $r = \frac{a}{b}$ of the muscle belly, isotonic muscle contraction can be simulated by adjusting a and b when the length of the muscle belly changes. Since $a = br$,

$$v = \frac{4\pi r b^2 c}{3} \quad \Longrightarrow \quad b^2 = \frac{3v}{4\pi r c}.$$

Letting l' denote the new length of the muscle belly, we have

$$c' = \frac{l'}{2} \tag{1}$$

$$b' = \sqrt{\frac{3v}{4\pi r c'}} \tag{2}$$

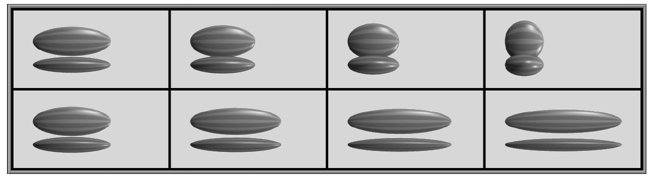

Figure 4: Volume preserving contraction (top) and stretching (bottom) of a muscle belly. Front and side views of the same muscle belly are shown in each frame.

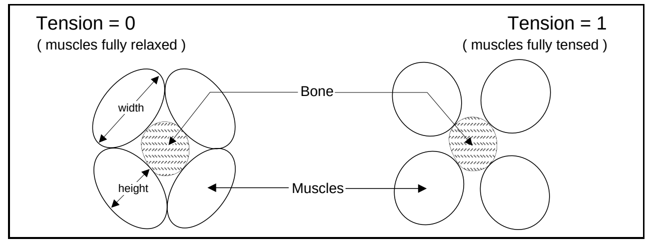

Figure 5: Simulating isometric muscle contraction.

$$a' = b'r. \tag{3}$$

Figure 4 shows how the muscle belly bulges when contracting, and how it thins out when stretching.

To simulate isometric muscle contraction, we introduce a *tension* parameter t to adjust the ratio r (see Figure 5). Assuming that $r_n = \frac{a_n}{b_n}$ is given for a muscle in a fully relaxed state, we define

$$r = (1-t)r_n + ktr_n = (1-t+kt)r_n, \tag{4}$$

where k is a tension control parameter[1] that regulates the amount of muscle bulging (increased height, reduced width) due to isometric contraction.

4.2 Fusiform muscles

Many skeletal muscles are fusiform and act in straight lines between their points of attachment. For these muscles we use a simple model with relatively few parameters, called the *fusiform muscle model*. This model provides a convenient mechanism for locating muscle bellies relative to underlying skeletal bones. Specifically, since muscles attach to different bones, the origin may be given in the local coordinate system of the bone where the muscle originates. Similarly, the insertion may be given in the local coordinate system of the bone where the muscle inserts. Muscles with tendons may be defined by giving two additional points, as illustrated in Figure 6. The model takes care of transforming all the points to a common coordinate system.

Like the joint types in Section 3.1, the fusiform muscle model is implemented in a class. We use two *class* parameters to define the volume v and ratio r of the muscle in its natural state, and a number of *instance* parameters to specify the location and orientation of the muscle.

Figure 7 shows a few frames of an animation sequence to illustrate the operation of the fusiform muscle model. Two fusiform muscles of the same volume are modeled, but only one has tendons. Notice the effect of the tendons on the perceived bulging of the muscle belly on the right. Notice also that the tendons retain their lengths, an important attribute of tendons which is not incorporated in Wilhelms' modeling of animal muscles [28].

[1] Empirical evidence shows a value of $k = 2.56$ provides reasonable bulging for acceptable visual representation.

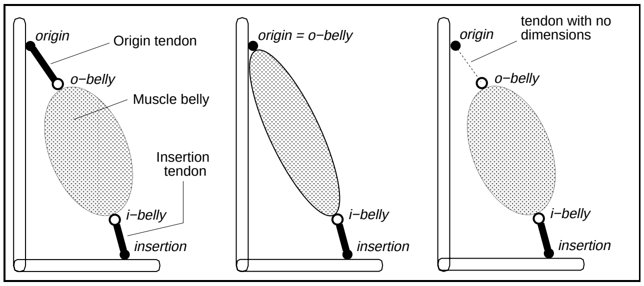

Figure 6: Parameters of the fusiform muscle model.

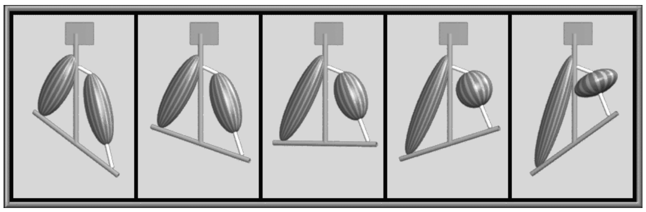

Figure 7: Operation of the fusiform muscle model with and without tendons.

4.3 Multi-belly muscles

Wide muscles with complex shapes cannot be modeled with the same ease as straight fusiform muscles. Although one could use multiple instances of fusiform muscles to approximate the shape of a complex muscle, a better alternative would be to use a generative approach in which any number of muscle bellies may be positioned automatically. The *multi-belly muscle model* accomplishes this task.

In order to locate and orient a number of muscle bellies automatically, we need to define the origin and insertion of the muscle to be represented. Spline curves [5] provide a convenient alternative to merely enumerating the individual origin and insertion points. Relatively few control points are needed to define these curves, and by using a parametric formulation of the spline curve, points along the curve can be sampled simply and efficiently. Thus, instead of origin and insertion *points*, the multi-belly muscle model requires that origin and insertion *curves* be specified.

Figure 8 illustrates the procedure for locating and orienting n muscle bellies between pairs of spline curves. Locating each muscle involves finding two points of attachment on each curve for every muscle belly, a task easily accomplished by sampling the curves and pairing-off corresponding sample points. Orientation of individual muscle bellies requires finding a reference vector to indicate the 'up-direction' of a muscle belly. As illustrated in Figure 8, the reference vector for each pair of points $(\mathbf{o}_j, \mathbf{i}_j)$ is the normal vector of the plane through three sample points, specifically:

$$\begin{array}{rll} \mathbf{o}_j, \mathbf{o}_{j+1}, \mathbf{i}_j & \text{if} & j = 1; \\ \mathbf{o}_{j-1}, \mathbf{o}_{j+1}, \mathbf{i}_j & \text{if} & 1 < j < n; \quad \text{and} \\ \mathbf{o}_{j-1}, \mathbf{o}_j, \mathbf{i}_j & \text{if} & j = n. \end{array}$$

The implementation of the multi-belly muscle model resembles that of the fusiform muscle model. The origin of each multi-belly muscle is represented by a list of control points defining the origin curve. Another list defines the insertion curve in a similar way. As before, the origin and insertion curves may be defined in whichever local coordinate system necessary; the class transforms the control points (and hence, the curves) into world coordinates prior to storing them. By default, ten muscle bellies are created between the origin and insertion curves. This default behavior can be changed

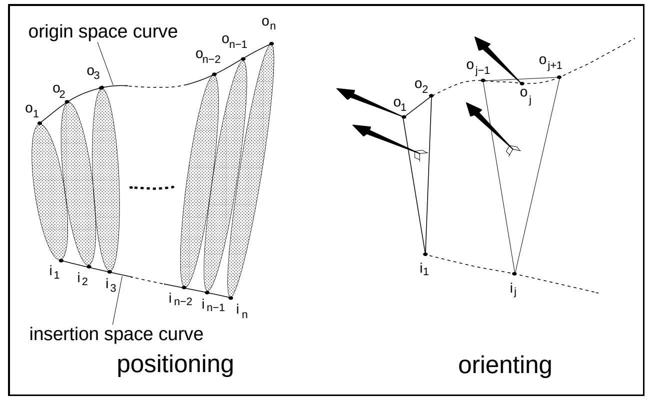

Figure 8: Locating and orienting muscle bellies in the multi-belly muscle model.

by specifying a different belly count before instantiating the muscle.

4.4 Muscles that bend

The *general muscle model* allows muscles with complex shapes to be modeled. It is useful for representing muscles that bend around underlying anatomical structures.

Motivation

The fusiform and multi-belly muscle models can be used to represent most skeletal muscles in the human body. Exceptions are muscles for which the simplifying assumptions of these models are unreasonable. Specifically, some muscles bend around underlying anatomical structures, others cannot be represented accurately by one or more straight muscle bellies, and yet others attach via wide, flat tendons to the underlying skeletal bones. Also, using many independent muscle bellies to approximate a single muscle with a complex shape is not always anatomically appropriate—the real muscle may not even have muscle bellies that can be individually differentiated.

Representation and parameters

To model muscles with complex shapes, we use tubularly-shaped bicubic patch meshes capped with elliptic hemispheres at either end. Figure 9 illustrates the construction of such a patch mesh. It is defined by sweeping an ellipse along the path defined by the control points $\mathbf{o}_c$, $\mathbf{o}_v$, $\mathbf{i}_v$, and $\mathbf{i}_c$. During the sweep, the lengths of the major axes of the ellipse are adjusted to create fusiform-like profiles in directions orthogonal to the path. In Figure 9, this fusiform profile is easily observed in the rendered side view of the muscle[2].

Parameters that control the shape of general muscles are given in Table 1. As before, *class* parameters are used to define the shape of the muscle in its natural state, while the location, direction, and orientation of the muscle are specified before the muscle is instantiated.

Two points $\mathbf{o}_1$ and $\mathbf{o}_2$ specify the origin of the muscle. The midpoint $\mathbf{o}_c$ of $\mathbf{o}_1$ and $\mathbf{o}_2$ is where the path originates. Together with another parameter, $\mathbf{o}_v$, point $\mathbf{o}_c$ determines the general direction of the muscle near its origin. The points $\mathbf{o}_1$, $\mathbf{o}_2$, and $\mathbf{o}_v$ are all given

[2] A similar (but less conspicuous) profile is present in the rendered front view; however, the bend in the muscle and the eccentricity of the ellipse tend to disguise the profile.

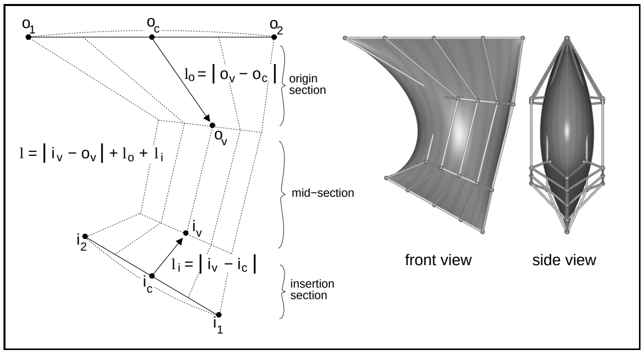

Figure 9: The general muscle model: contruction of a bicubic patch mesh by sweeping a varying ellipse along a cubic Bezier curve. For simplicity of illustration, the Bezier curve is defined in the plane of the page.

Parameters	**Comment**
Class parameters	*defines natural state of muscle*
V	muscle volume
r	height-to-width ratio of muscle's bulge
Other parameters	*locates, directs, and orients muscle*
$\mathbf{o}_1$, $\mathbf{o}_2$	defines origin of muscle
$\mathbf{o}_v$	directs origin section of muscle
$\mathbf{i}_1$, $\mathbf{i}_2$	defines insertion of muscle
$\mathbf{i}_v$	directs insertion section of muscle
h_o, h_i	height of muscle at origin and insertion
c	'depth' of capping elliptic hemisphere

Table 1: Parameters of the general muscle model.

in the local coordinate system of the bone where the muscle originates. Similarly, the points $\mathbf{i}_1$ and $\mathbf{i}_2$ specify the insertion of the muscle, and $\mathbf{i}_c$ and $\mathbf{i}_v$ determine the general direction of the muscle near its insertion. These points are given in the local coordinate system of the bone where the muscle inserts. The points $\mathbf{o}_c$, $\mathbf{o}_v$, $\mathbf{i}_v$, and $\mathbf{i}_c$ determine three lengths which are used in calculating the muscle's volume:

- the length of the origin section, $l_o = |\mathbf{o}_v - \mathbf{o}_c|$,
- the length of the insertion section, $l_i = |\mathbf{i}_v - \mathbf{i}_c|$, and
- the overall length of the muscle, $l = |\mathbf{o}_v - \mathbf{i}_v| + l_o + l_i$.

The parameters h_o and h_i determine the height of the muscle at each of its extremities, and c gives the undetermined radius of the capping hemispheres. The remaining parameters specify the volume of the muscle in its natural state, and the height-to-width ratio of the bulge of the muscle's mid-section.

Construction

The path along which the varying ellipse is swept is a cubic Bezier curve[3] defined by the control points $\mathbf{o}_c$, $\mathbf{o}_v$, $\mathbf{i}_v$, and $\mathbf{i}_c$. At $\mathbf{o}_c$ the ellipse has major axes with lengths $a_o = |\mathbf{o}_c - \mathbf{o}_1|$ and $b_o = \frac{h_o}{2}$, respectively. The major axes themselves are easily determined: the first is defined by the vector $\overrightarrow{\mathbf{o}_1\mathbf{o}_c}$, and the second by the vector $\overrightarrow{\mathbf{o}_{up}} = \overrightarrow{\mathbf{o}_c\mathbf{o}_v} \times \overrightarrow{\mathbf{o}_1\mathbf{o}_c}$. Similarly, the ellipse at $\mathbf{i}_c$ has major axes defined by $\overrightarrow{\mathbf{i}_1\mathbf{i}_c}$ and $\overrightarrow{\mathbf{i}_{up}} = \overrightarrow{\mathbf{i}_c\mathbf{i}_v} \times \overrightarrow{\mathbf{i}_1\mathbf{i}_c}$, with lengths $a_i = |\mathbf{i}_c - \mathbf{i}_1|$ and $b_i = \frac{h_i}{2}$, respectively.

[3]A cubic Bezier curve is used for the natural way in which it allows the direction of the path, and therefore the way the muscle bends, to be controlled.

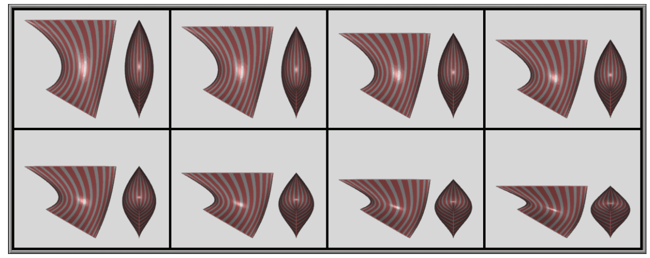

Figure 10: Operation of the general muscle model.

To determine the lengths a and b of the major axes of the ellipses at $\mathbf{o}_v$ and $\mathbf{i}_v$, we use the volume of the muscle and the height-to-width ratio of the muscle's bulge at $\mathbf{o}_v$ and $\mathbf{i}_v$. First, consider the muscle's volume, V. Since the area of an ellipse with major axes x and y is πxy, the volume of the muscle may be approximated[4] by

$$\begin{aligned} V &= l_o\pi\left(\frac{a_ob_o + ab}{2}\right) + \\ &\quad (l - l_o - l_i)\pi\left(\frac{ab + ab}{2}\right) + l_i\pi\left(\frac{ab + a_ib_i}{2}\right) \\ &= \frac{\pi}{2}(l_oa_ob_o + (2l - l_o - l_i)ab + l_ia_ib_i) \\ &= \frac{\pi}{2}(C + Lab), \qquad (5) \end{aligned}$$

where

$$C = l_oa_ob_o + l_ia_ib_i \quad \text{and} \quad L = 2l - l_o - l_i > 0.$$

Next, let the height-to-width ratio of the muscle's bulge at $\mathbf{o}_v$ and $\mathbf{i}_v$ be $r = \frac{a}{b}$, then Equation 5 becomes

$$V = \frac{\pi}{2}\left(C + Lb^2r\right).$$

Equations expressing the lengths a and b of the major axes of the ellipses at $\mathbf{o}_v$ and $\mathbf{i}_v$ may now be stated:

$$b = \sqrt{\frac{2V - C\pi}{\pi Lr}} \qquad (6)$$

$$a = br. \qquad (7)$$

Implementation

As before, we implement the general muscle model in a class with two class parameters corresponding to V and r in Table 1. Before instantiating a muscle of this class, the origin and insertion should be specified. Two lists of the form ($\mathbf{o}_1$, $\mathbf{o}_2$, $\mathbf{o}_v$) and ($\mathbf{i}_1$, $\mathbf{i}_2$, $\mathbf{i}_v$) should be used. The class transforms these points to world coordinates before storing them. Figure 10 shows the general muscle model in action. The figure illustrates how a general muscle deforms when the relative locations of its extremities are changed. Notice how the curvature of the muscle is maintained, and how the muscle deforms automatically when its extremities are moved closer together.

[4]The volumes of the capping hemispheres, which are small relative to the volume enclosed by the patch mesh, are ignored; also, the volume enclosed by the patch mesh is approximated by summing the volumes of three truncated elliptic cones, one for each section of the patch mesh, as annotated in Figure 9.

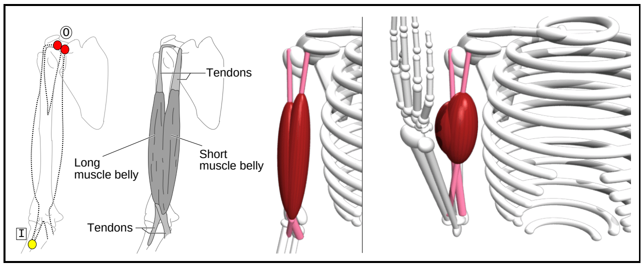

Figure 11: Front view of the biceps brachii and its behavior when the forearm is flexed at the elbow joint.

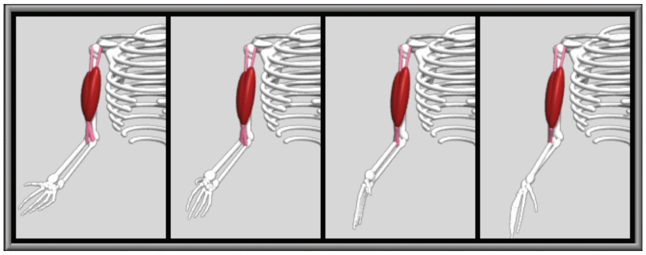

Figure 12: Behavior of the biceps brachii when the forearm is pronated while the elbow joint is flexed to 90.°

```
(define (the-arm-skeleton)
 (lambda
  (reference-skeleton)
  (model "clavicle" (ElevateDepress ProtractRetract)
   (SC-joint (ElevateDepress) (ProtractRetract))
   (clavicle)
   (separator
    (AC-joint (ElevateDepress) (ProtractRetract))
    (scapula)
    (biceps-brachii-origin))
   (model "humerus" (AbductAdduct FlexExtend Rotate)
    (SH-joint (AbductAdduct) (FlexExtend) (Rotate))
    (humerus)
    (model "ulna" (ElbowFlexExtend)
     (EL-joint (ElbowFlexExtend))
     (ulna)
     (model "radius" (PronateSupinate)
      (RU-joint (PronateSupinate))
      (radius)
      (biceps-brachii-insertion)
      (model "hand" (FlexDorsiflex RabductUabduct)
       (WR-joint (FlexDorsiflex) (RabductUabduct))
       (hand))))))
  (biceps-brachii)
))
```

Figure 13: AL function defining the arm skeleton and the multi-joint biceps brachii muscle.

4.5 Muscles of the arm and torso

To illustrate the application of the muscle models, we consider three typical muscles of the arm and torso:

1. *The biceps brachii*, the familiar muscle on the upper arm that flexes and supinates the forearm;
2. *The pectoralis major*, a large, fan-shaped muscle on the upper front part of the chest; and
3. *The brachioradialis*, a muscle that twists around the elbow joint and assists in flexing the forearm.

Two instances of the fusiform muscle model are used to represent the biceps brachii (see Figure 11). We define two functions for specifying the muscle's attachments and one for instantiating the muscle. Notice that the biceps brachii is a multi-joint muscle. It originates from the scapula, spans over the shoulder, elbow, and radioulnar joints, and inserts into the radius bone. Therefore, when specifying the attachments of the muscle in the hierarchy, the origin function must be called just after creating the scapula, and the insertion function must be called just after creating the radius. This ensures that the origin and insertion points will be transformed together with their underlying parts; the scapula in case of the origin, and the radius in case of the insertion. Another action performed by the biceps brachii is supination of the forearm, an action that is most powerful when the elbow joint is flexed to 90.° In this position, if the forearm is pronated and supinated in alternation, the biceps brachii can be seen to elongate and shorten correspondingly. Even though this motion is less dramatic in its effect on the biceps brachii, it nevertheless is important to simulate. Figure 12 shows the behavior of the biceps brachii when the forearm in pronated with the elbow joint in a state of flexion. Figure 13 repeats the hierarchical definition of the arm skeleton presented earlier, but now it includes calls to the origin, insertion, and instantiation functions of the biceps brachii. These function calls appear in *italics* in the figure.

The pectoralis major originates from the clavicle and the sternum (see Figure 14) and inserts into the humerus. Because of this natural division into two sections, we use two instances of the multi-belly class to represent the muscle. The figure shows the behavior of the pectoralis major when the arm is abducted at the shoulder joint. The model represents the general shape of the muscle quite well, and it even creates the armpit where the muscle bellies overlap near the insertion into the humerus.

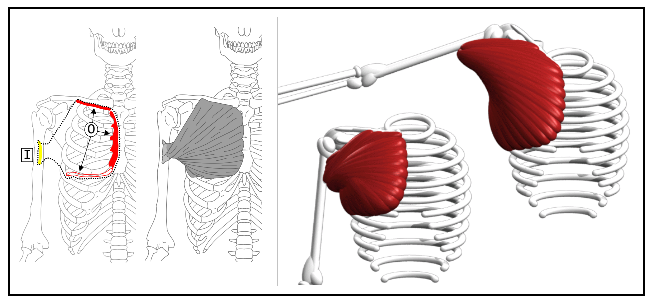

Figure 14: Front view of the pectoralis major and its behavior when the forearm is abducted at the shoulder joint.

We use the general muscle model and a simple tendon model [20] to represent the fleshy and tendinous portions of the brachioradialis (Figure 15), respectively. Figure 16 shows the behavior of this muscle when the forearm is flexed at the elbow joint. Notice how the muscle folds quite naturally as the elbow joint approaches full flexion. This behavior is made possible by allowing the two points defining the mid-section of the muscle ($\mathbf{o}_v$ and $\mathbf{i}_v$ in Table 1) to approach each other. Recall that these points are the second and third control points of the cubic curve defining the muscle's axis. As the angle between the origin and insertion section of the axis becomes more acute, the second and third control points move closer together and the bend in the muscle's mid-section becomes more pronounced. Of course, if the fold is not desired, the positions of the second and third control points can be adjusted as needed.

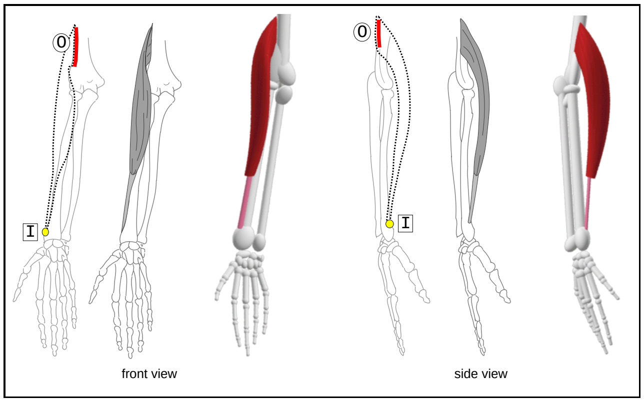

Figure 15: Front and side views of the brachioradialis.

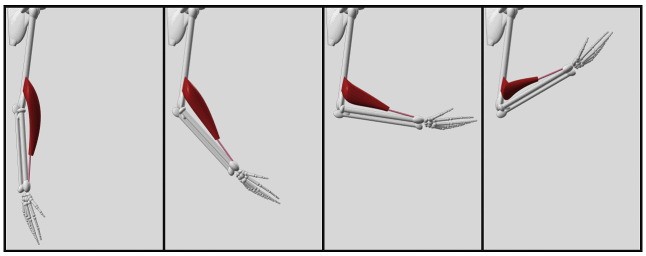

Figure 16: Behavior of the brachioradialis with flexion at the elbow joint.

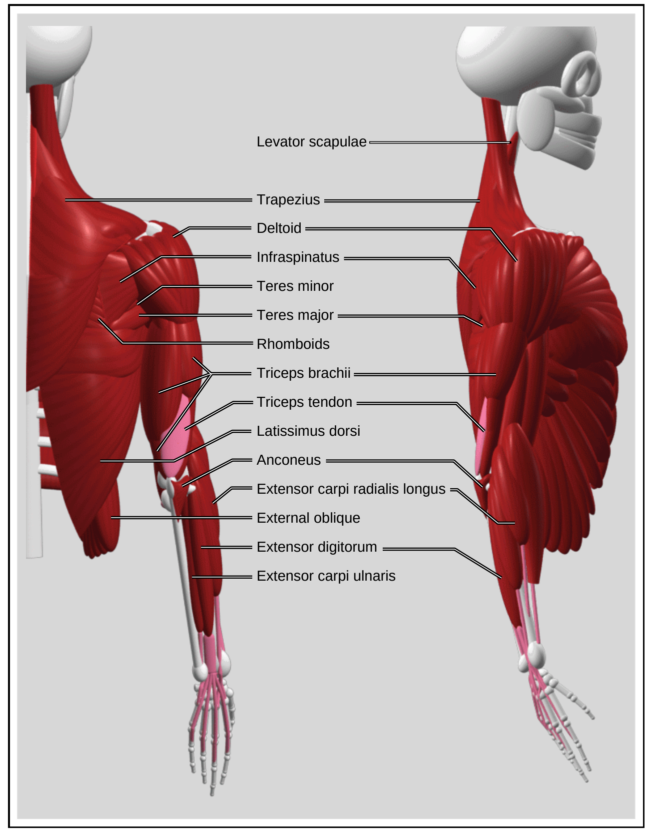

Figure 17: Muscles and tendons of the neck, trunk, shoulder, and upper limb.

4.6 Results and evaluation

We tested the muscle models on a variety of superficial and middle-layer muscles [8] that are responsible for joint movement in the upper limb. Figure 17 presents back and side views of some of these muscles. Notice how the general muscle model is used very successfully to model large muscles such as the trapezius and the latissimus dorsi. We also tested the deformation characteristics of the muscle models by creating an animation sequence to show how the biceps brachii muscle bulges when the forearm is flexed at the elbow joint. Selected frames of the animation sequence are shown in Figure 18.

Figures 17 and 18 show that the muscle models are capable of representing complex shapes with a high degree of realism, and that natural muscle shape deformation occurs when the underlying skeleton is moved. By implementing the muscle models in classes with well-defined interfaces, the instantiation of individual muscles is greatly simplified. Also, integrating the muscle layer into the hierarchical definition of the skeleton is straightforward. Origin, insertion, and instantiation functions for each muscle may be invoked at appropriate points in the hierarchy, allowing muscles that span over one or more joints to be defined with the same ease as the underlying bones in the skeleton.

5 CONCLUSION

This paper has presented a number of anatomy-based muscle models appropriate for simulating the behavior of skeletal muscles in humans. Each muscle model allows the extremities of muscles to be specified relative to different underlying bones, whether adjacent or not, and automatically adjusts the dimensions of the muscle when the extremities are moved closer together or further apart. The models are implemented in classes with consistent interfaces, thereby creating reusable components which may be used in contexts other than in human figure modeling, such as in 3D character animation and the animation of other animals with endoskeletons.

The muscle models manage the deformation of muscles due to isotonic contraction. These deformations are inherent in the models, completely automatic, and functionally dependent on the configuration (or pose) of the underlying articulated skeleton. To allow for isometric muscle contraction, we introduced a tension parameter to control the ratio of a muscle's height to its width, independent of the current pose. The muscle models take the muscle's tension as an instance parameter and deform the muscle accordingly. By binding the tension of individual muscles to articulation variables, users have complete control over the deformations of individual muscles.

We used a procedural modeling language to describe all our anatomy-based models. A language-based definition of complex hierarchical models is elegant and intuitive, and affords the creation of functional dependencies between different components. Interactive control is supported through the use of articulation variables, which may be used either directly, or in expressions, to modify components of the hierarchical model. Cooperating tools can be made available to give nontechnical users interactive control over the complex models.

We adopted an approach to modeling which parallels the one taken in the discipline of artistic anatomy. By analyzing the relationship between exterior form and the structures responsible for creating it, surface form and shape change may be understood best. We identified three general anatomical structures responsible for creating surface form and described one of these, the musculature, in some detail. Application of knowledge of the human anatomy to the development of human figure models is necessary if we hope to achieve a high degree of realism.

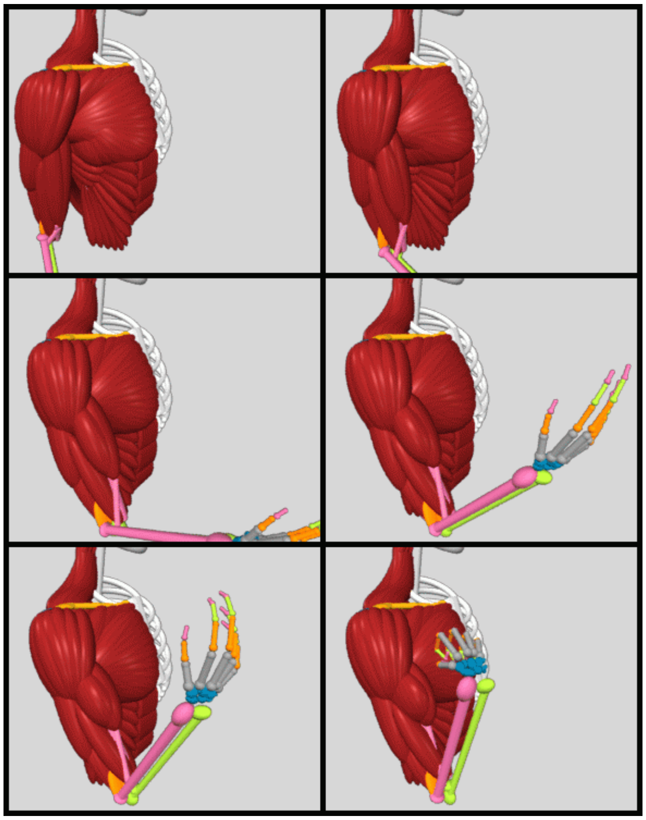

Figure 18: Behavior of the various muscle models with flexion at the elbow joint—isotonic and isometric contraction of the biceps muscle is simulated.

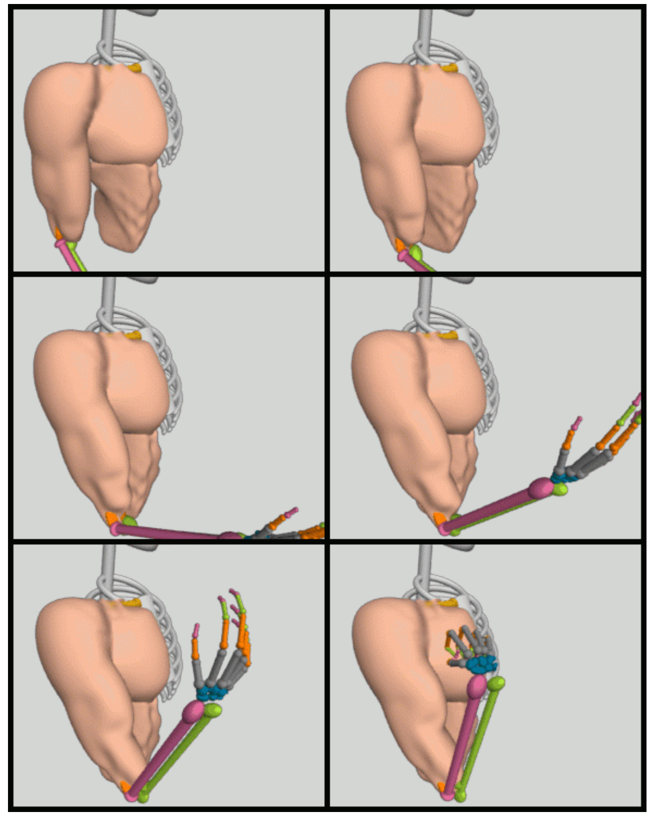

Figure 19: Application of a skin and fatty tissue model to muscles of the upper arm and torso.

We are currently investigating anatomy-based models for generating skin surfaces based on the influence of underlying deformable structures. The capability of implicit functions to blend individual primitives together is exploited in the generation of surfaces to represent the skin. Initial results look promising (see Figure 19). Implicit versions of the simple geometric modeling primitives are used to adjust the control points of bicubic patch meshes representing the skin. This technique also allows us to model fatty tissue between the muscles and the skin—adjusting the radius of influence of the implicit functions allows different thicknesses of fatty tissue deposits to be modeled.

Future research could analyze the structure and function of muscles further to enable a more automated approach to their creation than the one used here. If the origin, insertion, volume, and general shape of a muscle could be determined heuristically, perhaps based on the type of joint(s) being acted upon, or the desired action of the muscle, the creation of human figure models may be greatly simplified. Used in conjunction with a method for generating articulated skeletons automatically, this approach has great potential in creating new or fictional articulated figures for 3D animation applications.

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