Anatomical Human Musculature Modeling for Real-time Deformation

ZUO Li, LI Jin-tao, WANG Zhao-qi
Institute of Computing Technology, Chinese Academy of Sciences
100080, Beijing, China
E-mail: {lzuo, jtli, zqwang}@ict.ac.cn

ABSTRACT

Human musculature is an important structure for appearance and deformation of body surface. In this paper, we propose a new method of muscle modeling based on both anatomical and real-time consideration. Furthermore, we introduce our muscle modeling system. In the system muscle can be constructed and edited easily through appointing some radial and transverse cross-section control parameters. Deformation of muscle model can be achieved through axial deformation and cross-section's deformation. User can adjust the precision of models to meet different requirements. The effects are satisfactory when we apply the model to our Human Modeling System. This modeling approach can also be used to model other soft tissues.

Keywords

Human modeling, Deformation, Musculature, Human anatomize

1. INTRODUCTION

Almost since the introduction of graphics displays, researchers have been trying to model and animate realistic human bodies. However, it remains one of the greatest challenges in computer graphics not only because the complicacy of human body that composes of rigid bodies and soft tissues but also because of the high sensitivity of our eyes to familiar objects like human figures. We hope virtual human has not only realistic appearance and rational behavior, but also the realistic deformation effect of skin and clothing produced by body animation. To achieve this, layered approach to represent human figures has been adopted, in which skeletons support one or more layers, typically muscle, fatty tissue, skin, and clothing layers. The basic idea of the approach is that the more close the model to the structure of human body, the more realistic effect we can achieve.

But few of layered body models in present systems could achieve both realistic appearance and real-time deformation because of the complexity of the model geometry and the algorithm of the deformation. Models are commonly too complicated to achieve fast deformation if they are closed to real human body. Many researches had been done about the layered approach and have achieved preferable effects [4][17][18][19][20]. Most researchers use articulated structures that are too simple to be deemed anatomically appropriate, while some other models are too complexity to animate in real time.

Muscle layer is an important layer in the layered body modeling. Firstly, the shape and deformation of muscles determine the appearance of human body partially; secondly, the construction and deformation of muscle occupy majority calculation time in the whole body modeling. Therefore, It is valuable for human modeling to manage to reduce the complexity of muscle modeling and at the same time to maintain its veracity.

In this paper, we propose a new method of anatomical musculature modeling to realize realistic and real-time figure animation. The muscles are modeled using pure geometric theories and the deformation is based on the physiological characteristics of muscle. The process of muscle modeling is composed of two steps: specify the control axial curve of muscle, and then appoint its control cross-sections. The binding of axial curve with cross-section and rendering of muscle surface can be achieved by our system automatically.

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In the following subsections, we briefly survey subsistent muscle modeling techniques and the anatomy of human muscle.

1.1 Related Work

There are many merits to model objects based on geometrical theory such as rapid computing speed, easy control. Thereby, as a complicated object, muscle layer is commonly constructed based on geometry in the layered body modeling systems. Present geometrical muscle models are often too simple to simulate 3D forms of muscles, such as the model proposed by Wilhelms[11]. His model is composed of three spheroids (one for muscle body, the other two are tendons of the muscle). He updated the muscles as deformable discrete cylinders in the latter work. These coarse polygons only simulate restricted shapes of the muscles. LEMAN[21] developed by Turner uses implicit surface (include sphere and cylinder) to model muscles. The deformation is implemented by changing the global parameters of implicit surface, which is not intuitionally and interactive. Shen[18][19] and Scheeper[20] also implemented muscle models using spheroids. The ellipsoidal muscle model can only simulate simple spindle muscles and their deformations. The model constructed by Amaury and Thalmann[1][2][3] is relatively close to our work. They proposed a concept named "Action Line", which is a mass-spring line fixed at two ends. The global bend of the "Action Line" achieved by the force enforced by simulated gravity. And the bend at joints is realized by the collision detection with a proper sized sphere. The modeling method needs to modify elastic parameters of every action lines to achieve proper curvature for realistic effects. Furthermore the bend at the joint introduced complex calculation of operating force, because it was realized by the interaction between action line and a proper sized sphere. Moreover, the surface of muscle is modeled by hand directly. Hence the workload of modeling is so heavy that the deformation of model could not achieve real-time speed.

1.2 Human Muscle Anatomy

In this paper we merely study skeletal muscles, because this kind of muscles play the most important role in the deformation of human body's surface relative to other muscles. Muscle modeling is the most complicated portion in the modeling of the whole body because of its anatomical characteristics.

It is well known that skeletal muscles, which are the middle layer between skin and skeleton, spread all over the human body. There are 700 skeletal muscles in the human body, and their shapes and volumes are quite different from each other. Different muscles have different shapes and thus have different functions. Muscle is attached on bones or other muscles in turn or by layers, and some spans multi-joints. The shape of muscle changes much when it is in different contraction states[9]. The skeletal muscles' contractions produce the motions of the bones.

Muscle is composed of belly and tendons structurally. Belly is contractile central part of skeletal muscle and it is composed of muscle cells. Tendons on each end of skeletal muscles are attachments to act as transmitters. Generally, each skeletal muscle spans joints and attaches on the bones, or one end of it attaches on the bones and the other attaches on skin. Usually the attachment to the more stationary bones is called the origin while the other end is called the insertion. The shape of the belly and tendon that is close to the surface layer influence the shape of the surface skin greatly. Anatomists distinguish contraction of muscle as two types: Isotonic (same force) contraction and isometric (same length) contraction. Isotonic contraction means the length of the muscle is shortened and belly is thickened so that the motion of bones to which the muscle is attached is produced. While isometric contraction means the length of the muscle dose not change but belly is thickened under the resistance.

2. MUSCLE MODELING

In anatomical papers, the positions of origins and insertions of muscles relative to bones are often used to describe the position of muscles. Thus, during the muscle modeling, if we can specify the attached points of the muscle on the bones, we can specify the position of muscles. Furthermore, while the posture of skeleton is changed, the positions of muscle's attached points change accordingly. Hence, the length, position and flexion of muscles that are determined by the points will be changed. After we have determined the position of the muscle, we should specify the shape of the muscle. CT pictures of muscles are regarded as anatomical data and used to describe the internal structures and external contours of muscles in medical applications. Inspired by the factor, we define the muscles' cross-sections according to the CT slices of muscles. The shape and area of cross-sections is used to reflect the figure of muscles. Hence, deformations of the muscles can be achieved by the modifications of the cross-sections. Then, we can outline the surface of muscles by the control points of these cross-sections.

Therefore, our muscle models are composed of two important parts: Control Axial Curve and Control Cross-Section. Control Axial Curves is used to control lengths, positions and directions of muscles. Controlling Cross-Section is used to control the contour and size of muscles.

2.1 Control Axial Curve

Control Axial Curve is an open 3th-degree rational B-spline. The curve differ greatly from the Amaury's elastic "action line", which is introduced in section 1.1. we can use spline curve to simulate the smooth control curve of muscle. It has higher fidelity than polygonal lines to simulate the natural shapes of muscles. Rational B-spline is an approximate spline that has been widely used in geometrical modeling. The degree of spline polynomial is independent of the number of control points. Further more, the curve can be controlled locally. According to these properties, the number of control points can be added and deleted freely by the need of modeling. A 3th-degree B-spline curve[13] is defined by

$$C(u)=\sum_{i=0}^{n} N_{i,3}(u)Pi, a \le u \le b. \qquad (1)$$

Where the $\{P_i\}$ are the control points, the $\{N_{i,3}(u)\}$ are the 3th-degree B-spline basis functions, defined on the nonperiodic knot vector

$$U=\left\{\underbrace{a,\cdots,a}_{4},u_4,\cdots,u_{m-4},\underbrace{b,\cdots,b}_{4}\right\}.$$

Control points are attached on the surface of bones and their positions are determined by human anatomy. The coordinates of these points are expressed by the local coordinate system of the attached bone. Similar to real human muscles, the control points of Control Axial Curve may span several different bones.

2.2 Control Cross-Section

Control Cross-Section is used to define the outer contour of muscle model, which is modeled by close 3th-degree rational B-spline to simulate CT slices of muscle, with the center located on the corresponding Control Axial Curve. The direction vector of cross-section parallels the tangential direction of axial curve at the cross point. We define the muscle's Control Cross-Section in two steps: firstly, determine the position and direction of cross-section relative to the control axis. Secondly, determine the shape of cross-section. The cross-section's control points determine its shape. The arrangement of these control points is parted equally around the Control Axial Curve by means of ray casting.

We use parameter u in the formula (1) to denote the position of the cross-section relative to the Control Axial Curve. We can get global coordinates of cross-section through the value of u. Its range is from 0 to 1. Three steps are required to compute a point on a B-spline curve at a fixed u value: First, find the knot span in which u lies. Second, compute the nonzero basis functions, $\{N_{i,3}(u)\}$. Last, multiply the values of the nonzero basis functions with the corresponding control points. Through these steps, we can get the position of cross-section in the axial space.

The direction vector of cross-section parallels the first order derivative of axial curve at the cross point u. The derivative of control curve at point u can be calculated by following formula

$$C'(u)=\sum_{i=0}^{n-1} N_{i,2}(u)Q_i. \qquad (2)$$

Where $Q_i = p\cdot\frac{p_{i+1}-p_i}{u_{i+p+1}-u_{i+1}}$.

Up to now, the position and direction vector of Control Cross-Section relative to Control Axial Curve are calculated.

We reference the approach used by Shen[17] to define the positions of the control points of the cross-section. The number of the control points is denoted by n. We cast n radial lines from the cross point on the axial curve as shown in figure 1. The radials are equally divided in the cross-section surface. The length of every radials R_i is specified by CT slides of muscle or just by modeler. The O_j denotes the position of the cross-section relative to the Control Axial Curve. The P_i (i= 0~n) is control points on the edge of the section that getting from the casting radial lines.

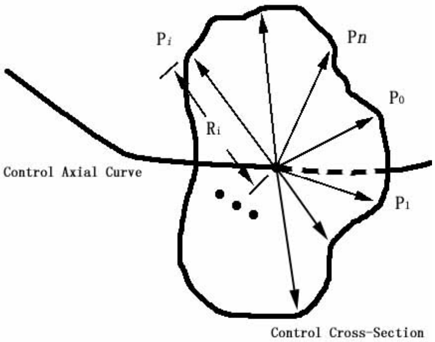

Figure 1. Construction of Control Cross-Section.

2.3 Binding Control Points in Axial Space

The deformation of muscles is achieved based on extended axial deformation. 3D axial deformation is an effective approach to deform the object through the deformation of the 3D axial curve. Commonly, two steps of operation are needed to deform objects using axial deformation: first, each vertex of the object is attached to one point P_n of axial curve. And its local coordinates (u,v,w) in the axis' local coordinate system are computed. Second, the deformed vertex is obtained by computing the associated local coordinate system at P_n' homologous to P_n on the deformed axis, and transforming the (u,v,w) coordinates from this coordinate system to the world coordinate system. In conclusion, three problems we should considered when we are using axial deformation:

1. Binding a vertex to the axis;
2. Defining local coordinate frames on the axis;
3. Computing the coordinates of deformed vertices.

In our muscle modeling system, only control points of the cross-section are needed to bind to the axial space. Suppose P is a point on the edge of the cross-section S. C(u), $u \in [0,T]$ is a 3D axis cross through the cross-section. P_N is the projection of P on the curve C(u), and $\mathrm{P}_N = \mathrm{C}(t)$. V is direction vector from P_N to P, $\mathrm{V} = \mathrm{P} - \mathrm{P}_N$. Apparently the dot product between V and derivative of $C(t)$ is 0, that is $\mathrm{V} \cdot \mathrm{C}'(t) = 0$. Then,

$$P = C(t) + (V \cdot L_x(t))L_x(t) + (V \cdot L_y(t))L_y(t) + (V \cdot L_z(t))L_z(t) ,$$

where $(L_x(t), L_y(t), L_z(t))$ is the axial local coordinates at C(t).

Axial local motion frame is a local coordinate system moving along axis. Although Frenet frame is the most popular and useful frame, it has two problems: 1). There is no definition of local frame at the point of vanishing curvature. 2). It will produce unnecessary rotations about the tangent vector for a non-planar curve with an area of high torsion. Using the rotation minimizing frames is a good solution for the above two problems. We chose the rotation minimizing frames defined by Klok[6] in terms of a differential equation with initial conditions. The local coordinate axis $L_x(t)$, $L_y(t)$, $L_z(t)$ of axial curve C(t) is defined as follows:

$$L_x(t) = C'(t) \big/ \left\| C'(t) \right\|,$$
$$L_y{}'(t) = -(C''(t) \cdot L_y(t))C'(t) \big/ \left\| C'(t) \right\|,$$
$$L_z{}'(t) = -(C''(t) \cdot L_z(t))C'(t) \big/ \left\| C'(t) \right\|$$

Denote $u = V \cdot L_x(t)$, $v = V \cdot L_y(t)$, $w = V \cdot L_z(t)$, then

$$P = C(t) + uL_x(t) + vL_y(t) + wL_z(t) \qquad (3)$$

Thus, the point P on the edge of cross-section can be specified uniquely by quadreple (t,u,v,w) in the axial space defined using C(t) and local coordinate frame $(L_x(t), L_y(t), L_z(t))$. In this way, the control points of cross-section are bound in axial space.

2.4 Simulation of Muscle Deformation

So far we have defined the positions, the directions and the shapes of muscles. Muscle is an elastic tissue capable of contraction. Let's consider the production of the human body's motion: the contraction of the muscle causes the bones to which it is attached pulling toward each other, which causes the motion (flexion or extension) of the joint. Muscle bulges when it is contracted and shortened, and become thin when it is relaxed and stretched; Whereas in our modeled muscle, the reverse happens: first, specify the angles of the joints; second, calculate the variation of muscle's length and position; last, produce the deformation of the muscle surface according to these variations. In this section, the approache of simulating the muscle deformation along with the volume preservation are introduced.

The position of the axial control curves' control points are expressed by the local coordinates of the bones. Thus, the movements of the bones produce the displacements and the deformations of the corresponding control axial curves. Suppose $\mathrm{P}_N = \mathrm{C(t)}$ is the bound point of V on the axial curve. We denote the coordinates of V by (t,u,v,w) in the coordinate system that P_N is in. The new position of V, V_{AxDf}, can be calculated as follows: Let $\mathrm{P}_N' = C(t')$ to be the new position of P_N after the deformation of axis. We can learn from the definition of axis that the value of parameter t' equals the parameter t that the P_N on the original axis. Thus, the coordinate of V_{AxDf} in the local coordinate system that P_N' in is still (t,u,v,w). We can compute the global position of V_{AxDf} according to the global position of P_N' combined with the local coordinate (t,u,v,w). Thus, we can get the deformation of muscles based on the gesture of human body automatically.

Based on the anatomy, there are few changes of the muscle volume during the deformation of the muscle. We realize the volume preserve of the muscle by adjusting the area of cross-section. Suppose the initial length of muscle is l_0. The areas of cross-sections are $\{S_k \mid k = 0,1,...,n\}$ respectively. The length after the dilation of muscle is l_1. Then, the scale between the area of cross-section and original area can be $S_k' \big/ S_k = l_0 / l_1$ approximately. Thus, the change of the distance between the control points and the center of cross-section is $r = d_k' \big/ d_k = \sqrt{l_0 / l_1}$.

Where, d_k is the distance from the control points to the center of the cross-section. We can add the distance parameter r to the quadreple (t,u,v,w). Then, the new position P' of cross-section control point P is

$$P' = C(t) + ruL_x(t) + rvL_y(t) + rwL_z(t), \quad (4)$$

The isometric contraction of muscle can be achieved by adjust the value of r in the formula (4) through the adjustment of muscle's tension parameter.

2.5 Rendering of Muscle Surface

The render of muscle surface is the last step of muscle modeling. In order to obtain smooth muscle surfaces while preserve the information we have designated on the muscles, we render the surfaces as bicubic NURBS surfaces. The points that composed of the two ends of control axis and the control points of cross-sections are used as the points to be interpolated by a NURBS surface. We are here interested in NURBS surfaces that are closed in the contour direction and opened in the axial direction. We use the method mentioned in [12] to compute global surface interpolation. The obtained control points are act as the bi-directional control net of the NURBS surface. Detailed computation of control points can be found in [12].

A NURBS surface of degree 3 in both u and v directions is a bivariate vector-valued piecewise rational function of the form

$$\mathrm{Q}(u,v) = \frac{\sum_{i=0}^{m}\sum_{j=0}^{n} w_{i,j}P_{i,j}N_{i,3}(v)N_{j,3}(u)}{\sum_{i=0}^{m}\sum_{j=0}^{n} w_{i,j}N_{i,3}(v)N_{j,3}(u)} \qquad 0 \le u,v \le 1 \quad (5)$$

The $\{P_{i,j}\}$ forms a bi-directional control net. The weight set is $\{w_{i,j}\}$, $\{N_{i,3}(v)\}$ and $\{N_{j,3}(u)\}$ are the non-rational B-spline basis function defined on the knot vectors U and V.

3. MUSCLE MODELING SYSTEM

We develop an interactive graphical system to realize the modeling of skeletal muscles of human body. In the system, modeler can appoint the attachment points of muscles on the skeletal model, define the control axes and control cross-sections conveniently and rapidly.

In our interactive system, muscle modeling is composed of two steps: Firstly, appoint the axial control points of muscle on the skeleton, which is the sublayer of muscle layer. The control points are used to define the axial control curve of muscle. Then, the position, direction and the contorted degree of muscle can be decided accordingly. Secondly, define the cross-sections of muscle. In this step, the cross-section's position relative to control curve and the contour of cross-section is appointed. The rendering of muscle surface is also composed of two steps: Rendering algorithm takes the axial control points as the control points of NURBS curve, produce the axial curve automatically. Then, the position of cross-section can be calculated using the approach introduced in section 3.2. Until now, we have got all of the control points of NURBS surface. At last, the surfaces of muscle are constructed by formula (5). In the following sections, we introduce every step that is needed to construct a whole deformable muscle model in detail.

3.1 Construction of control axial curve

The number of control points needs to be determined by reference to the shape and the manner of the muscle before we construct a control axial curve. 2 to 4 control points is enough for a common muscle to reflect its position and how the muscle is attached to the bones. Skeletal muscles are the source of motions. Hence, they often span one or more joints. We appoint the control points of muscle's axial curve on the surface of bones directly. But in the interactive graphical interface of the system, the superposition of bones at the joints is inevitable. For convenience, system provides modeler with facility to select the attached bone before appointing every control points. The coordinates of these control points are denoted as the local coordinates of the attached bone. Thereby, before the coordinates are sent to the rendering functions of B-spline curve, they should be translated into global forms. Be limited to the space, in this paper we do not discuss the hiberarchy of skeleton and the transformation of coordinates from local to global. According to the global coordinates of these control points, control axial curves can be dynamic rendered by the system. The editing process of the control axial curve is shown in figure 4 and figure 5. Red points in the figure are the control points of axial curve. And that green lines are control axial curve plotted as open cubic rational B-spline. The left and right side of figure 3 are respectively the front view and the side view of a control axial curve of left pectoralis major. A control curve that is being edited is shown in figure 4. In figure 5, partial control axial curves of left upper limbs are added on the skeleton.

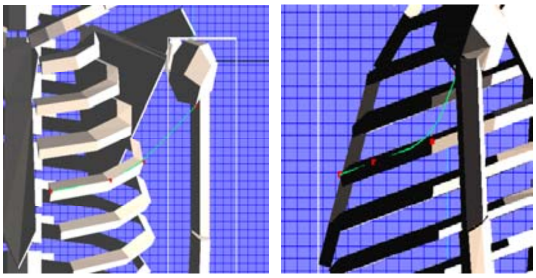

Figure 3. A control axial curve of left pectoralis major （front view and side view）

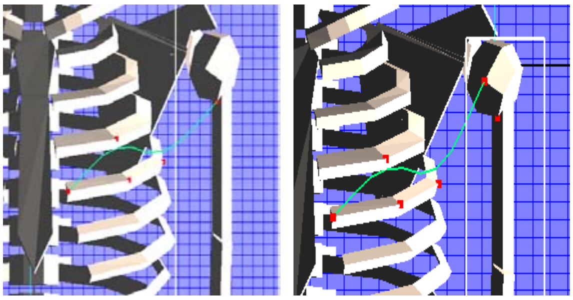

Figure 4. A control axial curve in edit

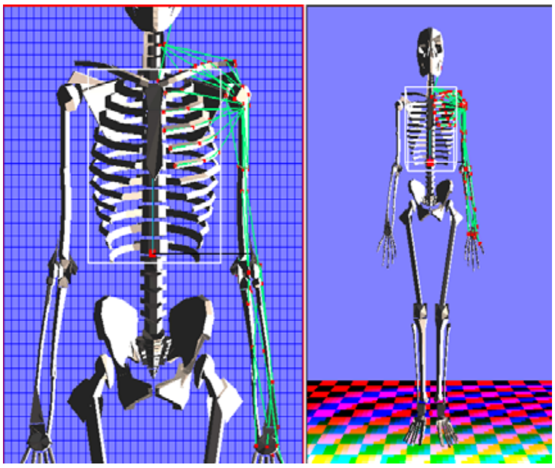

Figure 5. Partial control axial curve of left upper limbs

3.2 Construction of control cross-section

The number of control cross-sections is determined by the precision needed by modeler and the complexity of the muscle's shape. Modeler can specify much more cross-sections according to the slice pictures of CT when the model is used in the medicinal applications. However, 2 or 3 cross-sections are enough when the model used in the application of common animation productions. The position of cross-section relative to control curve, denoted by u, is assigned interactively, range from 0 to 1. While the *u* is changed from 0 to 1, control cross-section moving from insert point to end point along the control axial curve. Similarly, the number of control point of cross-section can also be specified by the complexity of the contour of cross-section. The distance between each control point of cross-section relative to the control axial curve is specified after the number of cross-section has been specified. In our system, the contour of cross-section determined by these control points is shown by polygon line segment interactively. The process of the cross-section's construction can be done automatically through the manipulation of CT pictures of muscle. At present, we implement the process interactively.

Two control cross-sections that defined on the control axial curve are shown in figure 6. The positions of cross-sections are shown by cerise points. Thin white lines denote the contour of cross-section. These two cross-sections use 6 and 4 control points respectively. As shown in figure, cross-sections are orthogonal section of control axial curve and the vertexes of polygon distributing around the axis equably. In the right side of figure 6, the motion of section along the axis and adjusted control points of section is shown. The muscle surface rendered by NURBS is shown in figure 7 and figure 8. The influence of adjusting the position of cross-section on the shape of muscle is shown in right sides of figure 7 and figure 8. Figure 9 shows the left upper limbs that added partial muscle models in front view and side view. The effect of the constructed model is rather satisfactory.

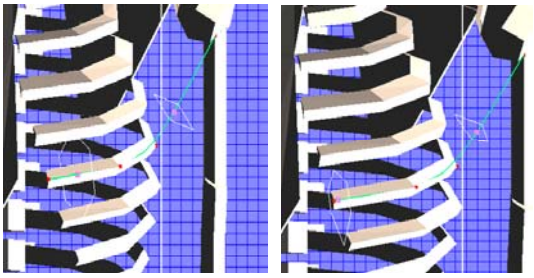

Figure 6. Construct Control Cross-Section (Position and shape of cross-section has been adjusted in right side)

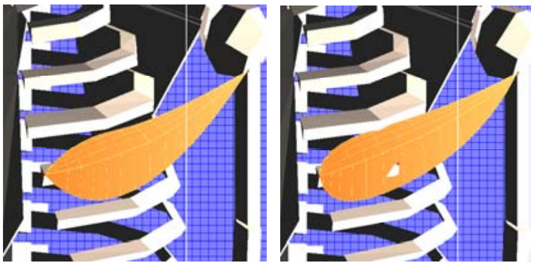

Figure 7 Rendering of muscle (front view)

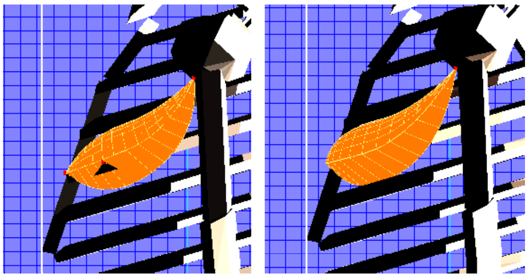

Figure 8. Rendering of muscle (side view)

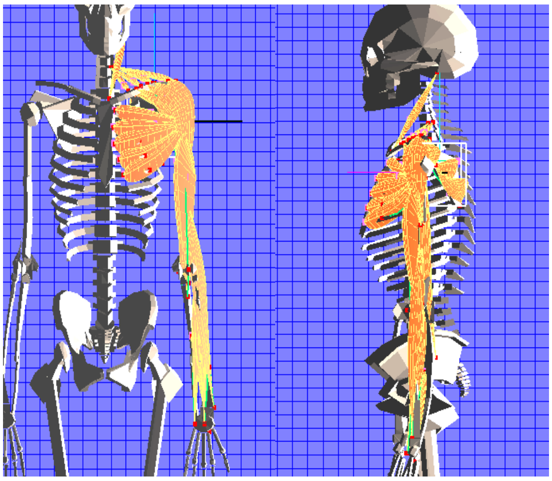

Figure 9 Partial muscle models of left upper limbs

3.3 Implementation of muscle deformation

After we have appointed the control axial curves and control cross-sections, the binding of control points and the axial curve is implemented automatically in our system, to achieve realistic muscle deformation. The detailed discussion of binding is in section 2.3. After the binding is finished, the deformation of muscles can be implemented automatically according to the varieties of joints' angles. Figure 10 shows the deformation sequence of the muscles when the left arm is bending.

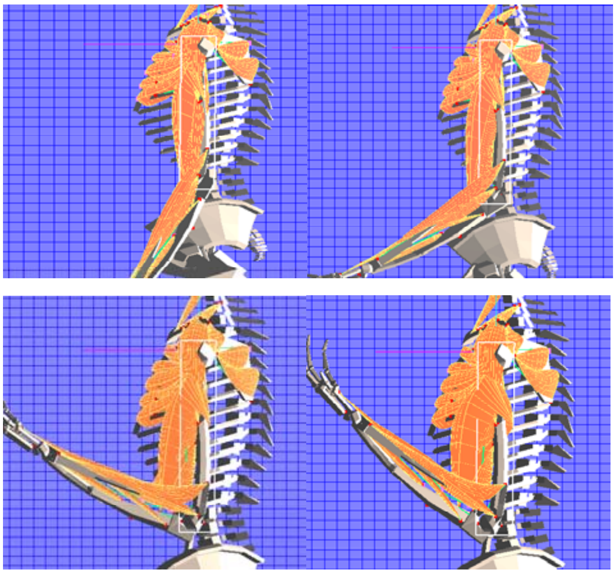

Figure 10 Deformation sequence of left arm

4. CONCLUSION

In this paper, we propose an approach of muscle modeling that can satisfy not only the correctness of anatomy but also the real-time speed of realistic deformation. The system of muscle modeling that we have developed is also introduced. We discuss the process of muscle modeling using our modeling system in detail.

Our muscle modeling method combines control axial curves used to define the position and direction of muscle, and control cross-sections used to define the shape of muscle. The deformation of the model is based on axial deformation combined with cross-section's deformation. So we can construct arbitrary complicated muscles realistically with our modeling system. The deformation of model is not based on biomechanics or physical theories but based on pure geometrical method. The approach avoids the computational complexity that introduce by physical theories to achieve real-time speed of deformation. Indicated by our experiment, the approach proposed in this paper is an effective method in muscle modeling. It can also be used to model other soft tissues.

At present, modeler constructs the Control Cross-Section of muscle interactively. We are going to implement the function by CT pictures automatically.

5. ACKNOWLEDGMENTS

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