Anatomically-based modeling and animation of human upper limbs

Kyung-Ha Min*, Seung-Min Baek*, Gun A. Lee*, Haeock Choi+, and Chan-Mo Park*

*Virtual Reality Laboratory
Dept. of Computer Science and Engineering
Pohang University of Science and Technology
San 31 Hyojadong, Pohang, 790-784, KOREA
Tel: +82+562-279-5661
Fax: +82+562-279-5699
{minkh,sogmi,endovert,parkcm}@postech.ac.kr

+GIS Research Team
Computer & Software Technology Lab.
Eletronics & Telecommunications Research Institute
161 Kajong-Dong, Yusung-Gu, Taejon, 305-333, KOREA
Tel: +82+42-860-6660
Fax: +82+42-860-4844
hochoi@etri.re.kr

Abstract

We propose an anatomically-based modeling and animation scheme for a human body model whose shape was created from 3-D scan data of a human body. The proposed human body model is composed of three layers: a skeleton layer, a muscle layer, and a skin layer. The skeleton layer, represented as a set of joints and bones, controls the animation of the human body model. The muscle layer deforms the skin layer realistically during animation. We create the muscles in that layer using soft objects, also known as blobby objects or metaballs, and deform them through the insertion/origin points of the muscles and the volume-preserving constraints. To deform the skin layer during animation, we bind the skin layer to both the skeleton layer and the muscle layer by finding corresponding joints and muscles of the vertices on the skin layer. We applied the proposed scheme for modeling the upper limb and shoulder of human body in this paper.

Keywords

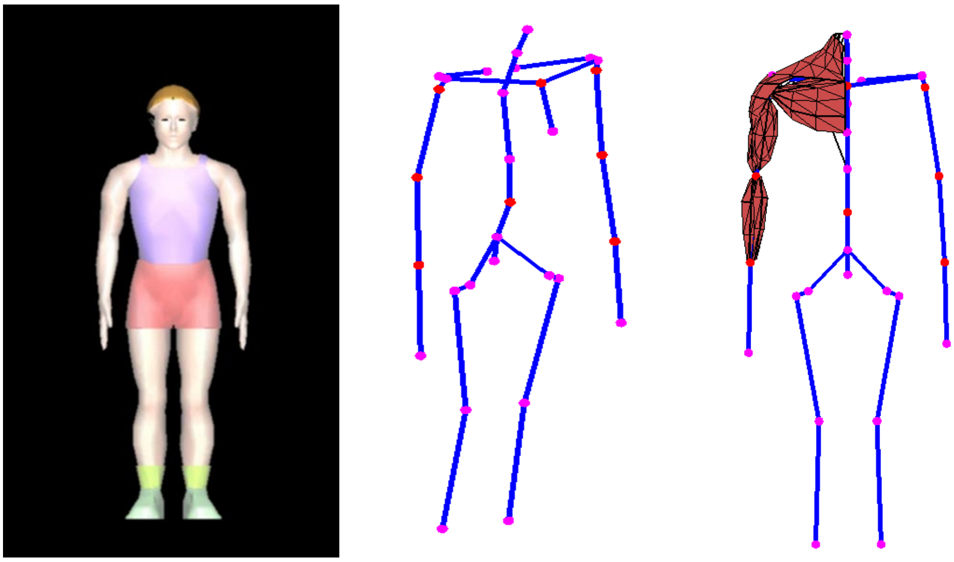
Human body modeling and animation, anatomically-based modeling, soft object, implicit surface, deformation

1. Introduction

Human body modeling and animation has long been an important area in computer graphics and virtual reality. Recently, beyond academic purposes, a need for realistic human body modeling is increasing in the field of entertainment, such as game characters or digital animations. Since the human body has a complex shape, it is difficult to represent the shape using geometric methods such as spline surfaces or superquadrics. Therefore, well-trained designers are required to create a human body model of a realistic shape. These difficulties in modeling the human body can be solved through a sampling method, which creates the shape of the human body by collecting and reconstructing geometric data from real human beings or from sculptures. The development of 3-D digitizing techniques and reconstruction schemes are improving the accuracy and efficiency of the sampling method. The most important problem in creating a human body model using a sampling method is to apply animation to the model, which includes the schemes for both motion control and deforming the shape.

The purpose of this paper is to develop an easy and efficient scheme for deforming a human body model whose shape is created through 3 D digitizing methods. Even though several schemes have proposed [CHAD89, THAL90, THAL91, SING95], they have difficulties in deforming the shape realistically. We apply anatomically-based modeling and animation approaches [SCHE97, WILH97] for this purpose. Scheepers et al. extended Chadwick et al.'s layered structured character model to create muscles in the following three forms: muscle bellies, fusiform muscles, and multi-belly muscles. The skin of the model, generated from the muscles, is deformed according to muscles, which are deformed under the constraint of volume preservation. Wilhelms et al. created muscles as a deformed cylinder, which is similar to the generalized cylinder. They generate the skin of the model by polygonizing the implicit surfaces generated from the muscles and skeletons. While both methods provide a realistic deformation scheme for human body, they provide no method for deforming the human body model created through the 3-D digitizing methods.

In this paper, we propose a layered structure of the human body to provide a realistic deformation scheme for the human body model. The layered structure is composed of three layers: a skeleton layer, a muscle layer and a skin layer. *The skeleton layer* represents the skeletal structure of the human body, which is composed of joints and bones. The motion of the body is controlled by manipulating the angles of the joints. *The muscle layer* represents the muscular structure of the human body. We apply soft objects to create muscles, which are classified into three types according to the primitives of the soft objects. We control the deformation of the muscle through the joint angles of the skeleton layer under the following constraints: the insertion/origin points of the muscle on the bones are attached during animation, and the volume of the muscle is preserved. *The skin layer* is created through the 3-D digitized points of a real human being. The three layers are



(a) The skin layer (b) The skeleton layer (c) The muscle layer

Figure 1. The human body model composed of three layers

illustrated in Figure 1.

The skin layer determines the positions of the joints of the skeleton layer and the geometry of the muscles of the muscle layer. To deform the skin layer realistically during animation, we bind the vertices on the skin layer to the joints of the skeleton layer and the muscles of the muscle layer simultaneously. We implement the global deformation of the skin during animation by applying the rotation of a joint to the vertices on the skin those are bound to the joint. The global deformed shape, however, has some problems: the shape near the joints becomes degenerate, and the local deformed shape of the skin from the deformation of the muscle is not supported. To improve the shape of the skin, we provide local deformation of the skin from the deformed shape of the muscles. The local deformation is implemented by applying the field function of the soft object that represents muscle to the vertices on the skin.

This paper is organized as follows. In section 2, we review the related works on human body modeling and animation. In section 3 and 4, the modeling and animation schemes for the skeleton layer and muscle layer, respectively, are presented. In section 5, the implementation details and results are outlined. Our conclusions and proposals for future work are presented in section 6.

2. Related works

One of the earliest approaches to human body modeling was based on the use of mathematical representations: for example, the stick and surface model in which the human body is modeled as a set of patches [WITH].

The first human body models exhibiting a reasonable degree of realism and motion control capability were developed by the Thalmanns and Badler. The well-known Marilyn and Humphrey models created by the Thalmanns et al. were implemented with sampled data from sculptures [THAL90]. The Marilyn and Humphrey models permitted skin deformation during motion through the Joint-dependent Local Deformation (JLD) operators [THAL91]. Badler introduced Jack, whose shoulder was accurately modeled as a clavicle and shoulder pair. Badler adjusted the spatial relationship between the clavicle and shoulder based on the position and orientation of the upper arm [BADL92].

Chadwick et al. have introduced other new and innovative approaches to human body modeling[CHAD89]. They developed a structured layered model based on anatomy and physiology. In the structured layered human model, each layer has a specific purpose; for example, the skeleton layer is designed for motion control, and the skin layer is used to model shape. Scheepers et al. further refined the human-body model based on anatomy [SCHE97]. In this model, they proposed to have three layers: skeleton, muscle, and skin; the skeleton layer controlled the motion of the human. Changes in the skeleton and muscle layers caused the deformation of the skin layers. Wilhelms et al. proposed a human-body model whose muscles were modeled using deformed cylinders and skin from the polygonization [WILH97]. Maure et al. proposed a musculo-skeletal model of the human upper limb based on biomechanics for dynamic simulation [MAUR96].

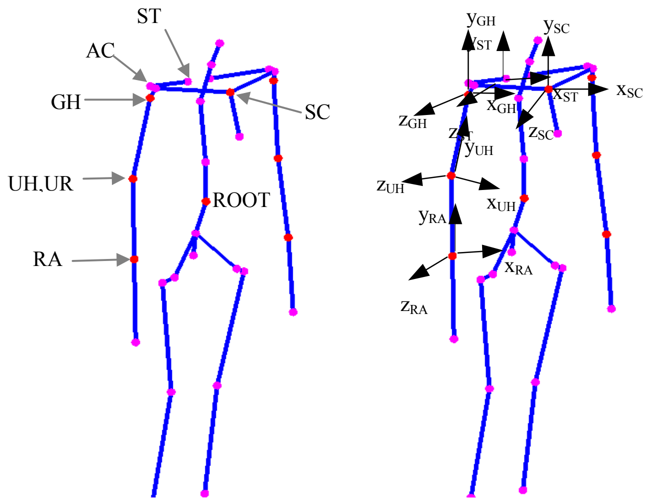
3. Modeling and animation of the skeleton layer

3.1 Modeling of the skeleton layer

The skeletal structure of the human body is defined as a set of joints and bones. Relation between the joints are represented as a tree structure, whose root node is at the center of the body, and leaf nodes are located at the leaves of the limbs, such as hands or feet. In this paper, we model four joints of the upper arm and three joints of the shoulder. The joints of the upper arm are the radiocarpal articulation joint (RA), the ulno-humeral joint (UH), the ulno-radial joint (UR), and the gleno-humeral joint (GH); the joints of the shoulder are the acromio-clavicular joint (AC), the sterno-claviclular joint (SC), and the scapulo-thoracic joint (ST). The positions and the local axes of the joints are illustrated in Figure 2. The lengths of the bones are determined from the skin layer to which the skeleton layer is attached.

3.2 Animation of human body using the skeleton layer

To animate a human body by manipulating the skeleton layer, we bind polygons on the skin



(a) The joints in upper arm and shoulder

(b) The local coordinates of the joints

Figure 2. The joints in the upper arm and shoulder and their local coordinates

layer onto the appropriate joints of the skeleton layer [MIN99]. Before defining the binding relation, we define a distance metric between a face on the skin layer and a joint on the skeleton layer. Let us denote the centroid of a polygon *f* as f_c, and a child joint of a joint *v* as *child(v)*. Consequently, *d (f, v)*, the distance between *f* and *v* is defined as

$$d\,(f,\, v\,) = min\,(\,|f_c - v|,\, |f_c - child(v)|,\, |f_c - l(v)| + \delta(v)\,),$$

where *l(v)* is a line segment whose endpoints are *v* and *child (v)*, and $\delta(v)$ is an offset for the correct binding. A polygon *f* on the skin is *bound* to a joint *v*, if *d (f, v)* is minimum among all the joints in the skeleton layer. However, this binding strategy entails a problem: the polygons in some parts of human body may have the wrong binding. For example, the skin under the arm part of the upper body is bound to the upper arm, since it is located closer to the upper arm than the upper body. This improper binding is corrected by assigning $\delta(v)$ to each joint, which is an offset value determined from the width and the position of the body parts.

4. Modeling and animation of the muscle layer

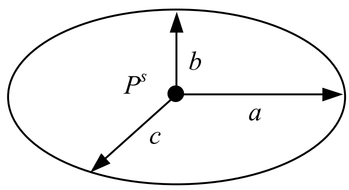
4.1 Modeling of the muscle layer

We apply soft objects to create muscles. A soft object is defined as a set of points that satisfy $f(p) = 0$, where $f(p)$ is named as a *field function*. In specifying a field function, we design a simple geometric object, named as a *primitive*. From this strategy, the input for the field function is the distance from the primitive to a point, which is normalized by the *radius*. Consequently, a soft object, denoted as s_i, is specified as a triple of $\{p_i, f_i, r_i\}$, where p_i is the primitive, f_i is the field function, and r_i is the radius [MIN00]. With multiple primitives, the field function is computed as a sum of the individual field functions from individual primitives.

Each muscle is connected to the bones at two points: the origin point and the insertion point. The origin point does not move, while the insertion point is translated due to the motion of the joint. The muscle is deformed by translating the insertion point of the muscle.

Three different types of primitives of soft objects are applied for modeling different shapes of muscles. The first primitive is *a point primitive*, which generates an ellipsoid. In representing ellipsoids, we specify the lengths and the directions of the three axes, as well as the position of the point primitive. The soft object defined by point primitive is denoted as S^P, the point primitive is denoted as p^s, and the lengths of the three axes are denoted as (a, b, c). The insertion point and the origin point of S^P are denoted as $S^P\,(p_i)$, and $S^P\,(p_o)$, respectively. The data structure for this soft object is illustrated in Figure 3 (a), and the shape of S^P is illustrated in Figure 3 (b). We model biceps brachii and triceps brachii of the upper arm by using this soft object.

```
struct Muscle_Point {
    float ps[3];
    float a, b, c;
    float dir[3];
    float r;
    float pi, po;
};
```



(a) Data structure for S^P (b) Shape for S^P

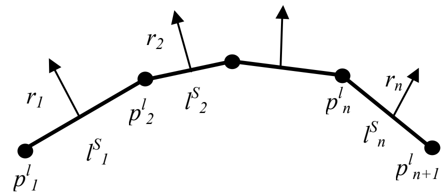
Figure 3. Modeling muscles using S^P

The second primitive is *a set of linked line segments*, which generates a generalized cylinder. The soft object defined by the set of linked line segments primitive is denoted as S^L, and the line segments are denoted as $L^s = \{l^s_1, l^s_2, ..., l^s_n\}$, where each l^s_j' is an individual line segment. Each l^s_j is defined by two points $\{p^l_j, p^l_{j+1}\}$ and radius r_j, for $1 \leq j \leq n$. The insertion point and the origin point of S_L are denoted as $S^L\,(p_i)$, and $S^L\,(p_o)$, respectively. The data structure for this soft object is illustrated in Figure 4 (a), and the shape is illustrated in Figure 4 (b).

The third primitive is *a triangular mesh*, which generates a complex shape that cannot be created using the previous two soft objects. We apply this object to model complex muscles such as deltoid, pectoralis major, and trapezoid. The soft object defined by triangular mesh is denoted as S^T, and the triangular mesh is denoted as $T^s = \{t^s, t^s_2, ..., t^s_n\}$, where each t^s_k's are individual triangles, where each t^s_k is defined by three points $\{p^t_a, p^t_b, p^t_c\}$ and radius r_k. The insertion point and the origin point of the muscle are represented as S^T are $S^T(p_i)$, and $S^T(p_o)$, respectively. The data structure for this soft object is illustrated in Figure 5 (a), and the shape is illustrated in Figure 5 (b).

```
struct Muscle_Lines {
    float pl[n+1];
    float r[n];
    float pi, po;
};
```

(a) Data structure for S^L

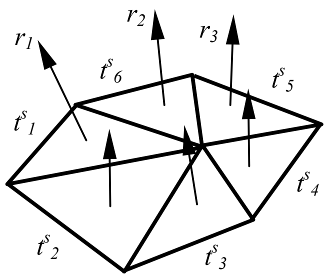


(b) Shape for S^L

Figure 4. Modeling muscles using S^L

```
struct Muscle_TMesh {
    float trig [n][3];
    float r[n];
    float *pi, *po;
};
```

(a) Data structure for S^T



(b) Shape for S^T

Figure 5. Modeling muscles using S^T

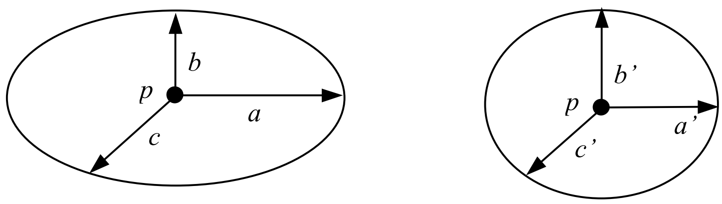
4.2 Deformation of the muscles

The shape of the muscle is deformed under two constraints: the insertion point of the muscle is translated according to the motion of the joint. The volume of the muscle is preserved. According to the constraints, the muscles of each type are deformed as follows:

- Muscles modeled by S^P

  The distance between the insertion point and the origin point is changed, which indicates the change of the length of an axis of S^P. Let a be the length between $S^P(p_i)$ and $S^P(p_o)$. From the translation of $S^P(p_i)$ to $S^P(p_i')$, a becomes to a', which is defined by $|S^P(p_i') - S^P(p_o)|$.

  Volume of S^P, denoted as $V(S_P)$, is approximated as $(4/3)\pi a\, b\, c$, which is the volume of an ellipsoid. Since a becomes to a' under the translation, $V(S^P)$ is changed to $(4/3)\pi a' b' c'$, where b' and c' are lengths of the changed axes. Let us assume that $b'$is proportional to c' as b is proportional to c. From this assumption, we select k such that $k = c/b = c'/b'$. Since we have a constraint of volume preserving, $V(S^P) = (4/3)\pi a\, b\, c = (4/3)\pi k\, a\, b^2 = (4/3)\pi k\, a'\, b'^2$. From this, $b' = b\sqrt{a/a'}$ and $c' = k\, b'$. The deformed shape is illustrated in Figure 6.



(a) Shape before deformation (b) Shape after deformation

Figure 6. Shape deformation of S^P

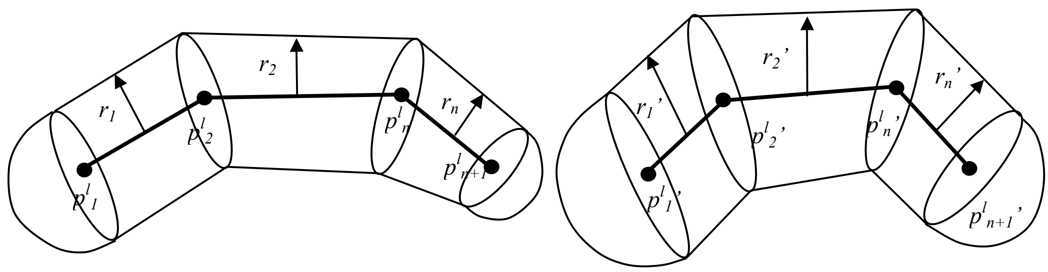
- Muscles modeled by S^L

Under the motion of the related joint, the position of $S^L(p_i)$ is translated to a new position, denoted as $S^L(p_i')$. Since $S^L(p_i)$ corresponds to p^l_{n+1}, the $(n+1)$-th point of L^s, the internal points of L^s are translated to new positions. The direction of translation is $(S^L(p_i') - S^L(p_i))/|S^L(p_i') - S^L(p_i)|$, and the length of translation for each point p^l_j is determined as $|S^L(p_i') - S^L(p_i)| * |p^l_j - p^l_1| / |p^l_j - p^l_{n+1}|$, for $1 \le j \le n$.

$V(S^L)$, the volume of the S^L, is approximated as the sum of $V(S^l_j)$, the volumes of S^l_j, which is the soft object determined from line segment l^s_j and the volume of the hemisphere of the both endpoints. From this approximation,

$$V(S^L) = \sum_{j=1}^{n} V(S^l_j) + \frac{\pi}{2}(r_1^2 + r_n^2), \text{ where } \quad V(S^l_j) = \pi r_j^2 l_j$$

We assume that $V(S^l_j)$ is preserved for $1 \le j \le n$ and the change of the volume of the hemisphere is negligible. From this, $\pi r_j^2 |l_j| = \pi r_j'^2 |l'_j|$, where $|l'_j|$ is computed as $|p^l_{j+1} - p^l_j|$. Now, r'_j is computed as $r_j\sqrt{|l_j| / |l_j'|}$. The deformed shape is illustrated in Figure 7.



(a) Shape before (b) Shape after deformation

Figure 7. Shape deformation of S^L

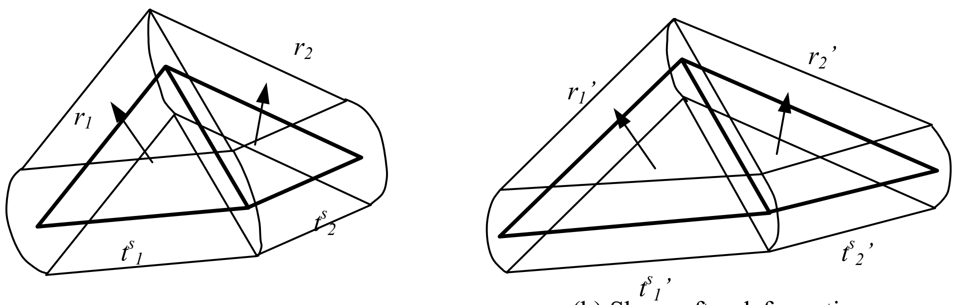
- Muscles modeled by S^T

Suppose $S^T(p_i)$ is translated to a new position, denoted as $S^T(p'_i)$. The new position of each internal point in the triangular mesh is computed similarly to the previous case. $p^t_k{}'$, the new position of point p^t_k, is determined by translating p^t_k along the direction of $(S^T(p_i') - S^T(p_i))/|S^T(p_i') - S^T(p_i)|$ by $|S^T(p_i') - S^T(p_i)| * |p^t_k - p^t_k|/|p^t_k - p^t_{n+1}|$, where p^t_{n+1} corresponds to $S^T(p'_i)$.

$V(S^T)$, the volume of the S^T is approximated as the sum of $V(S^t_k)$, the volume of the soft objects determined from triangle t^s_k and the volumes of the cylinders created from the boundaries of the mesh and the volume of the hemisphere of the corners of the mesh. From this approximation,

$$V(S^T) = \sum_{k=1}^{n} V(S^t_k) + \sum_{l=1}^{m} V(e_l) + \sum_{\omega=1}^{p} V(c_\omega),$$

where $V(e_l)$ is the volume of a cylinder created by a boundary edge, and $V(c_\omega)$ is the volume of the hemisphere created by the corner of the mesh. Now, we assume that $V(S^t_k)$ is preserved and the change of the volume of the cylinder and the hemisphere is negligible. $V(S^t_k)$ is defined as $2\,S(t^s_k)\,r_k$, where $S(t^s_k)$ is the area of the triangle and r_k is its radius. Since the volume is preserved, $2\,S(t^s_k)\,r_k = 2\,S(t'^s_k)\,r_k'$. From the formula, we determine r_k' as $r_k * S(t^s_k) / S(t^s_k{}')$. The deformed shape is illustrated in Figure 8.



(a) Shape before deformation (b) Shape after deformation

Figure 8. Shape deformation of S^T

4.3 Animation of human body using the muscle layer

The sequence for animating skin according to the deformation of the muscle is performed as follows:

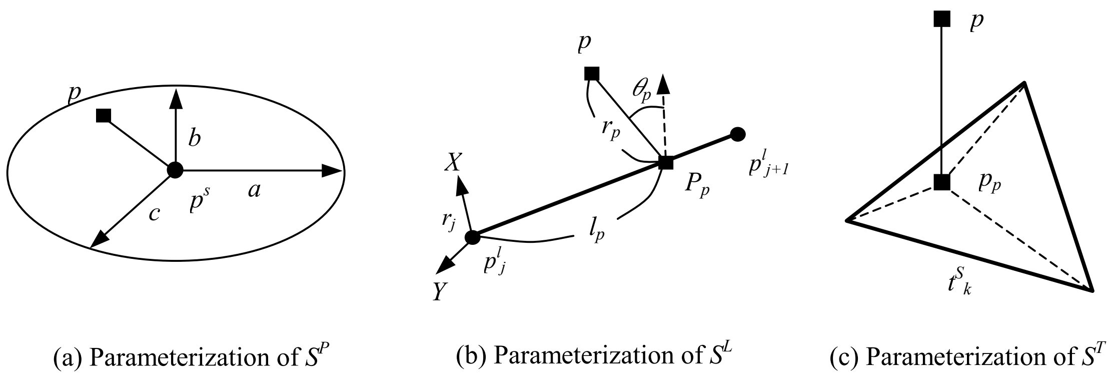
1. Vertices on the skin are parameterized onto the bound muscle.
2. The parameterized vertex is translated to the new parameterized vertex as the muscles to which they are mapped are deformed.
3. We compute the new position of the vertex on the skin from the new parameterized vertex determined in the previous stage.

4. Since the newly mapped vertex may have a different field function value, we translate the vertex to satisfy the field function from the muscle.

A vertex v on the skin is bound to a muscle m, which is represented as $S^m = \{ p_m, f_m, r_m \}$, if the field function evaluated at the vertex, denoted as $f_m(v)$, is greater than some positive value α. Note that α does not coincide with the threshold of the soft object. A polygon f on the skin is bound to a muscle m, if the field function evaluated at the centroid of the polygon, denoted as $f_m(f_c)$, is greater than α.

The parameterization from a vertex on the skin to its bound muscle computes parameters that determine the position of the vertex using the geometry of the primitives of the muscles. For a muscle represented by S^P, a vertex $p = (p_x, p_y, p_z)$ is parameterized as (θ_p, ϕ_p), where $p_x = a \sin \theta_p \cos \phi_p$, $p_y = b \sin \theta_p \sin \phi_p$, and $p_z = c \cos \theta_p$. The parameterization is illustrated in Figure 9 (a). For a muscle represented by S^L, we find l^s_j, which is the nearest line segment to the vertex. Let p_p be the projected vertex of p onto l^s_j and let p be parameterized to a cylindrical coordinate (l_p, r_p, θ_p), where l_p is the distance from p^l_j to p_p, and r_p is the distance from p to p_p, and θ_p is the angle of p on the local coordinate of l^s_j. The parameterization of S^L is illustrated in Figure 9 (b). For a muscle represented by S^T, we find a triangle t^s_k, which is the nearest triangle to p. Consequently, the position of p_p, the projected vertex onto t^s_k, is determined using a barycentric coordinate on t^s_k. The parameters in the barycentric coordinate are used as a parameter of p in S^T. The parameterization of S^T is illustrated in Figure 9 (c).

When the muscle is deformed during animation, the parameterized vertex on the muscle is translated to a new position. From this new parameterized vertex, we locate a new position of the vertex on the skin. However, the field function evaluated at the new vertex may not be identical to α. In such cases, we translate the new vertex to satisfy the field function along the normalized gradient of the field function evaluated at the vertex.



(a) Parameterization of S^P (b) Parameterization of S^L (c) Parameterization of S^T

Figure 9. Parameterization of Vertex

5. Implementation and Results

We implemented the proposed algorithm in a PC platform with Pentium III 550 MHz CPU and 256 MB Memory. The software platform was Microsoft Visual C++ 6.0 with OpenGL libraries. In this section, we show some of the resulting figures of our algorithm. Figure 10 shows the muscles modeled and attached to the skeleton layer. Figure 11 (a) shows the deformation of the muscle according to the motion of abduction of shoulder, and (b) shows the deformed skin. Figure 12 shows the deformation of the skin due to the deformation of the biceps brachii and the continuous deformation of the skin near the elbow.

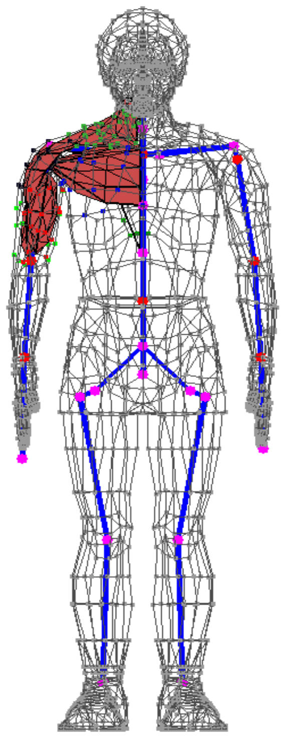
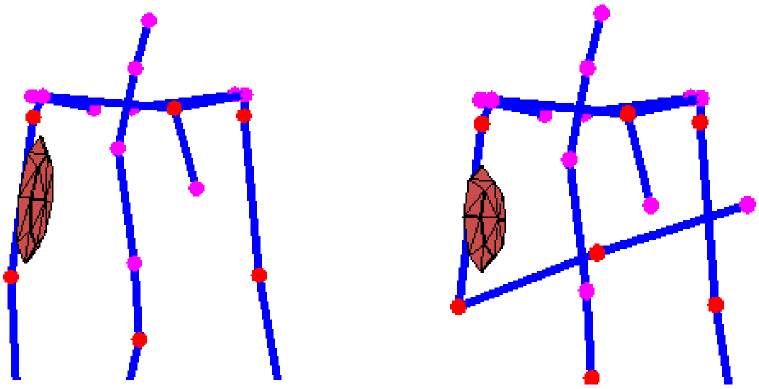


Figure 10. Muscle layer bound to the skin layer

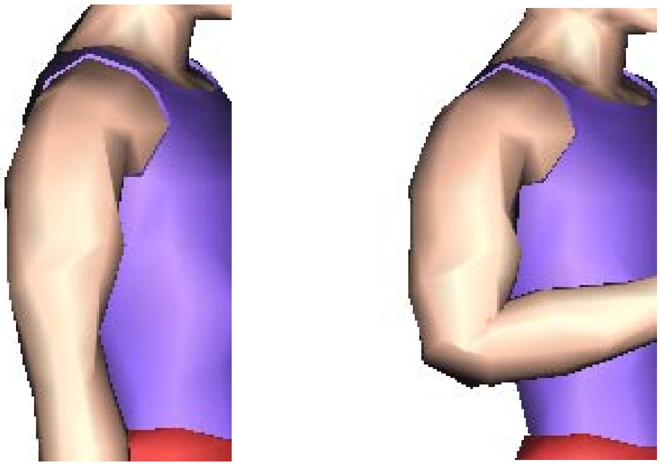
6. Conclusion and Future work

In this paper, we proposed an animation scheme for a human body model whose shape is created through the sampling method. The proposed animation scheme is based on an anatomically-based approach that builds two internal layers of the human body: the skeleton layer and the muscle layer. By using the skeleton layer, we can control the motion of the human body, and with the muscle layer, we can deform the skin layer according to the motion.

The goal of future work is to provide a complete skeleton model and muscle model for the human body. This complete model will include the modeling of legs and trunk. Additionally, the deformation of the skin can be made more realistic by modeling the fatty tissue layer that lies between the skin layer and the muscle layer. We plan to model the fatty tissue layer for the trunk of the human body model.

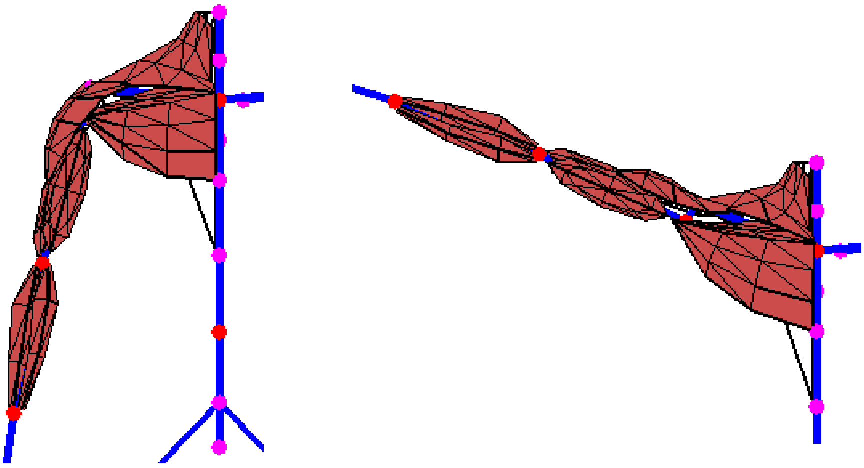


(a) Deformation of the muscle layer

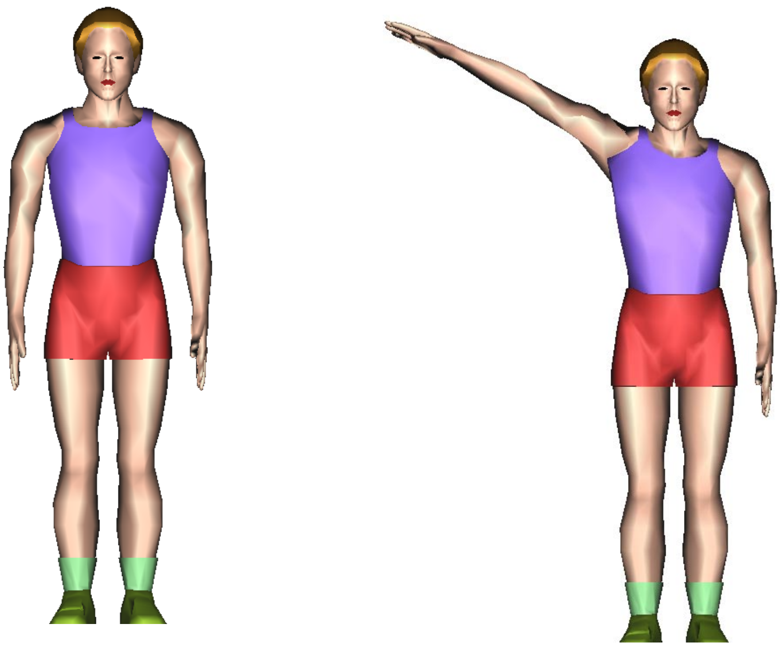


(b) Deformation of the skin layer

Figure 11. Deformation of skin by flexioning of the lower arm



(a) Deformation of the muscle layer



(b) Deformation of the skin layer

Figure 12. Deformation of the skin by abduction of the shoulder

References

[BADL92] Badler, N., “Graphical behaviors and animated agents”, In Advanced Techniques in Human Modeling, Animation, and Rendering. ACM SIGGRAPH Course Note #17, 1992.

[CHAD89] Chadwick, J., Haumann, D. and Parent, R., “Layered Construction for Deformable Animated Characters”, Computer Graphics, Vol. 23, No. 3, July, 1989.

[THAL90] Magnenat-Thalmann, N. and Thalmann, D., “Synthetic actors in computer-generated 3D films”, Springer-Verlag, 1990.
[THAL91] Magnenat-Thalmann, N. and Thalmann, D., “Human body deformations using joint-dependent local operators and finite element theory”, Making them move, Edited by Badler, Barsky and Zelzter, Springer-Verlag, pp. 243-262, 1991.
[MARI95] Marieb, E., `` Human Anatomy and Physiology, 3rd '', The Benjamin/Cummings Publishing Company, Inc., 1995.
[MART92] Martini, F., `` Fundamentals of Anatomy and Physiology '', Prentice Hall, 1992.
[MAUR96] Maurel, W., Thalmann, D., Hoffmeyer, P., Beylot, P., Gingins, G., Kalra, P. and Magnenet-Thalmann, N., “A Biomechanical musculoskeletal method of human upper limb for dynamic simulation”, Eurographics Workshop on Computer Animation and Simulation ’96, pp. 121 – 133, 1996.
[MIN99] Min, K., Choi, H., and Park, M., “Skin deformation for the animation of virtual humans”, International Journal of Virtual Reality, Vol. 4, No. 3, 1999.
[MIN00] Min, K., “Efficient modeling framework of soft objects”, Ph. D. Thesis, Dept. of Computer Science and Engineering, POSTECH, 2000.
[SCHE97] Scheepers, F., Parent, R., Carlson, W. and May, S., “Anatomy-based modeling of the human musculature”, In Computer Graphics Proceedings, Vol. 31, No. 4, pp. 163-172, 1997.
[SING95] Singh, K. and Parent, R., “Implicit Function based Deformation of Polyhedral Objects,'” Proceedings of Implicit Surface '95, pp. 113-128, 1995.
[WILH97] Wilhelms, J. and Gelder, A., “Anatomically-based modeling”, In Computer Graphics Proceedings, Vol. 31, No. 4, pp. 173-180, 1997.
[WITH] Withrow, C., “A dynamic model for computer-aided choreography”, Computer Science Department, University of Utah.