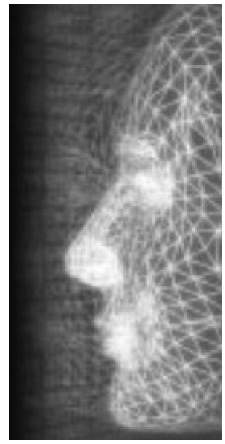
COMPUTER ANIMATION AND VIRTUAL WORLDS
Comp. Anim. Virtual Worlds 2006; **17**: 293–303
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/cav.133

Automatic muscle generation for character skin deformation



*By Xiaosong Yang and Jian J. Zhang**

As skin shape depends on the underlying anatomical structure, the anatomy-based techniques usually afford greater realism than the traditional skeleton-driven approach. On the downside, however, it is against the current animation workflow, as the animator has to model many individual muscles before the final skin layer arrives, resulting in an unintuitive modelling process. In this paper, we present a new anatomy-based technique that allows the animator to start from an already modelled character. Muscles having visible influence on the skin shape at the rest pose are extracted automatically by studying the surface geometry of the skin. The extracted muscles are then used to deform the skin in areas where there exist complex deformations. The remaining skin areas, unaffected or hardly affected by the muscles, are handled by the skeleton-driven technique, allowing both techniques to play their strengths. In order for the extracted muscles to produce realistic local skin deformation during animation, muscle bulging and special movements are both represented. Whereas the former ensues volume preservation, the latter allows a muscle not only to deform along a straight path, but also to slide and bend around joints and bones, resulting in the production of sophisticated muscle movements and deformations.

Received: 10 April 2006; Revised: 2 May 2006; Accepted: 10 May 2006

KEY WORDS: character skin deformation; anatomy-based character animation

Introduction

The realism of an animated character depends both on the motion and the appearance of the character. Skin deformation is thus essential for the animation of human and creature characters. Two broad approaches exist. The first involves the direct deformation of the character's skin, whiles the other is based on the character's anatomy, mainly the muscle shapes. The former approach is collectively known as the smooth skinning or skeleton-driven deformation.[1,†] It has been used in 3D animation production for many years and remains the most popular adopted by the animation industry. Its advantages include intuitiveness to use and efficiency to compute. However, as it employs simplistic shape blending techniques to an inherently very complex matter, it is unable to represent the range of possible skin deformations due to lack of reference to the underlying anatomical structure of the character.

On the other hand, the anatomy-based skin deformation techniques work in a more natural way to the character's body structure. Detailed skin deformation can be achieved by physical simulation of the muscles and skin. In recent years, they have gained increasing popularity. These techniques model characters in a bottom-up fashion, where the animator starts from a skeleton, onto which individual muscles are laid up. The skin as the top layer envelopes and takes the shape of the underlying anatomical structure. This bottom-up process, however, is against the conventional workflow and is both time-consuming and tedious to rig, because it requires the animator to start by modelling muscles rather than the character. Human and creature characters used in film making and games design often have a complex look. Building a character bottom-up by layering

*Correspondence to: J. J. Zhang, National Centre for Computer Animation, Bournemouth Media School, Bournemouth University, Poole, Dorset BH12 5BB, United Kindom.
E-mail: jzhang@bournemouth.ac.uk

†Both smooth skinning and skeleton-driven deformation are interchangeably used throughout the paper. They both mean the same technique.

Contract/grant sponsor: British Arts and Humanities Research Council; contract/grant number: B/RG/AN5263/APN12727.

individual muscles is unintuitive and does not serve well the development of artistic creativities. As such, despite the degree of realism the anatomy-based approach can afford, it has not lived up to its potential in the animation industry and has not been extensively adopted.

Due to the high degree of realism it affords, in this paper, we present a new anatomy (muscle)-based skin deformation technique for the animation of human and creature characters. The main difference of our method to existing anatomy-based techniques is that instead of requiring the animator to build the character in a laborious bottom-up manner by layering individual muscles on a skeleton, we start from an existing model, which can be either modelled or scanned. We then automatically estimate the major muscles, which will deform the skin during animation. Our objective is to retain the advantage of realism of the anatomy-based skinning approach and at the same time make it both easy to use and compatible with the animation workflow.

However, what needs pointing out is that it is mathematically impossible to extract all muscles from the skin shape of one pose. Our intention is not to extract all muscles automatically, but to identify only the muscles that exhibit obvious influence on the skin surface.

The muscles identified are those most important in terms of their contribution to the skin shape. We expect them to pick up most skin details that are vital to the visual quality of the animated character. We identify the muscles by studying the curvature properties of the skin surface. The skin areas not significantly affected by the muscles will thus be relatively smooth. These skin areas can therefore be effectively handled by the traditional smooth skinning technique. In other words, our skin deformation technique will combine the advantages of both anatomy-based and smooth skinning techniques.

In addition, this paper also makes the following contributions:

Existing anatomy-based animation techniques allow muscles to deform along a straight path, which is suitable only to a limited number of applications. To deform and slide muscles on other anatomical components, however, is much trickier. In this paper, we will discuss how muscles bending and sliding around a joint and around a bone can be modelled realistically.

Related Work

Significant improvement in skin deformation has been made over recent years. Many techniques treat the skin as a shell that moves by an explicit function of the skeleton. Vertices of the skin are deformed by a weighted combination of the joint transformations of the character's skeleton.[1,2] Collectively, such methods are known as the smooth skinning. They are easy to understand and intuitive to use. The tricky part is to assign the weights properly. In production, they are given (painted) by the animator, usually with trial and error. This is time-consuming and to achieve quality remains a challenge in certain areas of the body, such as the shoulder area.

As an improvement to smooth skinning, shape interpolation becomes popular recently for representing object deformations, such as the pose space deformation,[1] shape by example,[3,4] multi-weight enveloping[5] and example-based skeleton driven deformations.[6] The problem for this kind of methods is that the animator needs to produce a large number of models in the pose space, which itself is expensive. They require storing potentially large amounts of example data for shape interpolation.

The anatomy-based approach represents another major trend. Thalmann *et al.*[7] presented one of the early anatomy-based techniques using meatballs. Techniques with a higher level of detail on muscle modelling were later developed.[8–11] The obvious advantage of this group of methods is its ability in achieving detailed visual quality during animation. One of the difficulties of these techniques, however, is they are indirect to use as a result of their modelling process. Achieving a particular look of the skin requires the determination of the shape, number and the layout of the muscles underneath. It is not only tedious, but also against the animation workflow where the animator usually starts from an already modelled character that has many subtle skin details needing to be preserved during animation. How to retain the advantage of the anatomy-based approach without using the bottom-up approach was recently studied by several researchers.[12–14] Doug[12] approximated the original deformable animation by estimating proxy bone transformations and vertex weights for deformable shape sequences. Eftychios[13] presented another method to automatically determine muscle activations from tracking a sparse set of surface landmarks. But the muscle model was constructed from a volumetric data in the bottom-up manner. Pratscher[14] segmented a human character into regions and associated two ellipsoidal muscles to each of the region. These ellipsoids are then deformed to conform to the skin shape. To deform the skin during animation with these simplistic muscles, geometric functions including volume preservation are used. However, as they use only a pair of muscles for each moving region, the deformation it can offer is limited and only simple deformation shapes can be represented. In addition, not all characters are muscular and the influence of muscle is not always visible in all skin areas. Smooth skin areas cannot usually be realistically deformed using muscles.

In this paper, we present a new muscle-based skinning method, whose objective is to combine the advantage of the anatomy-based approach with that of the smooth skinning. It aims to achieve visual realism without burdening the animator with the need of building characters in a bottom-up fashion. We start from an already modelled character rather than the other way around. Our method can deform both muscular and smooth skins.

Overview

Similar to most existing anatomy-based approach,[15–19] ours is also a three-layered skin animation system, which consists of a skeleton layer, a muscle layer and a skin layer. But the process starts from an existing skin surface model scanned or constructed by the animator. Briefly, our method works as follows:

- For a given character (with both skin surface and a skeleton), by studying the skin surface properties, we estimate the shape and position of the major muscles that contribute significantly to the skin shape at the rest pose. These muscles are automatically extracted. They offer the default setup of the anatomic structure for the character. The animator is allowed to choose which muscles to use and edit them to perfect the shape and size of the muscles.
- Following skeleton movement, the muscles will deform observing necessary deformation properties, such as volume preservation. They are not only able to stretch and squash, but also bend and slide around bones and joints to mimic the complex muscle deformations.
- As we estimate only the major muscles, which will not cover all skin areas of the character, the deformation of the remaining skin areas unaffected by the muscles will be dealt with by the traditional smooth skinning technique. This approach allows different skin types and characters to be skinned effectively. Since smooth skinning is a well-established technique and has been introduced by many publications, in this paper we will focus on the discussion of the muscle-related issues.

The rest of the paper is organised as follows. Muscle extraction and deformation are presented in the next section. The section ‘Skin Deformation’ discusses the hybrid skin deformation technique. The results are given in the ‘Result’ section. The last section concludes the paper where we also discuss possible future work.

Muscle Extraction and Deformation

Muscles are complex anatomical elements whose shape and motion determine the surface shape of the skin that they support. Muscles are usually positioned on top of bones and other muscles, some of which span multiple bones. Depending on their state of contraction, muscles can have different shapes and can influence the skin surface differently. A skeletal muscle typically has a contractile belly that determines the shape and two tendons at both ends, known as the origin and the insertion.

One point to be noted is that our goal here is not to reproduce physical reality. It would be extremely difficult to speculate the real muscle structure from the skin surface; and in terms of animation there is no pressing need for such accurate modelling. What is essential, however, is to offer the animator a flexible toolkit where he/she can produce skin deformation both with control and with minimal unnecessary manual preparation. This is achieved in our system by estimating an initial muscle structure automatically according to the input character model. Due to the complexity of the human body structure and the diversity of the artistic intention, this derived initial muscle model serves only as a starting point, and the animator can further edit the shape and position of the muscles, choose which muscles to use.

Muscle Extraction

Most animated human and creature characters have a complex shape. For the purpose of storytelling, building a character by layering many individual muscles is sometimes distracting and does not help the development of artistic creativity. In this section, we discuss a technique that constructs muscle models directly by analysing a given skin shape.

Profile Curves of Skin Model. Curvature is a good indicator to the change of a surface shape. Surface bumps can be identified by analysing the distribution of curvature properties. Here we present a cross-section-based method for the analysis of the local curvature properties of a surface. The cross-sections are arranged according to the skeleton structure of a character body. Because almost all muscles are linked between skeletal bones, cross-section curves can best represent the muscle shapes whenever the cross-section planes are perpendicular to the central line of the muscle. For an arm or leg, the distribution of the cross-sections is straightforward (Figure 1(a)). Figure 1(b) shows the final extracted cross-section curves for the monster's arm.

For the torso, there are several muscle groups following different directions. Two big muscle groups are centred at the shoulders. Another typical group is around the neck to control the head movement. For both, we use different cutting surfaces to extract the profile curves.

For the abdominal regions, parallel horizontal cutting planes are adopted. Figure 1(c) illustrates the cutting surfaces for different regions. What's to be noted is that the cutting surface groups in different regions may overlap. But each muscle group will be handled by the dominating cutting surface group.

Identification of Potential Muscles. Identifying muscles using profile curves in the neck, chest and abdominal regions is relatively straightforward. This is because these profile curves are approximately planner. Therefore, variations of the profile curves can be easily identified leading to the recognition of potential muscles.

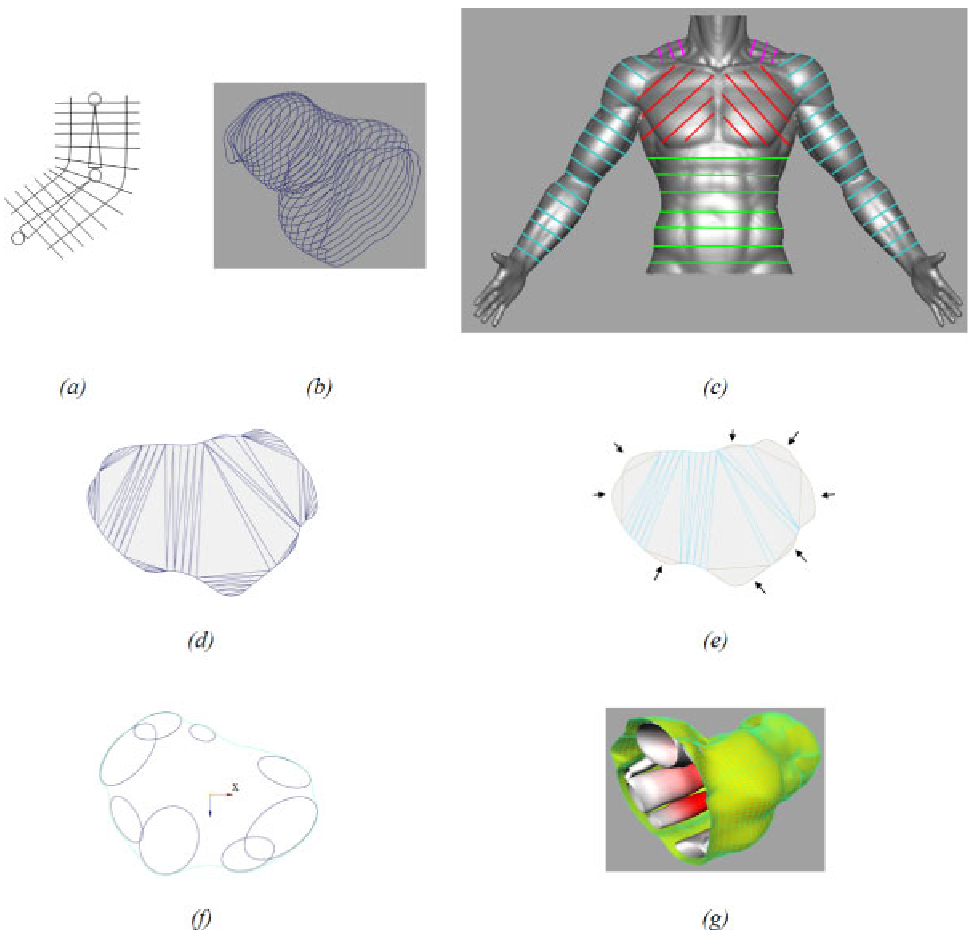


Figure 1. Muscle Extraction: (a) Cross-section planes for an arm or leg; (b) cross-section curves extracted for the monster's arm; (c) Illustration of cutting surfaces for different muscle groups; (d) constrained delaunay triangulation; (e) triangle merge result from CDT (arrows pointing out the potential muscles); (f) muscle cross-sections; (g) construction of 3D muscle models.

To extract major muscles in the limbs is less easy. In the following we discuss how muscles in these body regions can be identified and automatically generated.

To identify the potential muscles, we need to identify and mark out the bulged areas from each body region, such as an arm. This is achieved by identifying the 'bumps' from all the cross-section curves and linking them together. Each such bump is likely to correspond to a muscle.

Cross-sections are closed planner curves. To identify the bulges resulting from the underlying muscles, we approximate each cross-section curve by a closed polyline. Constrained delaunay triangulation (CDT)[20] is used to generate a triangulated mesh within this region. Figure 1(d) shows such a mesh, from which one can see several possible bumps arising and they are related to the potential muscle deformations on the character's skin.

To identify the bumped regions, we collapse the local triangles in these bulged regions along the boundary of the mesh using an algorithm presented in Reference [21] for pruning branches of a triangulated mesh. Triangles are classified into three types: terminal triangles (with two external edges), sleeve triangles (with one external edge) and junction triangles (with no external edge). We then merge all the triangles within the local bulged region using the so-called semicircle rule. The procedure works as follows. First, we start from a terminal triangle and draw a semicircle using the internal edge as its diameter. The semicircle is on the same side as the triangle. If all vertices of the triangle lie on or within the semicircle, the internal edge is removed allowing it to be merged with the adjacent triangle. We then draw another semicircle using the internal edge of the newly merged triangle as diameter. The semicircle should be on the same side of the two merged triangles. If all the vertices of the merged triangles are on or within the semicircle, the internal edge, which is currently used as the diameter of the semi circle, is removed and a further adjacent triangle is merged into the region. This procedure carries on until the merging process reaches a junction triangle or when at least one vertex of the merged region lies outside the semicircle. The arrived merged region is a bulge on the boundary of the cross-section curve and is likely to correspond to a muscle. Figure 1(e) shows the result of the merged triangles, where eight bumps are identified indicating eight potential muscles affecting this cross-section. To identify all affecting muscles for each body region, all cross-section curves have to go through this merging operation.

Construction of 3D Muscle Models. The human body is a very complex structure. To identify and define all muscles from the surface model is mathematically an under-specified problem. Our goal is only to construct a basic muscle structure.

In our method, we use an ellipse as the basic form of the muscle's cross-section. Five parameters (C_x, C_y, θ, a, b) are needed to define each ellipse. Here C_x, C_y are the coordinates of the centre, θ is the rotation angle between its long axis and x-axis, a and b are the ellipse's two axis. To solve for these parameters, we can use any curve fitting algorithms. However it needs to be pointed out that not all the vertices in the identified region are involved and not all vertices have the same contribution to the final ellipse. The start triangle of the merge operation, that is the terminal triangle, has the highest weight to the fitting process. As the vertices move away from the terminal triangle, they have increasingly less contribution to the final shape. Figure 1(f) shows the constructed muscle cross-sections. Some muscles intersect, which seems contradictory to the physical reality. Nevertheless, since only a small portion of an ellipse affects the appearance of the skin surface, this doesnot cause a problem in our experience.

Once muscle cross-sections are constructed for all cutting planes, we are able to link them all together to form a 3D muscle model. However, since only a part of the muscle is visible on the skin surface, the derived cross-sections do not represent the whole muscle. The remaining part of the muscle between the last recognised cross-section (end cross-section) and the extremity point, origin or insertion, has to be extrapolated. Many blending methods can be used to solve this problem. In our development, we employ a closed mesh whose axial profiles are represented with Hermit curves, which link the end cross-section with the extremity point, as they ensure tangent continuity at the connection.

If a muscle has only one branch, we can simply loft the adjacent ellipses to form a closed surface mesh. In some cases, however, bifurcation or even multiple branches exist. To get around this problem, we place an auxiliary transition curve at the intersection of the joining branches, in a similar way to [22]. Figure 1(g) shows the final 3D model.

User Control. The muscles extracted so far serve as an estimate of the internal structure of the character. The purpose of establishing this initial muscle structure is to relieve the animator from the tedious muscle building and layering tasks, allowing him/her to concentrate on the quality of the animation. This overcomes the primary problem that existing anatomy-based skinning techniques suffer.

In order for the muscles extracted to satisfy the user's intention, it is important that the user is able to exercise his/her control over the process. To this end, we provide three options. The first one is that the user can choose which muscles to be extracted by marking out a corresponding region on the skin. The system then ensures the user-identified muscles are extracted. Second, the user is given freedom to selectively remove muscles or add additional muscles. In the case of Figure 1(g), for instance, the animator may well choose to use only two or three major muscles, instead of eight! Finally, we allow the animator to edit the muscles including their shape, size and the locations of the extremity points (insertion and origin).

Muscle Deformation

For each muscle, we can link the centre of each ellipse to form a curve, which we call the root curve. It defines the central path of the muscle. The default positions of the extremities of the muscle are decided by extending the root curve at the ends of the muscle to the skeletal bones. The nearest point of the extension part of the root curve to the bone is regarded as a default extremity point (insertion or origin). In any case, the animator is able to edit these points to achieve a desired result.

During animation, muscles are stretched or bulged by the motion of the linked bones. It is important that the muscle volume is preserved during animation. Each muscle has three defining components: the root curve, the cross section ellipses and a surface mesh. The root curve has a similar function to the action line[23] and is used to deform the muscle surface mesh.

Each cross section ellipse has two dimensions (a_i, b_i), and a u_i parameter, which is defines its position on the root curve, where $u_i \in [-1,1]$. In order to preserve the volume of the muscle during motion, we define a factor k to control the bulge effect just like we did in Reference [24]. Figure 2(a) shows the volume preserved bulge effect of a muscle model.

Muscle Movement

The root curve controls how a muscle deforms. Skeletal muscles move fairly freely and can take various movement forms. In this section, we discuss three types of typical muscle movements: straight line movement; bending around a joint; and bending around a bone. Although the first was fairly straightforward, the latter two are much trickier, and their modelling directly impacts upon the realism of animation.

Straight Line Movement. This is the simplest form and is easily modelled. The movement of the muscle surface is completely determined by the insertion and origin points. These two points form the base of the transformation.

Bending Around a Joint. Some muscles or tendons wrap around a joint (Figure 2(c)), such as the medial head of the triceps. Comprehensive simulation of such movement involves a number of issues including collision avoidance and sliding between the muscle and the joint, and therefore can be computationally expensive.

In order to satisfy the visual quality without involving expensive calculations, we represent the joint with a virtual sphere whose radius is specified by the user. The length of the muscle is divided into three sections, as shown in Figure 2(b), and each section is computed within its own local co-ordinate system. P_o and P_i are the tangent points from the origin and insert to the virtual sphere of the joint, respectively. All these points are on the same plane determined by the origin, insertion and the joint centre J. The X-axis bends around the joint. For section I, the X-axis of the coordinate system is a straight line from the origin to P_o. It is the same for section III, except that the X-axis starts from P_i to the insertion. For section II, the X-axis bends around the joint sphere.

As the X-axis of all three sections are continuously linked, the muscle can slide around the joint seamlessly resulting in realistic results (Figure 2(c)). This simulation is very useful for the simulation of the muscle sliding effect under a skin surface.

Bending Around a Bone. In some cases, muscles bend around a bone, such as the brachialis, which starts from the origin on the anterior surface of the humerus shaft, continuing around to the lateral side of the bone, reaching the insertion on the ulna. This is the most complicated movement among the three types.

We formulate this problem in a similar way to the second type of movement. The X-axis continues from the origin through two tangent points on the virtual cylinder of the bone to the insertion point. The local coordinate systems on the root curve of the muscle are marked out in Figure 2(d).

In order to find the two tangent points on the virtual cylinder, we use two types of coordinate systems

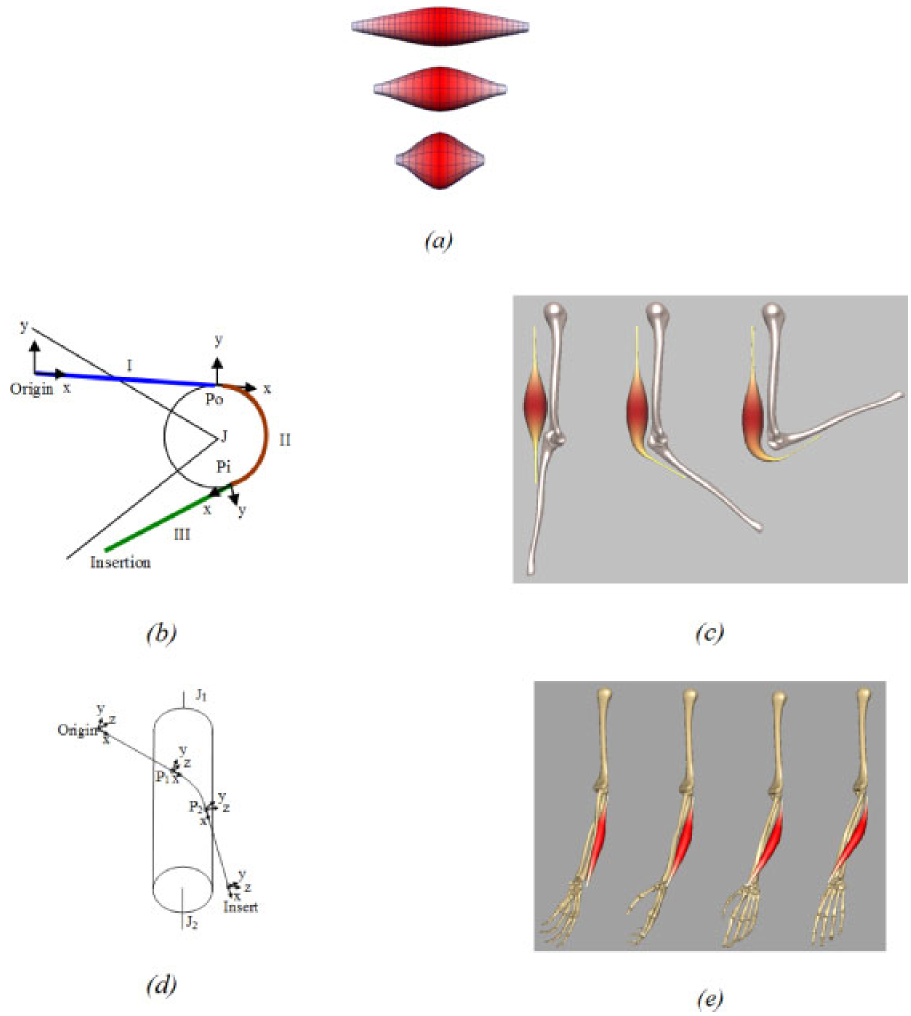


Figure 2. Muscle deformation: (a) Muscle bulge effect; (b) local coordinate systems for muscles bending around a joint; (c) examples for muscle bending around a joint; (d) local coordinate systems for muscles bending around bones; (e) examples for muscle bending around bones.

together, cylindrical and Cartesian systems. The coordinates of two tangent point P_1 and P_2 are defined as:

	Cylindrical	Cartesian
P_1	(θ_1, h_1)	$(r\cos\theta_1, r\sin\theta_1, h_1)$
P_2	(θ_2, h_2)	$(r\cos\theta_2, r\sin\theta_2, h_2)$
P	$(\theta, h) = (\theta_1 + t \times (\theta_2 - \theta_1), h_1 + t \times (h_2 - h_1))$	$(r\cos\theta, r\sin\theta, h)$

where P is the point on the curve between point P_1 and P_2 on the cylinder surface, r is the radius of the cylinder. The tangent direction at point P is $V_t = (-r\sin(\theta)\ (\theta_2 - \theta_1),\ r\cos(\theta)\ (\theta_2 - \theta_1),\ (h_2 - h_1))$ in the Cartesian system. Let the coordinates of the origin and insertion be (x_1, y_1, z_1) and (x_2, y_2, z_2). In order to find the four unknown variables $(\theta_1, h_1, \theta_2, h_2)$, we consider the following relations:

$$\begin{aligned} \vec{v}_1 &= k_1 \vec{v}_2 \\ \vec{v}_3 &= k_2 \vec{v}_4 \\ \vec{v}_1 \cdot \vec{v}_5 &= 0 \\ \vec{v}_3 \cdot \vec{v}_6 &= 0 \end{aligned} \tag{1}$$

where k_1 and k_2 are two unknowns to be determined and

$$\vec{v} = (r\cos\theta_1 - x_1, r\sin\theta_1 - y_1, h_1 - z_1)$$
$$\vec{v}_2 = (-r\sin\theta_1(\theta_2 - \theta_1), r\cos\theta_1(sin\theta_2 - \theta_1), h_2 - h_1)$$
$$\vec{v}_3 = (x_2 - r\cos\theta_2, y_2 - r\sin\theta_2, z_2 - h_2)$$
$$\vec{v}_4 = (-r\sin\theta_2(\theta_2 - \theta_1), r\cos\theta_2(\theta_2 - \theta_1), h_2 - h_1)$$
$$\vec{v}_5 = (-r\cos\theta_1, -r\sin\theta_1, 0)$$
$$\vec{v}_6 = (-r\cos\theta_2, -r\sin\theta_2, 0)$$

By solving the above equations, we obtain:

$$\begin{aligned}
\theta_1 &= 2\arctan\left(\frac{y_1 \pm \sqrt{-r^2 + x_1^2 + y_1^2}}{r + x_1}\right)\\
\theta_2 &= 2\arctan\left(\frac{y_2 \pm \sqrt{-r^2 + x_2^2 + y_2^2}}{r + x_2}\right)\\
k_1 &= \frac{r\cos\theta_1 - x_1}{-r\sin\theta_1(\theta_2 - \theta_1)}\\
k_2 &= \frac{x_2 - r\cos\theta_2}{-r\sin\theta_2(\theta_2 - \theta_1)}\\
h_1 &= \frac{z_1 + k_2 z_1 + k_1 z_2}{1 + k_1 + k_2}\\
h_2 &= \frac{z_2 + k_2 z_1 + k_1 z_2}{1 + k_1 + k_2}
\end{aligned} \tag{2}$$

Notice that (θ_1, θ_2) have multiple possible solutions, where the user is asked to indicate the correct solution. In our implementation, the animator can use locators to define how the muscle wraps around a specified bone. Figure 2(e) shows a simple slim muscle sample starts from the left of the above bone, bending around it from the back to meet the insertion point on the right of the nether bone.

Skin Deformation

Once the muscles and their deformations have been generated, we are now in a position to produce the final skin shape of a character. However, although we have extracted the major muscles that visually affect the skin shape, other muscles that have little or no visual influence on the skin at the rest pose (i.e. those that do not bulge significantly) cannot be picked up by our aforementioned muscle extracting method. Further, characters can be muscular or feminine. Only a small number of muscles are visible for the latter type. Thus using the above method, it is inevitable that some skin areas cannot be well represented.

The popular smooth skinning technique, which is well described in Reference [1] is effective in areas where the skin surface is relatively smooth, but falls short when surface curvature varies significantly. This is because in these areas the surface is determined by the muscles underneath the skin, which have a complex structure and exhibit sophisticated motion and deformation patterns.

In this section, we present a hybrid skin deformation technique, which animates the skin surfaces using both the identified muscles and the traditional smooth skinning approach, allowing each method to play their strengths. But this means we will need both muscle and skin models. Fortunately, our approach starts from an already modelled character. Unlike other muscle-based techniques where the skin surface arrives only after all the underlying muscles have been modelled and placed, we donot need to compute the skin surface from scratch. The skin surface already exists at the rest pose.

Mathematically speaking, our hybrid technique can be viewed as an extension of the skeleton-driven deformation. Without involving muscles, the treatment is the same as that of the traditional smooth skinning, where each vertex is assigned a set of influencing joints together with a weight factor corresponding to each influencing joint. Deforming the character into a different pose involves transforming each vertex from the initial pose by all the influencing joints. The transformed positions are then blended together to give the final position of all the vertices. At a skeletal configuration c, a deformed vertex, V_c, can be computed by[4]:

$$V_c = \sum_{i=1}^{n} w_1 M_{i,c} M_{i,d}^{-1} V_d \tag{3}$$

where w_i are the weights, V_d is the location of a vertex at its initial pose, $M_{i,c}$ denotes the transformation matrix associated with the ith joint in configuration c and $M_{i,d}^{-1}$ the inverse of the transformation matrix associated with the ith influencing joint at the binding pose.

When the extracted muscles are used to deform the skin at relevant areas, each muscle is regarded as composed of several joints along its root curve. However, associated with each joint, the transformation has both rotational elements and a scaling factor that represents the degree of dilation of the muscle. This allows the influences of the muscles to be straightforwardly represented using Equation (3). The advantage of this strategy is that both smooth skinning and muscle deformation are formulated in a unified manner and can be implemented very easily, that is we still use Equation (3) to displace the skin vertices. The weighting factors control how skin is affected. In a muscular skin area, the muscles are given a dominating weight; in a smoother skin area, the weights to the muscles will be either zero or sufficiently small. Again, the user is able to edit the weights to tune the results.

RESULTS

We have implemented the above-discussed technique in a form of a plug-in of the animation package Maya. We tested it on two different characters, a monster character, which is extremely muscular, and an ordinary male character, which has both bumpy and smooth skin areas.

For the monster character, major muscles were extracted. The skin and some muscles are shown in Figure 3(a). By animating the skeleton, the extracted muscles were deformed, which in turn deform the skin. Figure 3(b) shows some snapshots of the animated monster character by the hybrid skin deformation technique.

The animation of the other less extreme male character would prove very challenging if using the current smooth skinning technique, especially in the neck, shoulder and elbow areas. The first step is to estimate and generate the major muscles, which can be further edited by the user. Figure 3(c) shows the skeleton and the major muscles of the torso. Then we can animate the muscles by animating the skeleton. As explained earlier, muscle deformation takes into account simple properties, such as volume preservation, as well as more supplicated motion and deformation patterns, including sliding around joints and bones. This ability is essential for achieving realistic muscle deformations (Figure 3(d)). Figure 3(e) gives the superimposed result of

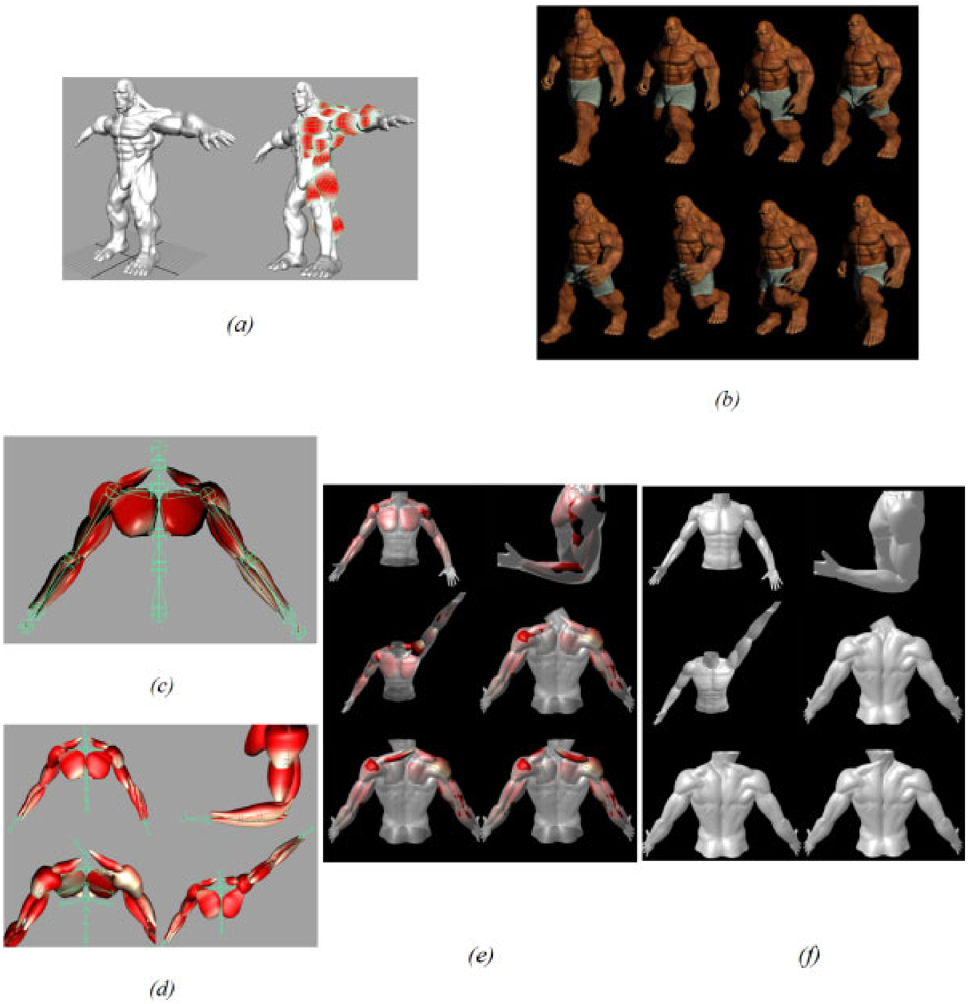


Figure 3. Examples for character skin deformation: (a) monster character and major muscles; (b) animation of textured monster character; (c) skeleton and extracted major muscles of the torso for the ordinary male character; (d) muscle deformation; (e) superimposed muscle deformation and smooth skinning deformation (SSD); (f) final skin deformations.

muscle deformation and smooth skinning deformation. The intersections highlight the differences between these two different skinning techniques. By a weighted combination of both animation results, the final result arrives (shown in Figure 3(f)). It is evident from the figure that the traditionally tricky areas, for example the neck and shoulders, deform visually satisfactorily, and the smoother skin areas behave well too.

Conclusion and Future Work

The anatomy-based skinning approach is able to achieve detailed realism. The disadvantage, however, is its user-unfriendliness, as it usually requires the animator to build a character by layering many individual muscles before the skin shape arrives.

In this paper we have proposed a new anatomy-based skin deformation technique. The main contributions of this paper are that (1) it can extract the major muscles automatically by studying the surface geometric properties of a character, therefore saving the animator from doing the tedious muscle building work; (2) in addition to simple straight line movements, two more sophisticated muscle movements and deformations are formulated, which are muscle sliding around a joint and sliding around a bone, making it possible to simulate a wide range of complex muscle deformations; (3) a hybrid skin deformation was developed which combines the strengths of both prevalent approaches—anatomy based and smooth skinning. An added advantage of our technique is its compatibility with the current animation workflow, as we start from an already modelled character. Thus the animator is able to continue with their familiar animation practice, rather than being forced to learn a different production approach.

This is our first attempt to make the anatomy-based skin deformation approach in line with the conventional animation practice. Despite its advantages, our experience has revealed some limitations and gaps which should be dealt with in the future:

A key task of the presented technique is to model muscles pertaining to the animation of the body of a character. As skin surface only offers a limited amount of structural information, in our current development, we assume the muscles to have a simple shape, that is having elliptical cross-sections. We believe this is a little too simplistic for complex muscles. Muscles of more sophisticated shapes will need to be considered. The challenge, however, is how muscles of a complex shape can be identified and constructed.

Currently, we have developed three muscle deformation types, that is the straight line movement; sliding around a joint; and sliding around a bone. They cover most muscle deformation types. In the real life, however, muscles deform in a much more sophisticated manner. In the future, we will develop efficient muscle deformation techniques to address the sliding and contact issues between muscles.

Muscles deform due to their physical reactions of the muscle fibres. Involving physics is certainly a promising way forward and is likely to produce more realistic outcomes. However, if a large number of muscles have to be physically simulated, a key question to answer is how to speed up the computation without compromising the accuracy. This will also be included in our future work.

ACKNOWLEDGEMENTS

We are grateful to Autodesk for their donation of the Maya software licences.

References

1. Lewis JP, Cordner M, Fong N. Pose space deformation: a unified approach to shape interpolation and skeleton-driven deformation. In *Proceedings of the 27th annual conference on Computer graphics and interactive techniques*, ACM Press/Addison-Wesley Publishing Co. 2000; pp 165–172.
2. Magnenat-Thalmann N, Laperrire R, Thalmann D. Joint-dependent local deformations for hand animation and object grasping. In *Proceedings on Graphics interface '88* (Edmonton, Alberta, Canada); pp 26–33.
3. Sloan PJ, Rose CF, Cohen MF. Shape by example. In *Proceedings of the 2001 Symposium on interactive 3D Graphics* SI3D '01. ACM Press, New York, NY; pp 135–143. DOI=http://doi.acm.org/10.1145/364338.364382
4. Mohr A, Gleicher M. Building efficient, accurate character skins from examples. *ACM Trans Graph* 2003; **22**(3): 562–568. DOI=http://doi.acm.org/10.1145/882262.882308
5. Wang XC, Phillips C. Multi-weight enveloping: least-squares approximation techniques for skin animation. In Proceedings of the 2002 *ACM SIGGRAPH/Eurographics symposium on Computer animation*, ACM Press, 2002; pp 129–138.
6. Allen B, Curless B, Popovic Z. Articulated body deformation from range scan data. In Proceedings of the 29th annual conference on *Computer graphics and interactive techniques*, ACM Press, 2002; pp 612–619.

7. Shen J, Thalmann D. Interactive shape design using metaballs and splines. In *Proceedings of Implicit Surfaces '95*, Grenoble, pp 187–196.
8. Scheepers F, Parent RE, Carlson WE, May SF. Anatomy-based modeling of the human musculature. In *Proceedings of the 24th annual conference on Computer graphics and interactive techniques*. ACM Press/Addison-Wesley Publishing Co., New York, NY, 1997; pp 163–172. http://doi.acm.org/10.1145/258734.258827
9. Wilhelms J, Gelder AV. Anatomically based modeling. In *Proceedings of the 24th annual conference on Computer graphics and interactive techniques*, ACM Press/Addison-Wesley Publishing Co., 1997; pp 173–180.
10. Nedel L, Thalmann D. Modeling and deformation of the human body using an anatomically-based approach. In *Proceedings of the Computer Animation*, IEEE Computer Society, 1998; 34p.
11. Simmons M, Wilhelms J, Gelder AV. Model-based reconstruction for creature animation. In Proceedings of the 2002 *ACM SIGGRAPH/Eurographics symposium on Computer animation*. ACM Press. 2002; pp 139–146.
12. James DL, Twigg CD. Skinning mesh animations. *ACM Trans Graph* 2005; **24**(3): 399–407. DOI= http://doi.acm.org/10.1145/1073204.1073206
13. Sifakis E, Neverov I, Fedkiw R. Automatic determination of facial muscle activations from sparse motion capture marker data. *ACM Trans Graph* 2005; **24**(3): 417–425.
14. Pratscher M, Coleman P, Laszlo J, Singh K. Outside-in anatomy based character rigging. In Proceedings of the 2005 *ACM Siggraph/Eurographics Symposium on Computer Animation*, SCA '05, ACM Press; pp 329–338.
15. Chadwick JE, Haumann DR, Parent RE. Layered construction for deformable animated characters. In Proceedings of the 16th annual conference on *Computer graphics and interactive techniques*, ACM Press, 1989; pp 243–252.
16. Scheepers CF. *Anatomy based surface Generation for Articulated Models of Human Figures*. Doctoral Thesis, The Ohio State University, 1996.
17. Singh K. Realistic human figure synthesis and animation for VR applications. Doctoral Thesis. UMI Order Number: UMI Order No. GAX96-12277, Ohio State University, 1995.
18. Wilhelms J. Modeling animals with bones, muscles, and skin, in *UCSC-CRL-95-01*. University of California: Santa Cruz, 1995.
19. Albrecht I, Haber J, Seidel H. Construction and animation of anatomically based human hand models. In Proceedings of the *2003 ACM SIGGRAPH/Eurographics Symposium on Computer animation*, San Diego, California, 2003; pp 98–109.
20. Chew LP. Constrained delaunay triangulations. *Algorithmica* 1989; **4**(1): 97–108.
21. Igarashi T, Matsuoka S, Tanaka H. Teddy: a sketching interface for 3d freeform design. In *ACM SIGGRAPH 99*, 1999.
22. Ekoule AB, Peyrin FC, Odet CL. A triangulation algorithm from arbitrary shaped multiple planar contours. *ACM Trans Graph* 1991; **10**(2): 182–199.
23. Aubel A, Thalmann D. Efficient muscle shape deformation. in *Deformable Avatars* , IFIP TC5/WG5.10 *DEFORM'2000 Workshop*. Geneva, Switzerland: Kluwer, 2000.
24. Yang XS, Zhang JJ. Hybrid skin deformation for character animation , Pacific Grtaphics , Macao, China, 12–14 October 2005; pp 10–12.

Authors' biographies:

Xiaosong Yang is a research fellow in the National Centre for Computer Animation, Bournemouth Media School, Bournemouth University, United Kingdom. He received his bachelor (1993) and master degree (1996) in Computer Science from Zhejiang University (P. R. China), Ph.D. (2000) in Computing Mechanics from Dalian University of Technology (P. R. China). He worked as PostDoc (2000–2002) in the Department of Computer Science and Technology of Tsinghua University for 2 years, and research assistant (2001–2002) at the ' Virtual Reality, Visualization and Imaging Research Centre' of Chinese University of Hong Kong. His research interests include 3D modelling, animation, real-time rendering, virtual reality, virtual surgery simulation and computer aided design.

Jian J. Zhang is a professor of Computer Graphics at the National Centre for Computer Animation, Bournemouth Media School, Bournemouth University and Head of Research at Bournemouth Media School. His research interests include computer graphics, computer animation, physically based simulation, geometric modelling, medical simulation and visualisation.