The Visual Computer

Simulating wrinkles and skin aging

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We describe a methodology and framework to simulate facial animation and skin aging, taking into account skin texture and wrinkle dynamics. We split the facial simulation process into facial surface deformation and wrinkle generation. The first of these is based on a three-layered facial structure (muscle, connective tissue, and skin layers). The layer of B-spline patch muscles provides the relevant contraction forces to enable the skin deformation, while the layer of connective tissues constrains the range of skin movement. The wrinkle generation uses a synthetic texture, and wrinkles are formed dynamically, thanks to a linear plastic model. The wrinkle generation and rendering can be incorporated into real-time facial animation systems.

Key words: Facial animation – Aging – Wrinkles – Skin deformation – Real time

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1 Introduction

The initial effort to represent and animate human faces goes back to the 1970s. Since then, significant research breakthroughs have been made. Although the face is a relatively small part of the human body, it holds a lot of important clues for human communication, emotion, and identification. Recent interest in facial animation has been prompted by the blooming animation and game industries. Facial animation by computer is widely used in entertainment, teleconference, and virtual reality. However, realism in face modeling and animation remains an aspired goal. The task becomes even more challenging when wrinkle formation and facial aging are considered.

A human face has a layered structure composed of a skull, a muscle layer, covered by connective tissue, and an outer skin layer. Layered structures based on the simplification of facial tissues are often used for facial simulation by computers. The modeling and rendering of the outermost visible layer, the skin, is very important in enhancing the realism of the facial animation. The outer skin surface consists of a geometrical structure that manifests the form of visible skin. A close-up of the skin surface depicts a common microstructure with a rather well-defined geometrical form resembling a layered, net-like pattern. However, the visible lines, wrinkles, creases, and folds constitute a distinct macrostructure that may be specific to one part of the face. The micro and macrostructures over facial skin constitute major elements affecting the appearance of the human face.

Wrinkles are the most important macrostructures on the human face. Two types of wrinkles appear with facial animation: expressive wrinkles and age wrinkles. Expressive wrinkles appear on the face during expressions at all ages and may become permanently visible over time. The skin changes with age, thus more lines and wrinkles emerge, and with time the general appearance and texture of the facial skin become pronounced and rough. In addition to their visual effects, expressive wrinkles act as an important factor for understanding and interpreting facial expressions, and permanent visible wrinkles indicate a person's age. Figure 1 shows the microstructure and wrinkles on real skin.

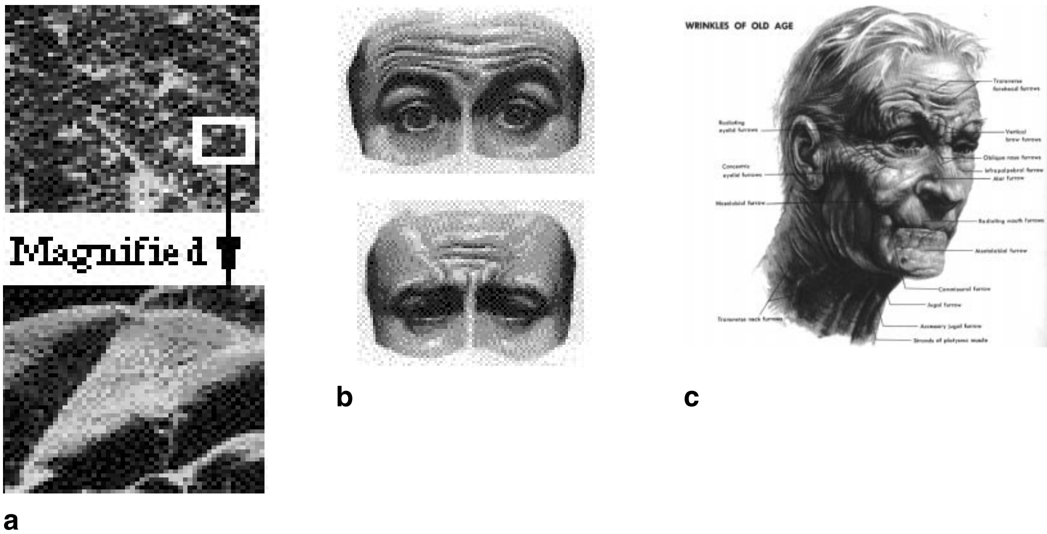


Fig. 1a–c. Micro and macrostructures on the human face: **a** microstructure; **b** expressive wrinkles; **c** aged wrinkles

1.1 Review of facial simulation and wrinkle models

Varied models are used to simulate facial animation and skin deformation for different purposes. There are geometric models, physically based models and biomechanical models that use either a particle system or a continuous system. Many geometrical models have been developed, such as the parametric model (Parke 1974, 1982), geometric operators (Waters 1987) and abstract muscle actions (Magnenat-Thalmann et al. 1988). There are also different kinds of physically based models, such as the tension net model (Platt and Badler 1981) and the three-layered deformable lattice structure model (Terzopoulos and Waters 1990; Lee and Terzopoulis 1995). The finite element method is also employed for more accurate calculation of skin deformation, especially for potential medical applications such as plastic surgery (Larrabee 1986; Pieper 1992; Koch et al. 1996).

Many research efforts have been undertaken for generating textures for animal skin, as well as human skin. Bump and color mapping techniques (Miller 1988), texture synthesis language (Kaufman 1988), face data recording (Nahas et al. 1990) and a microgeometrical model (Ishii et al. 1993) are used to simulate different skin patterns by texture.

There are a few facial animation models with dynamic wrinkles. Viaud and Yahia (1992) present a geometric hybrid model for the formation of expressive and age wrinkles, where bulges are modeled as spline segments and determined by an age parameter. There are also physically based facial animation models, where some wrinkles appear as the outcome of the skin deformation (Terzopoulos and Waters 1990; Wu et al. 1994).

Texture mapping offers a good and efficient simulation of static wrinkles, while the physically based approach can offer a better simulation of wrinkle formation. However, the present models do not provide a unified framework to generate different kinds of wrinkles and geometrical structures on the skin surface with facial animation and aging.

1.2 Our approach

Our approach uses available computer simulation techniques with guidance for facial animation and aging reality. The goal is to develop a system that combines the efficiency of the texture models and the dynamics of the physically based model. A three-layered structure is employed by the physically based facial animation model, which consists of a skin layer, a connective tissue layer, and a muscle layer (Wu et al. 1994). In the facial model,

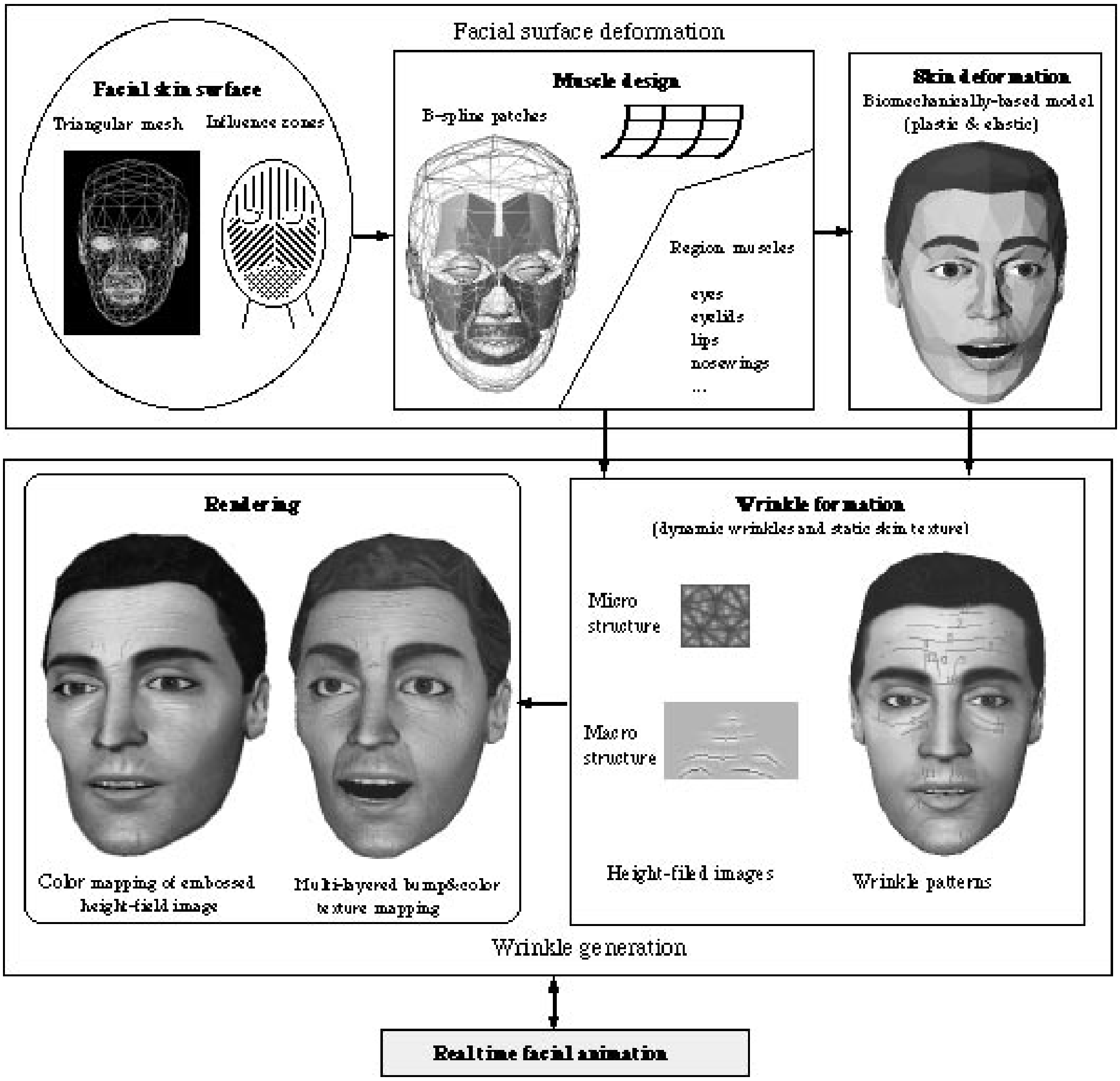


Fig. 2. The process of facial simulation and wrinkle generation

the skin surface is represented as a triangle mesh, having material properties associated with triangles and kinematic features associated with vertices. Facial muscles are mainly designed as B-spline patches according to the natural direction of muscle fibers; some additional pseudo-muscles are defined on the basis of skin regions. Connective tissues is simulated as a layer of springs between the skin and the muscle layer, which prevents the skin from leaving its rest position. The deformation of skin is activated by the simulated muscle layer, constrained by the connective tissue layer, and determined by a biomechanical model.

The wrinkle formation and rendering details are represented by several layers of color, bump, or displacement texture mapping. The texture images consist of synthetic patterns as well as real photos. Patterns for static wrinkles are represented in texture images. The dynamics of wrinkle simulation is computed with the strain measures of skin deformation of the 3D facial model. The information about the wrinkle formation modifies the corresponding texture image of synthetic wrinkle patterns. Photorealistic rendering can combine texture mapping of real photos and synthetic skin texture in a layered RenderMan rendering process (Upstill

1989). However, in order to apply wrinkle generation to the real-time facial animation system, bump mapping is replaced by color mapping of the embossed wrinkle height-field texture image. Figure 2 illustrates the main process of the facial simulation and wrinkle generation. The steps to produce the facial animation and wrinkles in our system are as follows:

- Start from an existing triangular facial mesh and divide it into several regions. Each region is defined as an influence zone for a group of muscles.
- Muscles are designed in two ways, namely, construction of B-spline muscle patches and definition of pseudomuscles by regions.
- Parameters of skin deformation, which are used for elastic and plastic skin models, are adjusted from a given set of default values. In addition, an aged face model is defined, and the changing shape of the face as it ages is taken into account.
- Specify micro and macrostructures of the skin surface in synthetic texture images. Wrinkles, the most important macrostructures on skin, are determined with the guidance of muscle contraction direction. A real photograph can be assigned to the facial model and combined with synthetic patterns in texture images.
- Several rendering options are provided after the deformation of the facial surface and wrinkle generation in the texture image. A multilayered render is used to generate photorealistic images with color, bump, or displacement mapping of combined texture images. When wrinkle generation and rendering are incorporated into real-time facial animation, bump or displacement mapping is replaced by color mapping of the height-field texture image of the embossed wrinkle. This is partly updated according to the facial actions in a real-time system.

The rest of the paper follows the steps just given, with concluding remarks at the end.

2 Skin mesh with influence zones

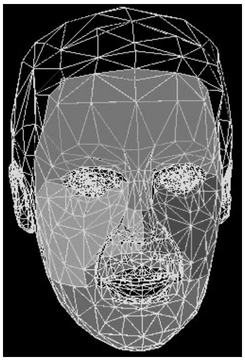
The external skin surface is a triangle mesh in our facial model. Several zones are defined on the skin surface, such as the upper face region, left middle face region, right middle face region, and lower face region. Each region covers the influence zone of a group of neighboring muscles, which are to be defined with the muscle design tool. Figure 3 shows the skin influence zones and the muscle groups corresponding to the zone. This region definition offers the facility of limiting the skin deformation in the regions that include contracting muscles. This reduces the calculation of skin deformation during facial animation. The skin zone is created by picking triangles interactively with a skin region tool.

3 Muscle design

Muscles are the principle motivators of skin deformation. A muscle is attached to the skin or bones at both ends so that when it contracts, it attempts to draw its attachment together. As most facial muscles are flat and close to the skin surface, their shapes are designed interactively with the guidance of the skin surface. Our goal is to provide simplified facial muscle simulation that enables anatomically reasonable skin deformation. Two types of approaches are developed to simulate muscle actions in our muscle design system: a muscle model based on B-spline patches and a pseudomuscle model with region specification. While the facial muscles are mostly simulated by B-spline patches in our model, the region-based pseudomuscles compensate for the facial actions involving bone movement, etc. To this end, we have developed an interactive tool that offers muscle-patch design, region specification and definition of muscle action. Figure 4 shows our muscle design interface.

3.1 B-spline patch muscles

Facial muscle mostly consists of clusters of fibers with a rather flat structure, so that surface models can be used to simulate muscles instead of volume models. A muscle has a biaxial structure and behavior because of its fiber configuration. Due to the biaxial nature along its two parameters, a B-spline patch is chosen for the muscle representation. The facial muscles are classified into two main types: linear muscles and sphincter muscles (Waters 1987). A linear muscle, such as the frontalis major muscle, which raises the eyebrows, contracts toward the static attachment on the bone. A



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Upper face:	*Forehead muscles* *A pair of corrugator muscles*
Left middle face:	*Left zygomatic muscles* *Left levator labii superior muscles*
Right middle face:	*Right zygomatic muscles* *Right levator labii superior muscles*
Lower face:	*Orbicularis oris muscle*

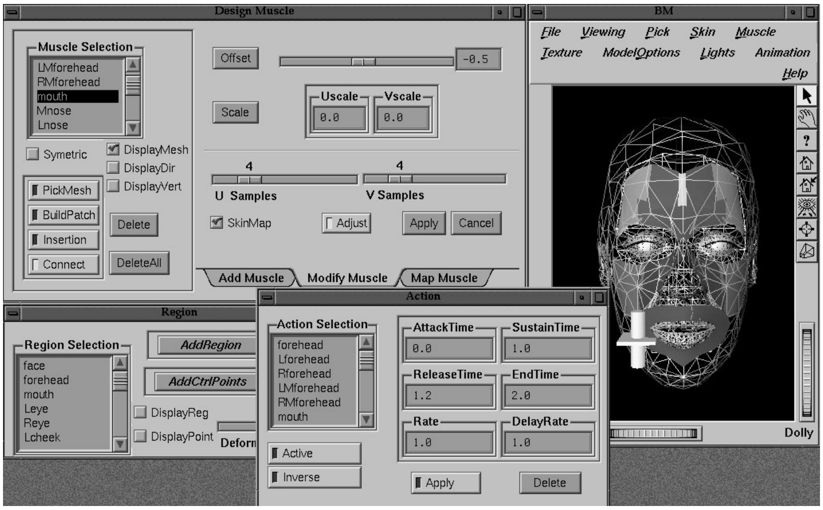

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Fig. 3. Skin influence zones with muscle groups

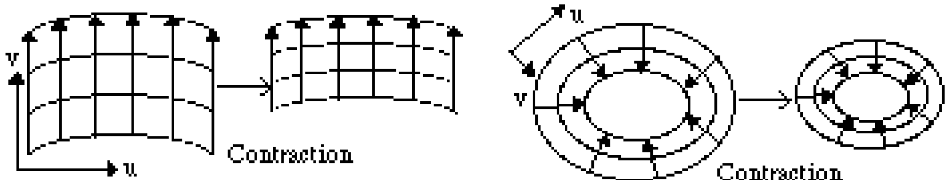
Fig. 4. Interface of the tool for muscle design

sphincter muscle contracts around an imaginary central point such as the orbicularis oris muscle, which draws the mouth together. Open B-spline patches are used to simulate the linear muscles, while the B-spline patches closed in one parametric dimension are employed to imitate the sphincter muscles (Fig. 5). The v parameter direction approximates the muscle fiber orientation, and intuitively it is considered that the transverse parameter dimension u indicates the potential wrinkle locations with skin deformation. The connection force from a muscle at its attachment is simulated with a Hookean spring.

The open and closed muscle patches can be designed in several ways: *mesh picking, muscle mapping*, and *mesh modifying*. In the following subsections, we describe these operations.

3.1.1 Mesh picking

To construct the muscle patch, a mesh of key points is interactively defined on the skin surface.This mesh roughly describes the shape of the muscle, as well as its fiber orientation. An offset value is defined as a distance from the skin to the muscle. Figure 6 shows the picked muscle



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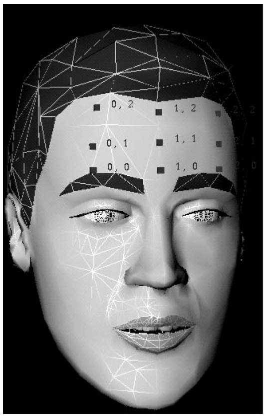

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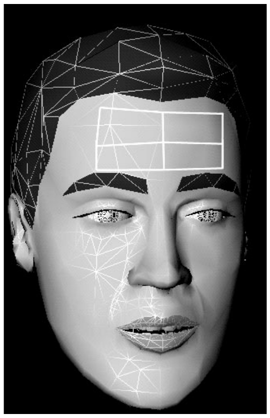

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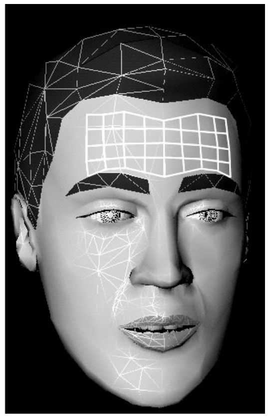

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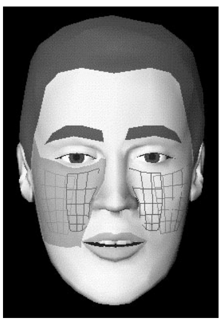

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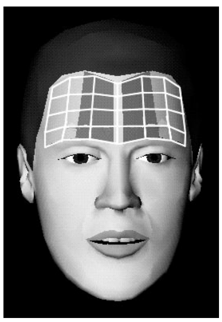

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Fig. 5a, b. Muscle operations: **a** linear muscle – open B-spline patch; **b** sphincter muscle – closed B-spline patch

Fig. 6a–c. Picking the muscle mesh: **a** initial picked mesh: **b** Initial B-spline patch mesh; **c** final B-spline patch mesh

Fig. 7a, b. Muscle mapping: **a** symmetry copy; **b** submuscles

mesh and the final muscle patch with the required resolution.

3.1.2 Muscle mapping

Another way to build a muscle is by mapping it directly from an existing muscle. Because of the symmetry of the face, muscles at one side of the face can be constructed by *symmetry copy* from the existing muscle on the other side. Figure 7a illustrates examples of muscle symmetry copy.
Another map operation is *submuscle mapping*. Facial expression is driven by a cluster of muscles. In some cases, a cluster of the muscles can be defined as a whole B-spline patch, while the submuscles are defined as various zones on it. For example, when a forehead muscle is defined as a cluster muscle, its left, left-middle muscle, and right, right-middle muscle can simply be defined as submuscles. Whenever the cluster muscle is built, we create the submuscle by specifying its region with the range of the *u, v* parameters on the B-spline patch. Thus it inherits the shape, influence skin region, and connection features from the cluster muscle. Figure 7b shows an example of submuscle mapping (cluster muscle in wire frame, submuscles in color shading).

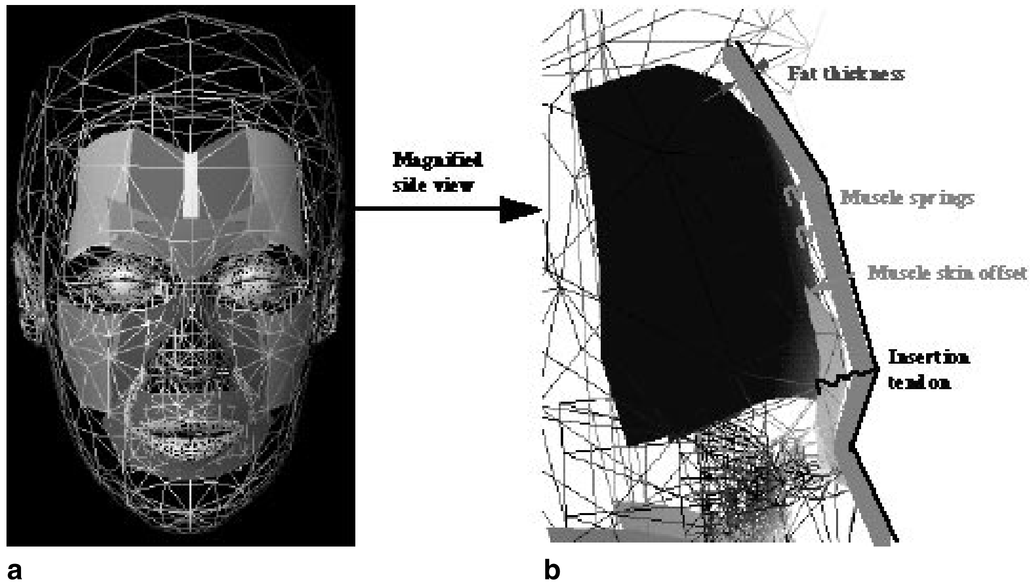


Fig. 8. **a** Facial muscle patches; **b** the connection between the skin and muscles

3.1.3 Mesh modification

If a muscle has already been constructed, but needs some small shape modification, one can use *single vertex displacement* instead of picking a new mesh from scratch. The displacement is applied to one single muscle mesh vertex at a time. The B-spline muscle patch is then rebuilt automatically by the interpolation of the displaced point mesh.
Geometric operators, such as scaling and offset, are also used to modify and move a muscle mesh. These operations provide a facility for importing the muscles from another face model and adjusting them to the new face.
In our model, main muscles are designed on different face zones. Figure 8 shows a B-spline patch muscle set designed on a face model and the connection between the skin and muscles.

3.2 Region-based pseudomuscles

Some facial animation features cannot easily be simulated by our skin/B-spline-patch-muscle approach because bone movement is involved, which is not included in our model, or because it contains regions of different facial structure. For example, jaw movement involves bone movement; the nose wings have a cartilage structure other than skin. To complete our physically based model, additional pseudomuscles based on regions are added as compensation to the B-spline patch muscle approach. In our pseudomuscle model, muscle actions are simulated by abstraction notation of muscles where deformation operators define muscle activities on defined regions (Kalra et al. 1992). The dynamics of different facial tissues is not considered. Each region muscle is defined by interactively picking a set of triangles and several control vertices on the skin surface. These regional facial actions include eye movements, upper/lower eyelid actions, jaw action, nose wings, lower eyelid, and lip movements.

4 Skin deformation

Various types of models, such as geometric models and physically based models, are used for skin deformation. In order to produce more accurate skin deformation and provide a potential for medical applications, we employ a biomechanical model. Moreover, a linear plastic model is extended to calculate the permanent skin deformation, which

Table 1. Values of defaule parameters used in the elastic membrane model

Mass density ρ	Skin thickness Ts	Young modulus E1	Young modulus E2	Poisson coefficient υ	Fat tissue connection *kc*
5 kg/m^2	0.003 m	10 mpa strain<=0.4	100 mpa strain>0.4	0.333	8000 N/m^2

provides measures of wrinkle formation due to aging. A set of mechanical and numerical parameters in elastic and plastic models has to be determined before we apply skin deformation. In addition, an aged face model is defined if we consider the shape change of the face to enhance the visual effects of aging.

4.1 Elastic membrane model

Various biomechanical models of skin have been proposed in the literature (Lanir 1987). For our purpose, we consider skin to be biaxial, incompressible and of constant thickness at each region. The skin cannot support negative stress, and hence buckles easily (Danielson and Natarajan 1975).
As skin is thin and quite flexible, a plane stress elastic model is applied for each triangle. Each triangle employs a local coordinate system according to the skin's biaxial behavior. One axis corresponds to the orientation of the potential wrinkle, while the other axis approximates the direction of the muscle contraction. In the case of small deformation, any three strain measurements in the triangle can be used to calculate the resulting strain vector. In the case of large deformation, the simplification of the resulting strain vector evaluations are based on the incompressibility of skin and the uniform direction of the skin deformation in each region. The principal strain direction (the direction with no shear strain component) is approximated by the potential wrinkle line, to which the muscle contraction direction is assumed to remain vertical in the deformed state. In this configuration, we calculate the resulting strain vector directly by measuring strain along the coordinate axes. The details about the elastic membrane skin model undergoing large deformations are described by Wu et al. (1997).
A two-phase linear stress-strain relationship is employed to describe the skin's elasticity. Hook's law is used for computing the stress components on the triangle, which are then employed to calculate the in-plane force along the triangle edges. Each edge force is finally distributed to its two vertices.
The physiology and elastic properties of skin are described mainly by a set of parameters, such as the Young modulus at small and large strain, the Poisson coefficient, the mass density, and the skin thickness. The average parameters of skin elasticity and connective tissues are derived according to the biomechanical data (Danielson 1973; Elden 1977; Lanir 1987). These values are used as the default parameters in the model and are listed in Table 1.
The size ratio of the synthetic model to the real model has to be specified for skin deformation calculations. Various mechanical data of skin deformation can be adjusted on the basis of these default values to customize facial models of various ages. Additional parameters include a damping constant to control the deformation speed and the constant of the spring simulating a muscle tendon. These two parameters are set empirically. The time step is adjusted automatically during the facial animation. Experiments prove that the skin deformation model with the given parameter values provides a stable and reasonable solution.

4.2 Plastic model

Plasticity causes irreversible atom dislocation and permanent deformation beyond certain force limits. The skin's remaining deflection after the removal of load is the result of plasticity. A linear plasticity model is used to simulate skin aging (Shanders 1973), which is applied to wrinkle formation in the model. The plastic component depends linearly on the load duration. We extend it to present the sum of plastic deformation as an integral of deformation within load duration (Wu et al. 1997). The linear factor of plasticity is set empirically to control the speed of aging. Therefore, the height of an age wrinkle is determined by the strain of skin deformation at that region and the age parameter.

4.3 Aged face model

Aging changes the shape of face and other features, such as the variation of skin with more visible lines and wrinkles and a rougher structure. In order to improve the visual realism of face aging simulation, geometric operations are applied interactively to the model of a young face to achieve an old face with more hollow cheeks and more pronounced nose tip. The model of the old face should be loaded before we determine the skin deformation with the aging process. To simulate the face shape variation with age, geometric interpolation is applied to the old and the young face models. The hair and eyebrow regions are also specified so that the color variation of an aged face can be applied.

5 Wrinkle generation in texture

An interface of texture design is provided in our system to generate wrinkles and skin surface structures. According to the characteristics of the surface, we classify of wrinkle design models into two types: static and dynamic models (Wu et al. 1996). For the static model, we define the shape and form of the wrinkles or other macrolines as geometrical structures on the planar skin surface. The dynamic wrinkle model accounts for the changes in the form and shape over time on the basis of the biomechanical skin model. A texture image corresponding to a region of skin is defined on which the static and dynamic wrinkles are modeled and animated. The following subsections present the design process of static and dynamic models.

5.1 Design of static structure

The physiology of wrinkles requires one to consider the micro and macrostructure of the skin surface for modeling the geometrical features of the skin texture. For the static model, the location and the form of the wrinkles or other lines are established on the structure of the skin surface. Real photos hold more skin details, including micro and macrostructure, which are used in combination with a synthetic skin structure. We now describe our method of modeling the geometrical features in the micro and macrostructure of the skin in texture image.

5.1.1 Microstructure

The microstructure appears to be a layered net structure determined by two major factors: the furrow pattern and the ridge shape. A detailed examination of this structure shows a triangular mesh pattern with several layers of furrows. A hierarchical triangulation is applied to a skin region to obtain geometrical patterns for the microstructure. The furrow pattern is generated by a Delaunay triangulation (Farin 1990) for each skin region. A ridge surface is defined as a function on the triangle base, and the height of the ridge increases from the edge to the center of the triangle.

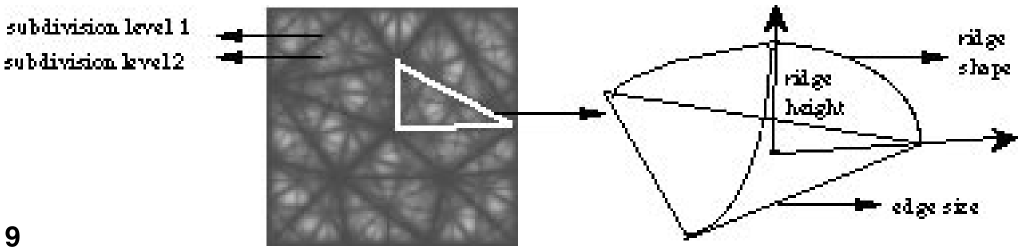
To define a microstructure on a region, *the edge size of triangulation*, *the ridge shape function, the ridge shape height,* and *the level of subdivision* are determined. Various kinds of micropatterns can be generated in the defined texture image (Fig. 9).

5.1.2 Macrostructure

In addition to microfurrows all over the body, macrofurrows such as palm lines and potential flexure wrinkle lines exist in some skin regions. These are modeled in the macrostructure. Two major factors are considered: macrofurrow location and its bulge shape.

In our system, there are two ways to locate the position of the macrofurrows by an array of points: *u line points* of a B-spline muscle patch and *picked points* of the macroline on skin surface. We obtain he B-spline curve by interpolation or approximation through the defined points and then map it to the texture image by choosing *cylindrical mapping* or *planar mapping*. For more natural visual effects, a *random deviation factor* is added to the furrow.

A bulge region is defined along the furrow line in the 2D texture image space (Fig. 10). The bandsize value determines the width of the bulge. We can choose from four types of bandsize: *uniform*, *increase*, *decrease* and *random*, according to which the bandsize is evaluated from one end of the line to the other. The bulge shape is defined as a height function of band width. Various kinds of shape functions with sharper or flatter bulges can be chosen for simulation. The height value of the function is also set to determine the intensity of the bulge.



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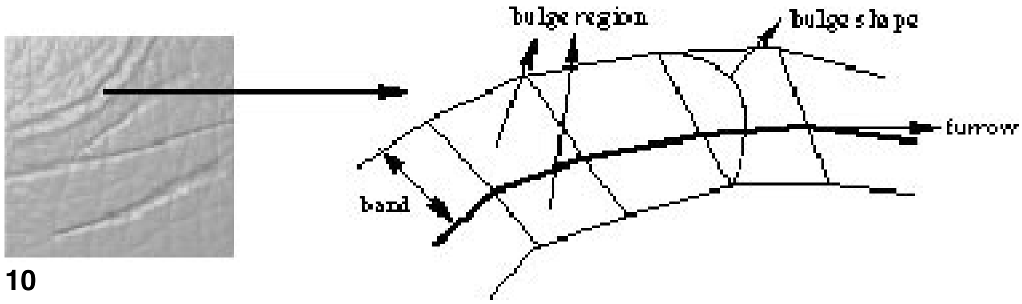

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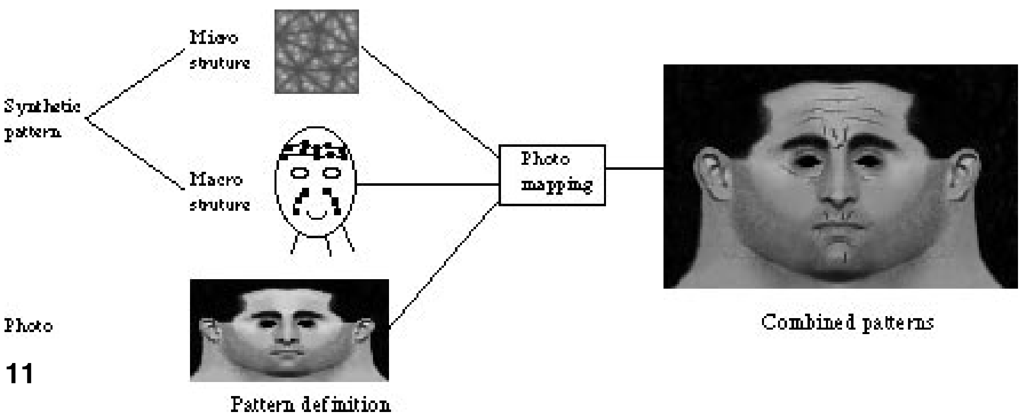

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Fig. 9. Synthetic microstructure

Fig. 10. Synthetic macrostructure

Fig. 11. The process of generation the structure of the skin surface

5.1.3 Real photo image

Real photos capture all skin details including the micro and macrostructure. Manipulating a 3D model of a face in conjunction with a real photo by texture mapping gives realism to the character animation. An interactive tool is used to match features from a 3D face model to a 2D photo image by selecting 3D feature points and projecting them to a 2D photo image. We obtain the texture coordinates of other vertices by using linear interpolation in a triangular domain (Kalra and Magnenat-Thalmann 1993; Sannier and Magnenat-Thalmann 1997).

To apply synthetic texture patterns with the real photo, we use *photo mapping* so that feature points

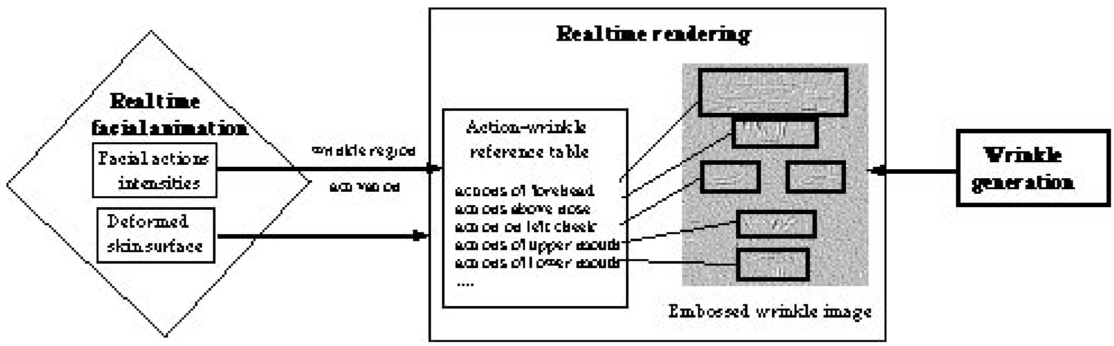

Fig. 12. Wrinkle generation in a real-time system

of wrinkles and macro lines in the skin surface are projected onto the photo image. The location of a wrinkle feature point inside a triangle of the 3D model in the 2D texture image can be determined by linear interpolation of the vertex texture coordinates. To do this, we use barycentric coordinates in our photo mapping method. The synthetic patterns are constructed through the feature points in the 2D photo image.

5.2 Dynamic wrinkle design

It is quite expensive to geometrically model all the wrinkles on the 3D skin surface. Thus, we deform the skin mesh according to the biomechanical model and form the wrinkle bulges by determining the bulge parameters from the skin deformation. Two types of wrinkles are described in the dynamic model by the texture image: expressive wrinkles and age wrinkles. The expressive and age wrinkles are specified as macrolines, which change dynamically with skin deformation. While the expressive wrinkles are determined by elastic skin deformation, the age wrinkles are formed according to the plastic model. The shape of expressive wrinkles and age wrinkles varies at different locations of the face and with different individuals. Nevertheless, a further analysis of wrinkle shape illustrates a general form with a narrow inward furrow accompanied with an outward bulge. We employ a wrinkle shape function composed of several piecewise functions. The width of the inward furrow, the outward bugle, and their heights are specified and adjusted to obtain natural wrinkle shape.

6 Rendering

Several rendering options are provided in our system to compromise between the time efficiency and the realism of the rendering: interactive display, photo realistic rendering, and real-time rendering. The interactive display uses the Inventor renderer directly with color mapping of combined texture images. The photorealistic rendering employs multilayered color and bump texture mapping; the real-time rendering updates only the texture image in the regions that include wrinkles. These wrinkles are associated with the activated facial actions generated by a real-time facial animation system.

For photorealistic rendering, RenderMan shaders are defined with several layers of mapping (color mapping, displacement or bump mapping). Synthetic surface structure patterns and real photos are used as the texture image. Blue Moon Render Tool (BMRT), which is RenderMan shareware (Gritz, WWW site), is used because of its direct support of user-defined shaders and multilayer rendering. Several parameters can easily be adjusted in the shader to obtain various rendering effects: the roughness of microstructure by bump intensity, the size adjustment of whole microstructure by repeated factors of texture coordinates, and the depth of wrinkles with the bump intensity of the animated texture images.

The wrinkle generation and rendering can also be incorporated into real-time facial animation. To generate wrinkles in real-time facial animation, we need to reduce the time of updating the wrinkle image and rendering during the animation. The

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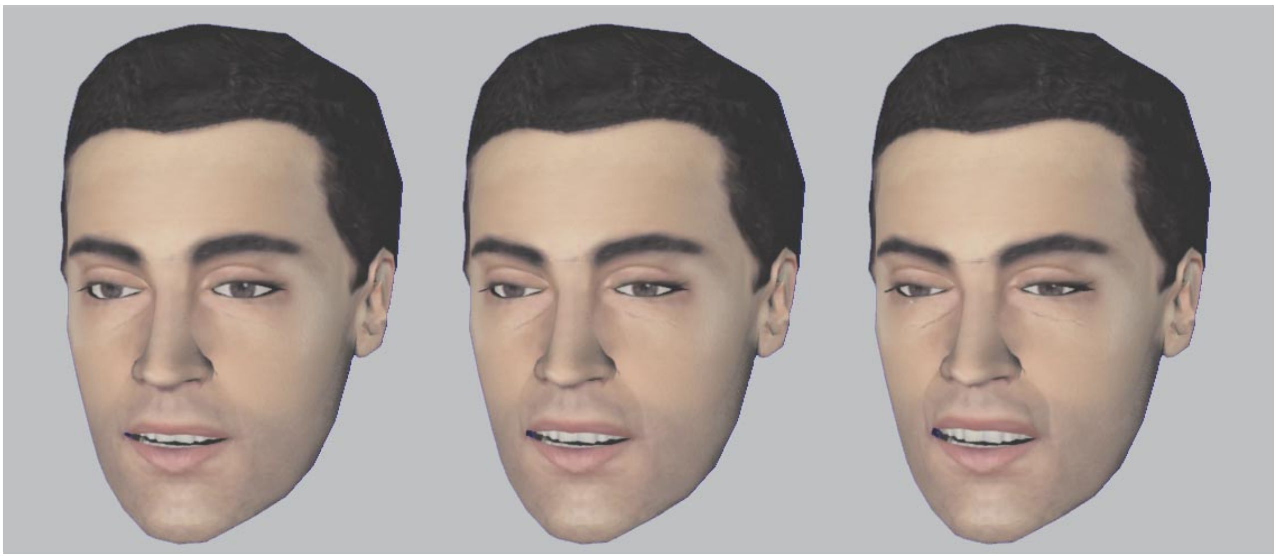

b

Fig. 13a, b. Facial animation with expressive wrinkles: **a** surprise; **b** disgust

wrinkle patterns on a face are divided into rectangular regions in the texture image, and a reference table specifies the correspondence between the facial action units and wrinkle regions. Only the wrinkle regions in the texture image associated with activated facial actions are updated during animation. Although bump mapping can produce more realistic rendering of wrinkles, it is quite expensive for real-time applications. To produce real-time facial animation with acceptable wrinkles, the embossing operation is applied to a wrinkle height-field texture image with maximum intensity. Color mapping is used instead of bump mapping on the embossed texture image. The wrinkle intensity is controlled by the intensity of the associated facial action unit during the anima-

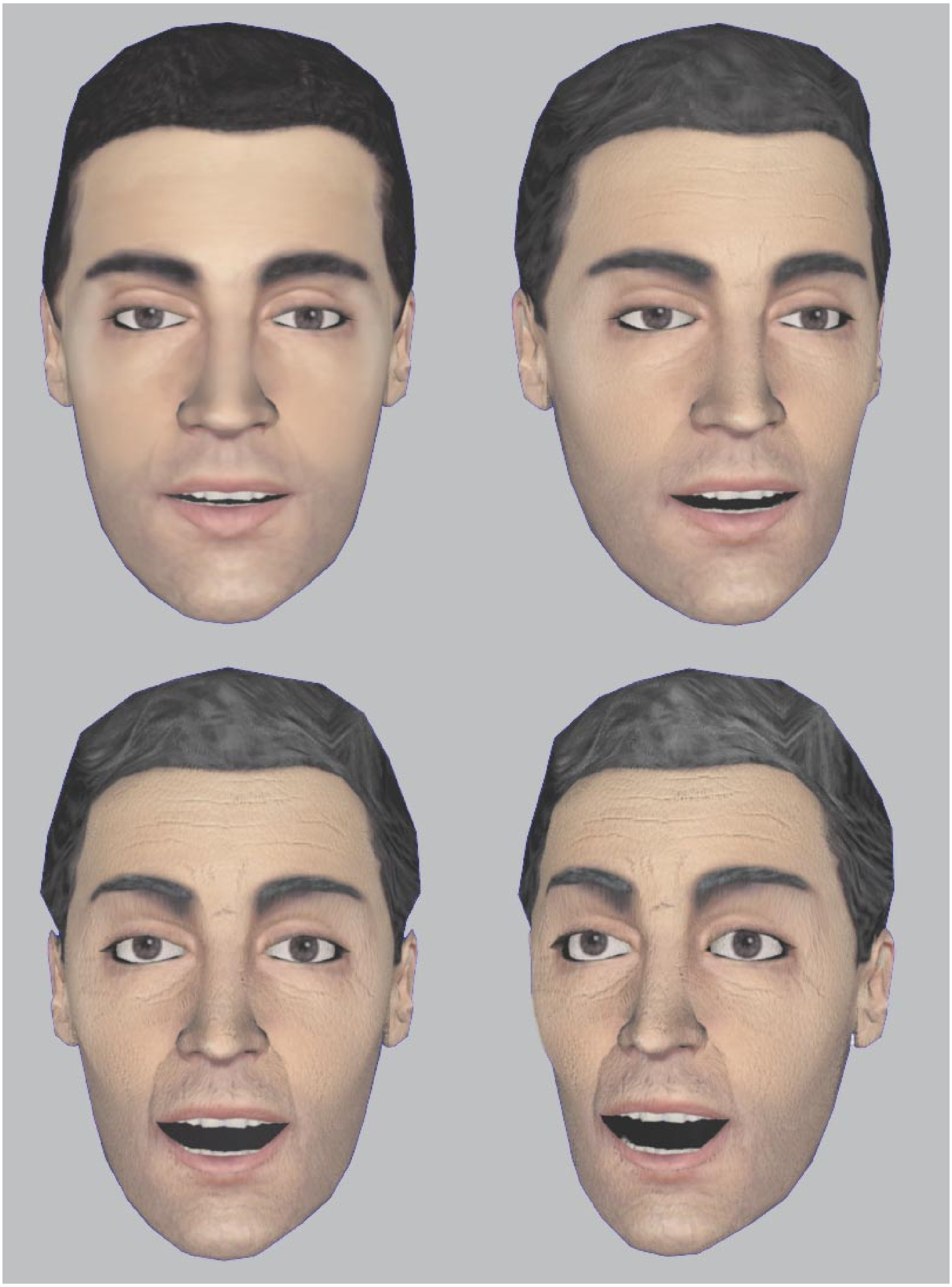

Fig. 14. Getting old?

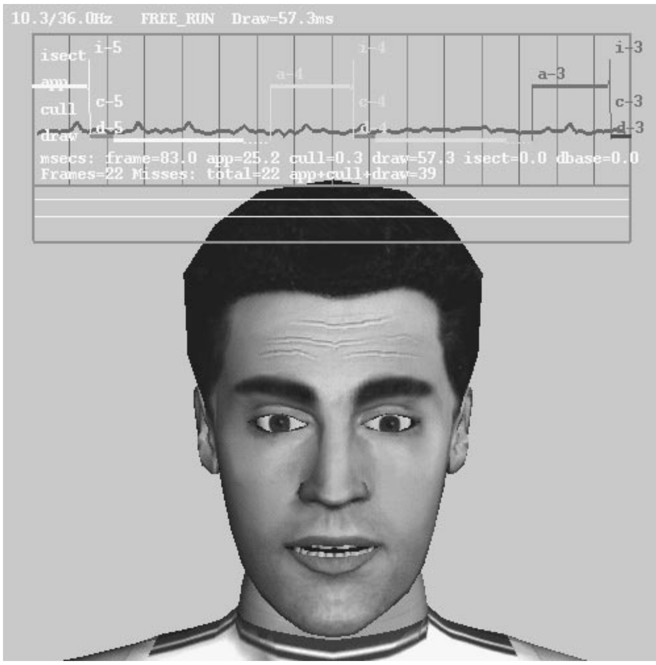

Fig. 15. Real-time wrinkle rendering

tion. Figure 12 illustrates the corporation between the real time system and wrinkle generation.

We demonstrate our model with some examples. Figure 13 shows a sequence of facial animation with expressive wrinkles. The expression of surprise in Fig. 13a is rendered directly with the SGI Inventor renderer. The expression of disgust in Fig. 13b is rendered with BMRT. Figure 14 shows a sequence of face-aging processes along with facial expressions where age wrinkles and varying synthetic microstructures are rendered with BMRT. Figure 15 shows the surprise sequence with expressive wrinkles on the forehead in real-time facial animation (on SGI O2, 200 MHz IP32 processor).

(For these animations, refer to the WWW site http://cuiwww.unige.ch/∼wu/Animation.html.)

8 Conclusion

We have presented a facial animation and aging system that simulates wrinkles and other facial details during the deformation of human skin. Facial muscles can be designed on an individual face. The skin deformation process uses biomechanical model and parameter values. Wrinkles and other details of the skin are designed on texture images. The dynamic model is applied to the simulation of expressive wrinkles and age wrinkles. The skin deformation and wrinkle formation processes are controlled by facial and aging actions. Various options are provided for interactive display, photorealistic rendering, and real-time animation.

Facial animation system based on actual medical data and biomechanics of facial tissues with finite element analysis would offer the foundation for wrinkle formation and growth, but it would be far too expensive to simulate this at an interactive rate. Our biomechanical model is suitable for applications that require acceptable accuracy and an interactive display. It is potentially a tool for facial surgery planning. The layered texture mapping combined with deformations gives an efficient approach to simulate the static and dynamic nuances of a face during facial animation.

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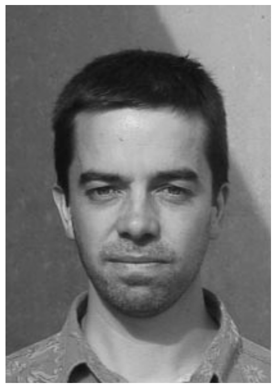

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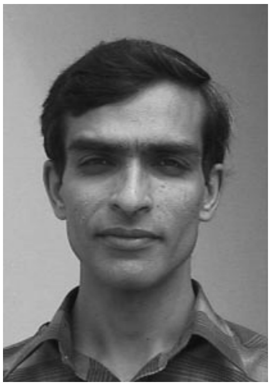

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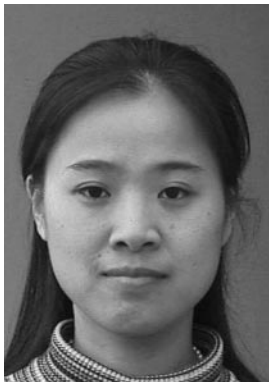

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