Realistic Deformation of Human Body Shapes

Amaury Aubel and Daniel Thalmann
Computer Graphics Lab
Swiss Federal Institute of Technology (EPFL)
CH 1015 Lausanne, Switzerland
Tel: +41 21 693 52 14 Fax: +41 21 693 53 28
e-mail: {aubel, thalmann}@lig.di.epfl.ch

Abstract

In this paper we propose a new, generic, multi-layered model for automating the deformations of the skin of human characters based on physiological and anatomical considerations. Muscle motion and deformation is automatically derived from an action line that is deformed using a 1D mass-spring system. We cover the muscle layer with a viscoelastic fat layer that concentrates the crucial dynamics effects of the animation. We present results on a female upper torso.

Keywords: skin deformation, anatomy, physiology, muscle, fatty tissues, physically-based modelling.

1 Introduction

Researchers have tried to model and animate realistic human bodies almost since the introduction of graphics displays. However, it remains one of the greatest challenges in computer graphics because of the high sensitivity of our eyes to familiar objects like human figures. Recent technological breakthroughs have partly solved this problem: laser scanner systems and 3D reconstruction algorithms now allow animators to display realistic, reconstructed virtual actors while motion capture eases the task of animating them. Nevertheless, deforming the skin of these actors mostly remains a manual, frame-by-frame process. This paper addresses this issue by proposing a new multi-layered body representation that produces automatic, fast, appropriate deformations of the geometric envelope (skin) given a moving hierarchical structure (skeleton). We rely on artistic anatomy and physiology to derive true models. Our final goal is the creation of a versatile, interactive tool that permits the modelling and animation of human figures with particular attention for the trunk. We are solely interested in the visual appearance. Biomechanical simulation of the different layers that make up the human body, as in [Chen92] for instance, is beyond the scope of this research.

1.1 Related work

Early work in the area reduced the body to a simple surface model deformed by an underlying skeletal structure. Chadwick et al. [Chadwick89] introduced an additional muscle layer. Since then, this multi-layered approach has established itself as the *de facto* standard for realistic modelling. However, surface models remain commonplace in real-time applications like video games or collaborative virtual environments.

Surface models

A surface model is either a triangular mesh or a set of surface patches, whose deformation is driven only by the motion of an underlying hierarchical structure or *skeleton*. In [Magnenat-Thalmann91], the Thalmanns introduce joint-dependent local deformation operators named JLDs to control skin deformations in the vicinity of joints. This technique, which uses a polygonal surface mesh, assigns each vertex point to a specific skeleton joint. Deformation is then implemented by writing specialised procedures for each joint, which deform the surface as a function of joint angle. Similar techniques are still used in most of the commercial animation systems available. Recent work with polygonal skin meshes concentrates on speeding up the deformation process: Kalra et al. organise skin vertices in a specific manner, grouping them in *contours* [Kalra98]. By setting the orientation and position of each contour, they obtain a smooth deformation of human limbs and trunk. As deformations are not computed on an individual vertex basis but for grouping contours, real-time results are achieved. Similarly, Sun and his colleagues restrict the number of computations by mapping a high-resolution mesh onto a lower-resolution control mesh [Sun99]. The deformations of the control mesh then drive those of the high-resolution skin.

Spline surfaces have also been used to smooth out discontinuities at the joints: Forsey applied hierarchical B-spline surfaces with control points attached to the skeleton links [Forsey91].

Multi-layered models

Chadwick et al. [Chadwick89] coat their articulated characters with an additional muscle layer. Each muscle is embedded into an FFD grid [Sederberg86]. Simply deforming the embedding space then produces muscular deformation. The FFD control points are moved using kinematics or dynamics. For dynamics, a volume mass-spring system is constructed, in which each node coincides with a unique control point and is connected to seven others by ideal hookian springs. A cartoonish character is used for demonstrative purpose, so the produced deformations need not look realistic.

Henne [Henne90] represents the skin by a mesh of bicubic surface patches, whose control points deform at joints in accordance with several constraints such as elasticity, area preservation, and implicit repulsive force fields that mimic bones and muscles. Deformations that occur away from joints are ignored by this approach.

Turner and Thalmann developed the LEMAN system [Turner93] to construct and animate articulated characters. Muscles and organs are represented by simple implicit surfaces (namely spheres, cylinders, and super ellipses). They are covered by an elastic surface, the skin, which is not permitted to penetrate the inner layers but remains free to slide over the muscles. Fat is modelled by specifying at each surface point an offset to the muscle layer. The emphasis is laid here on producing dynamics effects like squash and stretch rather than realistic deformations.

In their work on facial animation, Lee et al. presented a crude but efficient biomechanical model of the human face: a tri-layer mass-spring lattice roughly approximates the muscle, fat and skin layers [Lee95]. Different elasticity parameters are associated with each layer thus reflecting the heterogeneity of the tissues. Biphasic springs are used for the skin: they are readily extensible at low strains, and yield an increasing restoring stress after a certain threshold, which approximates fairly well the stress-strain relationship of the human skin. Soft volume-preservation constraints are also taken into account, thus ensuring a quasi-incompressibility of the tissues.

Yoshomito showed that implicit formulations like metaballs provided efficient ways of creating beautiful virtual humans at a reduced storage cost [Yoshomito92]. Shen et al. extended this approach by combining implicit surfaces and B-spline patches. Ellipsoids and ellipsoidal metaballs represent the gross shape of bone, muscle and fat tissue [Thalmann96]. The motion/deformation of each primitive with respect to underlying joints is specified via a graphical interface. A skin of fixed topology is extracted by casting rays from the skeleton segments in a star-shaped manner and using the intersection points as control points of B-spline patches. However, this technique reaches its limits when it comes to animating highly complex regions of the body. It becomes virtually impossible for the designer to specify a coherent behaviour for an ellipsoid if several joints influence it. This typically happens in areas with an important mobility e.g. the shoulder. Thus, the crease of the armpit often looks unrealistic.

More recent work aims at mimicking more closely the actual anatomy of humans or animals. Whilehms developed an interactive tool for designing and animating monkeys and cats [Wilhelms97]. In her system, ellipsoids or triangular meshes represent bones and muscle. Each muscle is a generalised cylinder made up of a certain number of cross-sections that consist in turn of a certain number of points. The muscles show a relative incompressibility when deformed. A voxelisation is used for extracting the skin mesh initially. It includes a filtering stage whose purpose is to blur the approximating muscles, and a decay that moves the isosurface at some distance from the underlying components. Afterwards, a spring mesh is constructed from the skin mesh. Each edge spring's stiffness is related to the adjacent triangles' areas [Van Gelder98] while the skin vertices are elastically anchored to underlying components. A relaxation procedure is performed for each animation frame. The number of iterations can be quite low, even for large motions, according to the authors. The skin generation in their approach seems highly impractical. The blurring stage removes the fine details without discrimination. In addition the user cannot control how the isosurface is moved away from the muscles.

Scheepers et al. stressed the role of underlying components (muscles, tendons, etc.) on the form, in their work on anatomically modelling the human musculature [Scheepers97]. They use three volume-preserving geometric primitives for three different types of muscles: ellipsoids are used for rendering fusiform muscles; multi-belly muscles are represented by a set of ellipsoids positioned along two spline curves; tubularly-shaped bicubic patches provide a general muscle model. Isometric contraction is handled by introducing scaling factors and tension parameters. The skin is obtained by fitting bicubic patches to an implicit surface created from the geometric primitives. The musculature of the shoulder and upper arm is detailed as an example and they achieve promising results. However, the authors mainly concentrated on modelling muscles in static postures. Using their system, it is therefore unlikely that multi-belly muscles like the pectoral or large flat muscles such as the dorsal can realistically be animated. Muscles and bones interpenetration cannot be avoided either.

1.2 Overview

The remainder of this paper is organised as follows. Section 2 exposes some important considerations borrowed from the artistic anatomy, as well as physiological notions that guided us in developing an elastic fat layer. In section 3, an overview of our approach is given and various trade-offs are explained and justified. This section also includes a brief description of the skeleton. In the following section we detail the muscle model, while in section 5 we focus on the outer layers. Lastly, section 6 presents our conclusions and possible future work.

2 Anatomical considerations and physiology

For centuries painters and sculptors have studied the anatomy of the human body to improve their work. Inspired by artistic anatomists, we have conducted a short study of the human anatomy and the physiology of soft tissues.

2.1 Muscles

The muscle layer is the main contributing factor to the surface form. Muscles account for half of the total mass of the body and fill in almost completely the gap between the skeleton and the skin [Richer81]. Anatomists distinguish three types of muscles: skeletal muscles, smooth muscles and the heart. They have different functions but exhibit the same fundamental mechanical and constitutive properties [Maurel98]. We shall only consider the skeletal muscles because the other kinds barely influence the surface form.

Skeletal muscles produce the motion of the bones. Structurally, they consist of a contractile, central part called *belly* and of tendinous extremities that connect the belly to the bones. In constitutive description, the belly is made up of bundles of elastic, contractile fibres. The bundles are wrapped into a single envelope called *fascia*. The belly's fibres are responsible for producing the contraction of the whole muscle. Tendons, which are hardly elastic, act as transmitters and help to move the weight away from the limbs' ends. Upon *isotonic contraction*, the volume of the belly increases thus amplifying its influence on the shape of the skin, whereas the total length of the muscle diminishes so that the bones to which the muscle is attached are pulled towards each other. Upon *isometric contraction*, the shape of the belly alters but the length of the muscle does not change, so no skeletal motion is produced. In a relaxed state, the belly undergoes the action of gravity and hangs somewhat loosely. Upon muscle contraction, neighbouring veins swell in order to accelerate blood irrigation, so that they sometimes jut out from the skin. Finally, muscles vary greatly in shape depending on their location: long fusiform muscles are found mainly in the limbs; short muscles appear around joints; large muscles cover the trunk [Richer81].

2.2 Fatty tissues and skin

Fatty tissues can be found either between the skin and the fascia, or in between deep organs. Fatty tissues in the former location form the *panniculus adiposus* and play an important, and often underestimated, role on the surface form. The skin lies directly on these fatty tissues that are in turn connected to the densely fibrous fascia. When the skin moves, subcutaneous fatty tissues slide relatively freely over the fascia whereas the skin clings tightly to the fat. Put differently, the skin and fat layers appear to move as a whole over the other internal tissues. The mobility of the skin and fat layer depends greatly on the location. In some places, these two layers stick strongly to the internal tissues thus creating permanent furrows and grooves.

Fatty tissues can be found in all individuals, whatever their age and constitution, but in various quantities. Thus fat is more abundant in women and babies than in men, which accounts for the chubbiness of their figures. In all cases, the fat layer plays a prominent role on the form of the buttocks and breast, both for men and women. From a mechanical point of view, fatty tissues are non-linearly viscoelastic, do not resist much to tension, and are considered incompressible.

The skin consists of two layers, the *dermis* and the *epidermis*. It is prolonged by the subcutaneous fatty tissues or *hypodermis*. In constitutive description, human skin is a non-homogeneous, anisotropic, non-linear viscoelastic, nearly incompressible material. Its mechanical properties vary with factors such as age, obesity, exposure etc. Unlike the fat layer, skin resists strongly to stress thus protecting the inner organs from injuries. Skin anisotropy is characterised by pre-stress lines called *Langer's lines* [Cox42]. Langer's cleavage lines are clearly related to the visible crease and wrinkle lines of the skin because the extensibility of the skin is lower along those directions and its stiffness is higher [Maurel98].

3 Overview of the model

Before anything else, we listed a certain number of crucial constraints and properties for our multi-layered model. These include:

- As the skin is the only visible layer, its geometry should be as detailed as possible. Similarly, the simulation time should be smaller for inner layers than outer ones.
- Important visual clues of the skin such as grain, colour variation, veins, hair, beauty spots and age wrinkles are not considered in our approach. Yet, most of them could be rendered using adequate texture maps [Wu97].
- A mechanical simulation of a clothing layer on top of the skin must be possible. Conversely, this also means the skin and inner layers could be constrained by the clothes.

Our proposed model consists of four layers:

1. A skeleton that is made up of 143 rigid bones (fig.1) that are placed interactively on top of the wireframe skeleton. The motion of the skeleton itself can be performed using any animation technique: direct manipulation via the graphical interface, inverse kinematics, keyframing, dynamics, etc.
2. A muscle layer consisting of most of the major superficial muscles. Each muscle is represented by a triangular mesh and an action line. In some regions, we add ellipsoids and ellipsoidal metaballs as in [Thalmann96] to fill in empty spaces left by organs and missing muscles. An implicit surface, corresponding to the *écorché*[1], is created from all the geometric primitives.
3. A fat layer with a viscoelastic behaviour.
4. A skin represented by a geometric mesh or spline patches. Unlike other approaches [Turner93, Wilhelms97] our skin is not an elastic surface. This permits to use very fine geometry e.g. laser scans without slowing down the simulation. As the skin is moreover anchored to the fat layer, it does move elastically. Though this is unacceptable from a biomechanical standpoint, it is justified for our purpose since the skin and fat layers appear to move as a whole, as explained in section 2.2. Finally, as the skin has a fixed topology, a mechanical simulation of clothes is possible.

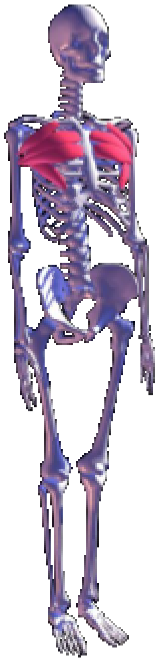

Fig. 1. Stylised representation of a human skeleton with pectoral muscles

4 Muscle layer

We believe the real difficulty with muscles lies more with the animation than with the modelling. It is very complex to automatically derive the appropriate position and deformation of a muscle in any possible posture. Note that in our approach, as almost always the case in computer graphics, the motion of the skeleton induces the muscular deformations contrary to what occurs in reality. Porcher-Nedel and Thalmann recently introduced the idea of abstracting muscles by an action line (a polyline in practice), representing the force produced by the muscle on the bones, and a surface mesh deformed by an equivalent mass-spring mesh [Porcher-Nedel98]. In order to smooth out mesh discontinuities, they employ special springs termed *angular springs* that tend to restore the initial curvature of the surface at each vertex. However, angular springs cannot deal with local inversions of the curvature. Also, the authors do not explicit how they constrain the surface mesh to follow the action line when it consists of more than one segment.

Our approach is comparable in that we, too, use an action line and a muscle mesh. The action line, represented by a polyline with any number of vertices, is moved for each posture using a predefined behaviour and a simple physically-based simulation. It is then used as a skeleton for the surface mesh and the deformations are produced in a usual way [Kalra98, Sun99].

---

[1] An *écorché* denotes the three-dimensional representation of the human body with the envelope of skin and fat removed.

4.1 Action line

First of all, the user specifies for each vertex of the action line a default behaviour: the vertex is mapped to a specific bone and its motion is defined with respect to a given number of joints. Then, a 1D mass-spring-damper system is constructed from the polyline. It is used for automatically determining new positions of the vertices. Currently, all vertices are given an equal mass. The user may choose at any time to deactivate the dynamic behaviour of a vertex, in which case the predefined behaviour takes over. An elastic relaxation is performed for each posture. The physical simulation is advanced very rapidly by relying on an implicit integration scheme since it yields an easily invertible tridiagonal matrix [Kass93]. We add attractive and repulsive implicit force fields (currently ellipsoids and ellipsoidal metaballs) to constrain the action line. Repulsive force fields prevent gross interpenetration while attractive fields help to refine the trajectories of the action line. When gravity is on, the dynamic vertices undergo its action to an extent depending on an isometric tension parameter, as in reality.

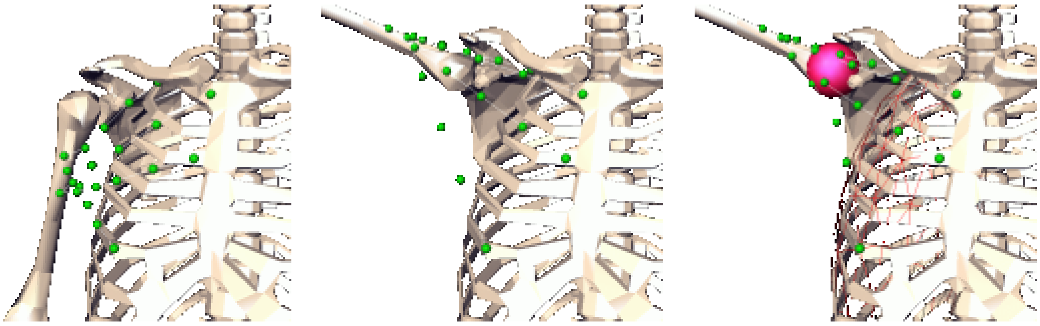

Fig. 2. Actions lines of the pectoral muscle during shoulder abduction. Right figure shows the use of two attractive force fields (solid and wireframe ellipsoids)

In practice, non-dynamic vertices correspond to the insertion and origin of the tendons. The action line can wrap itself around joints providing that the number and location of vertices is well chosen. Nearly rigid portions of the muscle such as tendons can easily be simulated because the stiffness of each spring is under user's control. The implicit integration easily handles these stiff segments. Analogously, increasing the number of vertices and fine-tuning the stiffness of the created springs can roughly approximate non-linear elasticity.

4.2 Muscle mesh

The mesh is currently modelled and adjusted around the action line by hand (fig. 3). The action line serves as a skeleton for producing surface deformations. Each muscle vertex is automatically mapped, as in [Sun99], to the two closest delimiting planes that pass trough an action line's vertex. Vertices positions are later found by linear interpolation of the position and orientation of the enclosing planes.

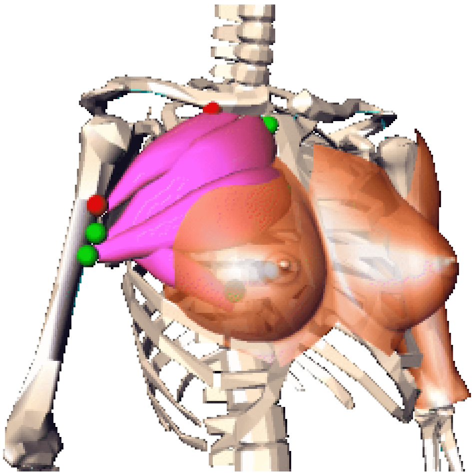

Fig. 3. Overview of the different layers

Isotonic contraction is simulated by scaling each vertex orthogonally to the action line. The scaling factor is individually computed based on the action line. We compute the elongation – defined as the current length divided by the initial length – for every segment of the action line (it is computed anyway when evaluating the spring's elastic force). We interpolate these discreet measurements with a cubic spline curve. Thus we obtain a smooth, individual elongation value for each muscle vertex that we use as the scaling factor squared root: $scaling = \sqrt{elongation}$. Though this empiric formula does not ensure volume preservation, we experimentally measured for various muscle shapes a maximal volume variation of 6% when the muscles shorten by 30%, which corresponds to the maximal physiological compression rate [Richer81].

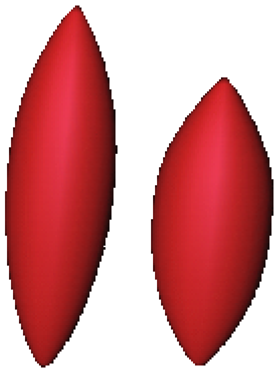

Fig. 4. Compression of a fusiform muscle with near-exact volume preservation

We use the muscle meshes and action lines as implicit primitives for generating the mesh of the *écorché*: the action line becomes the skeleton of the implicit primitive while the mesh defines its density function. This is especially useful for multi-belly muscles like the pectoral because it automatically blends together the different bellies. The novelty of our approach is that we associate a blending weight function with each segment of the action line. The density function therefore has an increased sharpness for certain segments. In this way we can make the tendons salient and the bellies look more undefined. Finally, rays are cast from the skeleton links in order to extract a mesh of fixed topology as in [Thalmann96]. The mesh is updated during animation by maintaining each vertex on the isosurface along a fixed ray originating from the skeleton.

5 Fat layer

All organic tissues of the body undergo the effects of inertia and gravity. Thus fatty tissues hang somewhat loosely under the action of gravity. So do muscles, but to a lesser extent, because they never are in a fully relaxed state [Richer81]. We therefore concentrate dynamics effects in the fat layer.

5.1 Mechanical model

Debunne et al. recently achieved real-time performance for simple virtual surgery simulation [Debunne99]. They used a linear elasticity model derived from the Lamé equation. They introduced approximations for the differential operators of the equation of motion that possess the nice property of being resolution-independent. As a result, their elastic model is well behaved even for irregular meshes. We adopt the same model, with minor variations, for simulating the fat layer. The major difference is that we do not make use of a multi-resolution mechanism as yet. Although the model assumes geometric and physical linearity (i.e. the deformations must remain small which amounts to having a small displacement field and a small displacement gradient), it is acceptable for a computer graphics purpose. Note that this would be inadmissible for biomechanical purposes as one generally considers small deformations do not exceed 0.1%. We briefly recall hereafter the theoretical background. For more details, refer to [Debunne99] and any good textbook on continuum dynamics (for example [Shames92]).

The Lamé equation for a homogeneous, isotropic, linearly elastic material is given by:

$$\rho \vec{a} = \mu \Delta \vec{d} + (\mu + \lambda) \nabla (div \vec{d}) + \vec{f}_{ext} \quad (1)$$

where ρ is the mass density, μ and λ are *Lamé constants* (they can equivalently be expressed in terms of the more widespread *Young's modulus* and *Poisson coefficient*), $\vec{a}$ is the acceleration of a small element of matter, $\vec{d}$ is its displacement and $\vec{f}_{ext}$ is the set of external forces acting on it. As usual, we discretise (1) both in time and space. Another way of looking at (1) is as the propagation of a longitudinal wave and a transversal one, whose velocities are respectively:

$$c_l = \sqrt{\mu / \rho} \text{ and } c_t = \sqrt{\left(\frac{\lambda + 2\mu}{\rho} \right)}$$

The time step for integrating (1) is chosen such that the waves propagate without "missing" discretisation nodes, a well-known cause of divergence for numerical simulations. Finally, artificial viscosity is also included in the model since we want to model a viscoelastic material. Besides, it grants additional stability to the simulation. The resulting model exhibits a much better robustness than the traditional mass-spring-damper network and an augmented realism.

5.2 Meshing and anchoring

The simulation takes as input any number of triangular meshes that make up an inner border (representing the *écorché*) and an external border (the skin). The enclosed volume represents the fatty tissues. The body is initially placed in a neutral posture for which the fat volume is meshed uniformly, with the voxel size being under user control. Then, innermost nodes are automatically anchored to the inner border by projecting them onto the surface. We parameterise the projection by the barycentric coordinates of the triangle to which it belongs. This way, providing the inner border keeps a fixed topology, the anchor moves naturally as the surface of the *écorché* deforms itself. Skin vertices, too, are automatically anchored to a certain number of nodes beneath using local frames for the attachments. This guarantees a smooth appearance of the skin, whatever the body's orientation and the amplitude of the local deformations. The position $\vec{x}$ of a skin vertex is thus given by the weighted average of its linked nodes' positions $\vec{p}_i$ plus the corresponding offset $\vec{o}_i$ expressed in the local coordinate system M_i:

$$\vec{x} = \frac{1}{\sum_{i \in links} w_i} \sum_{i \in links} w_i \left(\vec{p}_i + M_i \times \vec{o}_i \right) \quad (2) \text{ where } w_i = \frac{1}{\left\| \vec{o}_i \right\|}$$

The matrix M_i is formed by taking the vectors joining the node i to three neighbouring nodes. The deviation of the matrix from the singularity is measured for every triplet, and we pick up the "least singular". Finally, in places where the fat layer is too thin, skin vertices are automatically anchored to the inner border and neighbouring voxels.

5.3 Results

All parameters of the simulation are under active control of the user via a graphical interface. Volume preservation of the skin and fat layer is enforced naturally, for the Lamé parameters can directly encode it. The simulation is advanced by an explicit fourth-order integration scheme. We tried using a backwards Euler integration scheme (implicit) but found it produced huge matrices, though sparse, that could not be inverted quickly enough. Figure 4 shows a simulation of a female breast subjected to gravity using 904 voxels, out of which 254 are anchored to the inner border. The skin mesh contains approximately two thousand vertices and is intentionally shown untextured. On an Octane workstation with a R10000 processor, the initialisation stage takes a dozen second while the simulation reaches equilibrium in about thirty seconds that correspond to about one second of actual animation. The time step can be set as high as 0.01s without loss of stability. Constructing the local frames and updating the positions of the skin vertices using (2) takes a marginal share of the total simulation time.

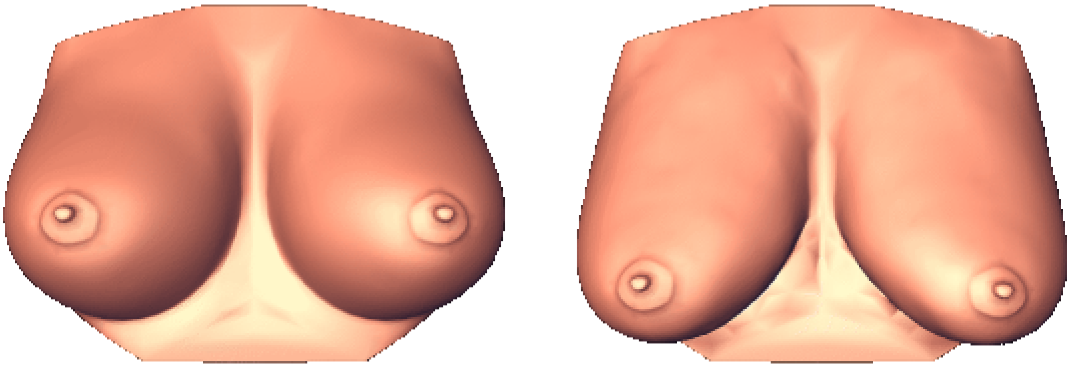

Fig. 5. Simulating the action of gravity on a female breast. Volume preservation is achieved by setting $\lambda = 200\mu$

6 Conclusion

We presented a new multi-layered model for automatically deforming the skin of human-like characters. We proposed a two-layered muscle model suitable for computer graphics applications. An action line is used for driving the motion and deformation of the outer layer, and even for the rendering stage as the skeleton of an implicit primitive. As the model makes use of a 1D mass-spring system, muscle deformation is performed in real-time. Our approach does require anatomical knowledge but there exists, fortunately, an exhaustive literature on the subject. Finally, unlike most previous works, we added a viscoelastic fat layer so as to enhance the resulting animation with important effects of dynamics like gravity and inertia. An elastic 3D fat layer is also a good candidate for interacting with a clothing layer on top of the skin.

We are currently working on improving the muscle model by adding twist springs to the action line so as to avoid uncontrolled twisting of the mesh. As for the fatty tissues, we are presently investigating the use of Langer's stress lines (see section 2.2.) for guiding the elastic deformations: we simulate anisotropy by making the Lamé parameters of each voxel direction-sensitive. Introducing a variable voxel size in the initial meshing of the volume would also help to better approximate complex shapes. This would not introduce instability because the approximations of the operators in (1) can handle some irregularity [Debunne99]. The last open issue of importance for future work is that the effect of gravity is already captured in laser scans or medical data e.g. the Visible Human Data Set [Ackermann95]. Further work includes generating the mesh of the *écorché* by fitting B-spline patches to the implicit surface and a complete multi-resolution simulation of the fat layer.

Acknowledgments

The authors are grateful to Thierry Michellod for designing all the models that appear in this paper. The authors would also like to thank the reviewers for their helpful comments. This work is partly funded by the European project MESH.

References

[Ackermann95] M. Ackermann, "The Visible Human Project", http://www.nlm.nih.gov/research/visible/visible_human.html, 1995.

[Chadwick89] J. Chadwick, D. Haumann, R. Parent, "Layered construction for deformable animated characters", Computer Graphics (SIGGRAPH '89 Proceedings), pp.243-252.

[Chen92] D. Chen, D. Zeltzer, "Pump it up: Computer animation of a biomechanically based model of muscle using the finite element method", Computer Graphics (SIGGRAPH '92 Proceedings), pp.89-98.

[Cox42] H. Cox, "The cleavage lines of skin", British Journal of Surgery, 29, 1942, pp. 234-240.

[Debunne99] G. Debunne, M. Desbrun, A. Barr, M-P. Cani, "Interactive multiresoution animation of deformable models", Computer Animation and Simulation' 99.

[Forsey91] D. Forsey "A Surface Model for Skeleton-Based Character Animation", Proc. Second Eurographics Workshop on Animation and Simulation (1991), pp. 155-170.

[Henne90] M. Henne, "A Constraint-Based Skin Model For Human Figure Animation". Master's Thesis, University of California, Santa Cruz, June 1990.

[Kalra98] P. Kalra, N. Magnenat Thalmann, L. Moccozet, G. Sannier, A. Aubel, D. Thalmann, "Real-Time Animation of Realistic Virtual Humans", Computer Graphics and Applications, Vol. 18, No. 5, 1988, pp. 42-56.

[Kass93] M. Kass, "Introduction to Continuum Dynamics for Computer Graphics", SIGGRAPH Course Notes 60, 1993.

[Lee95] Y. Lee, D. Terzopoulos, K. Waters, "Realistic Modeling for Facial Animation", Computer Graphics (SIGGRAPH '95 Proceedings), pp.55-62.

[Magnenat-Thalmann91] N. Magnenat-Thalmann, D. Thalmann, “Human Body Deformations Using Joint-dependent Local Operators and Finite-Element Theory”. In: Making Them Move (N. Badler, BA Barsky, D. Zeltzer, eds), Morgan Kaufmann, San Mateo, California, 1990, pp.243-262.

[Maurel98] W. Maurel, Y. Wu, N. Magnenat Thalmann, D. Thalmann, "Biomechanical Models for Soft Tissue Simulation", Springer-Verlag, Berlin/Heidelberg 1998.

[Porcher-Nedel98] L. Porcher-Nedel, D.Thalmann, "Real Time Muscle Deformations Using Mass-Spring Systems", Proc. CGI '98, IEEE Computer Society Press, 1998.

[Richer81] P. Richer, “Artistic Anatomy”, Watson-Gutpill Publications, New York, 1981, Translated by Robert Beverly Hale.

[Sederberg86] T. Sederberg, S. Parry, "Free-From Deformation of Solid Geometric Models", Computer Graphics (SIGGRAPH '86 Proceedings), pp.151-160.

[Shames92] I. Shames, F. Cozzarelli, "Elastic and Inelastic Stress Analysis", Prentice-Hall, 1992.

[Scheepers97] F. Scheepers, R. Parent, W. Carlson, S. May, “Anatomy-Based Modeling of the Human Musculature”, Computer Graphics (SIGGRAPH ’97 Proceedings), pp. 163-172.

[Sun99] W. Sun, A. Hilton, R. Smith, J. Illingworth, "Layered Animation of Captured Data", Animation and Simulation '99 (10th Eurographics Workshop Proceedings), Milano, 1999, pp.145-154.

[Thalmann96] D. Thalmann, J.Shen, E. Chauvineau, "Fast Realistic Human Body Deformations for Animation and VR Applications", Computer Graphics International'96, Pohang, Korea, June, 1996.

[Turner93] R. Turner, D. Thalmann, "The Elastic Surface Layer Model for Animated Character Construction", Proc. Computer Graphics International '93, Lausanne, Switzerland, Springer-Verlag, Tokyo, pp. 399-412.

[Van Gelder98] A. Van Gelder, "Approximate Simulation of Elastic Membranes by Triangulated Spring Meshes", Journal of Graphics tools, Vol. 3, No 2, 1998, pp. 21-42.

[Wilhelms97] J. Wilhelms, A. Van Gelder, "Anatomically Based Modeling", Computer Graphics (SIGGRAPH '97 Proceedings), pp. 173-180.

[Wu97] Y. Wu, P. Kalra, N. Magnenat-Thalmann, "Physically-based Wrinkle Simulation & Skin Rendering", Computer Animation and Simulation '97 (8th Eurographics Workshop Proceedings), Budapest, Hungary, 1997, pp.69-80.

[Yoshimoto92] S. Yoshimito, "Ballerinas Generated by a Personal Computer", The journal of Visualization and Computer Animation, Vol.3, pp.85-90, 1992.