

Modeling and Deformation of the Human Body Using an Anatomically-Based Approach

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Abstract

In this paper we propose a method to simulate human beings based on anatomy concepts. We believe that the closer our model is to reality, the better will be our results. Using this approach, we are developing our human representation. Our model is divided into three different layers and is presented in three steps: the rigid body conception from a real skeleton, the muscle design and deformation based on physical concepts, and the skin generation. Integration aspects and results are also presented.

1. Introduction

The problems involved in the simulation of human beings could be divided into two major steps: the creation of the human appearance, and the motion of the skeleton.

Modeling a human is a great challenge if we consider the numerous parts needed to compose a body. The first step is the basic structure modeling, the definition of the joints, their positions, orientations and the geometric model that will describe the body hierarchy. Next, we need to think about the body volume and on top of this, we can use a parametric surface to simulate skin, for example. With these three elements we can reach a good representation of a body, but this is not enough. The simulation of the face, hair, hands, feet, eyes, teeth, lips, etc. is also essential for the modeling of a complete human.

Simulating human motion is also a complex task. As the movement is rather intuitive, it is very difficult to take into account all the links involved in a simple movement, its natural balance and its multiple interactions with the environment. The nature of human behavior is also a factor to be considered. Each person has a unique way to be, to express his/her personality, to walk. Even if two

people are similar in their physical aspects, they may be very different in their behavior. The simulation of this aspect is a hard but necessary task in realistic human body animation.

In this paper, we describe our efforts in the human modeling aspect. Our first objective is to improve the complexity and the realism of motion. But, realism of motion needs to be improved not only from the point-of-view of joint as for robots, but also in relation to the deformations of bodies, hands and face during the animation. As the final motion is directly related to the model complexity, we believe that we can obtain more realistic movements if we apply the same principles used in nature. For this reason, we propose the modeling of a body based on anatomical concepts.

2. Background

The research on human animation started in the seventies [2] with the representation of humans by stick figures with only a few articulations joining the segments animated by a kinematic model. Later, to achieve more realist movements, researchers introduced physics-based models, and because humans do not act alone, they have also introduced behavioral models [2] to take into account the individuality of each character. More recently, the evolution of motion control models has made it possible to take into account the interactions between actors, actors with the environment and actors with real humans.

Concerning the body modeling, important efforts have been devoted to represent and deform the human body shape. The models presented until now can be classified into four categories: stick figure models, surface models, volume models and multi-layered models.

Systems using stick figure models consist of a hierarchical set of rigid segments (limbs) connected at joints. These models, called articulated bodies, may be

more or less complex, depending on the number of limbs and joints involved. Surface models are conceptually simple, containing a skeleton and an external shape, the skin (e.g. Thalmann *et al.* [16], Komatsu [8] and Forsey [6]). The main problem with the surface model is that it is hard to control the evolution of the surface across joints.

The volume models approximate the structure and the shape of the body with a collection of elementary volume primitives: ellipsoids, spheres, cylinders, etc. An example of the use of these primitives is “metaballs”, which considers the volume as a potential function and produces good, natural results [33]. These models generate better results than the surfaces models, but suffer from inadequate control mechanisms for a large number of primitives during the animation.

Finally, the multi-layered models contain the skeleton layer, intermediate layers to simulate the body volume (muscles, fat, bones and so on) and the skin layer. A good example of layered construction and animation of deformable characters is presented by Chadwick *et al.* [4]. Others multi-layered models were also developed, as the ones presented by Gascuel *et al.* [7], Singh *et al.* [15], Turner [19] and Thalmann *et al.* [17], for example.

Recently, multi-layered techniques were applied to anatomically-based models of humans and animals. Scheepers *et al.* [14] have presented a model where muscles (represented by deformable ellipsoids) react automatically to changes in the posture of the articulated skeleton and influence on the surface form. Wilhelms [20] proposes a multi-layered anatomically-based model to simulate animals. In her model, muscles are represented by deformable discretized cylinders.

3. The skeleton

Human body can be defined briefly as a conglomerate of skeleton, muscles, fat and skin. The skeleton is formed by bones (about 206 in total) attached with each other at joints. The base of a skeleton is the spine where the two pairs of limbs (arms and legs) and the head are connected.

In our work, we have used the basic skeleton structure presented by Boulic [3], but with new global positions for joints based on an anatomic approach. The BODY data structure is maintained with some generic information, including a topological tree structure for a vertebrate body with predefined mobility. The hierarchical topology orients the propagation of motion from the root to the terminal nodes. Each joint of a body is represented by one or more nodes in the tree, depending on the joint’s Degrees of Freedom (joints have up to three DOFs and each DOF corresponds to one node in the tree) and each node position is defined locally in relation to its parent node in the tree hierarchy.

Our simplified model of the human skeleton contains 31 joints with 62 DOFs. Neither facial animation nor hand

deformations are considered. So we do not represent joints inside the head or on the hands. The positions of the joints were computed from the analysis of a real skeleton. From a realistic reconstructed human skeleton, we have carefully determined the best position for each joint between the bones, based on the anatomy. In Figure 1 we can see the skeleton with bony landmarks highlighted, representing the positions of the joints.

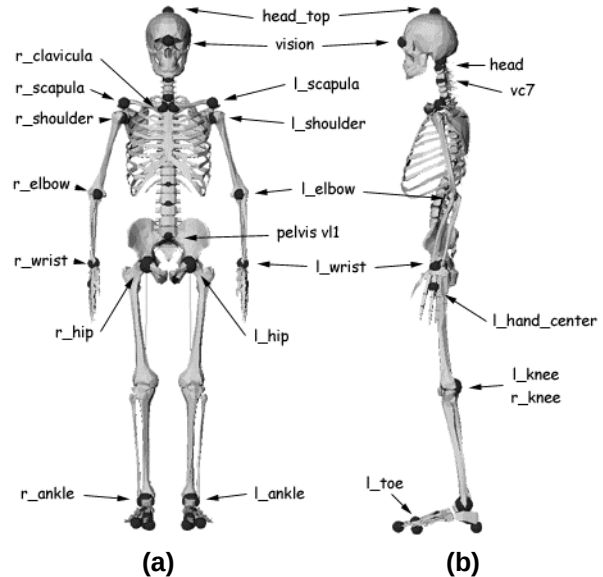


Figure 1. (a) Frontal and (b) lateral views of the skeleton with the joints positions highlighted

The higher part of the body hierarchy begins with the spine which was modeled with eight compound vertebrae. These compound vertebrae are divided into three groups, possessing different mobile characteristics: three lumbar vertebrae (vl) have tilt and roll; three thoracic vertebrae (vt) have limited or no tilt; and two cervical vertebrae (vc) have all three rotational mobilities, torsion, tilt and roll. The first lumbar vertebrae sits on the pelvic sacrum, while the last cervical vertebrae is under the atlas joint (see Figure 2).

Over the spine, the most difficult body part to model is the upper arm and the shoulder complex. We have chosen to represent the shoulder by three joints, with seven DOFs: clavicle (abduction and rotation); scapula (abduction and rotation); shoulder (flexion, abduction and twisting). Strictly speaking, the arm structure is attached to the spine as a child of the fifth compound vertebrae (vt5), while the two clavicles DOFs and the two scapula DOFs are not part of the arm structure, they only initiate its articulated chain. Figure 3 shows the bony landmarks that define the center of rotation for the three joints.

Bones are linked to joints in a hierarchical structure and modeled by triangle meshes defined locally in

relation to their parent joint. Our system is modeled with 73 bones, excluding the hands and feet that are represented by complete sets of bones. Bones do not change shape during animation, but can change position in relation to each other.

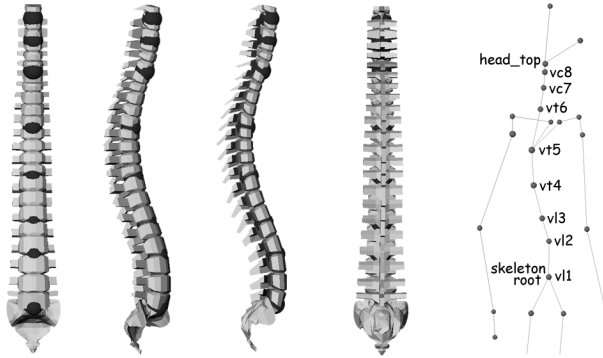


Figure 2. Several views of the spine with eight compound vertebrae

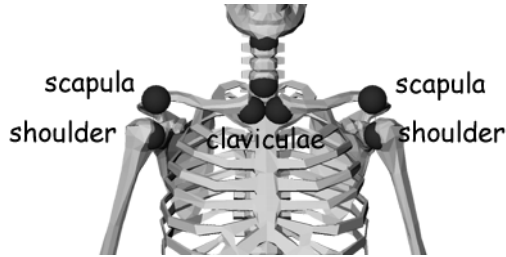


Figure 3. Center of rotation of the clavicle, scapula and shoulder articulations

We have added bones on the joints based skeleton, not only for aesthetic purposes but also because it is needed to attach the muscles (see Section 4). Another reason is that the visualization of the skeleton during animation allows the avoidance of forbidden postures, a tedious task when based only on a stick figure. The definition of the limit angles for each joint also became more precise when using bone representation between articulations.

4. The muscles

4.1. Action lines

The attachment of muscles to bones closer to the spine of the body is generally considered the *origin* while the other end is the *insertion*. Normally, the origin is the fixed point, while the insertion is where the muscle performs its action, though there is no formal rule about it. Most muscles are simply attached to two bones across a joint, and each bone may function as either the fixed point or the moveable one [5]. To mechanically quantify the force that a muscle produces over a bone, we can represent

muscles by lines, named *action lines*, with the same origin and insertion as a muscle.

4.2. Deformable shape

Our approach to simulating muscle deformations is based on the use of mass points linked by springs, and organized in such a way as to ensure a correspondence between the action line and the muscle shape. We assume that for all the cases, each muscle shape involves a whole or a part of an action line. Every point that forms the surface of a muscle is arranged between two neighbors in the horizontal and two others in the vertical sense, assuming the action line of a muscle as the up reference. In this sense, we can also say that the extremities of the muscle shape have the same positions as that of the action lines. Accordingly with this description, we conclude that our model is designed specifically to simulate fusiform muscles.

With the help of designers, we are studying separately the form and the behavior of each muscle and trying to model it accordingly to its biomechanically-based action line. In order to illustrate the process employed to design and deform muscles, we take the example of the *triceps*, a particularly complex muscle. The *triceps* corresponds to the fleshy mass placed on the back of the upper-arm and acts as an extensor muscle of the fore-arm. As its name implies, the *triceps* is composed by three heads, which are distinguished as the *inner*, the *outer* and the *middle* or *long head*. The *inner* head arises from the scapula, while the other two have their origin over the humerus. These three heads are their insertions points attached to the upper part of the ulna.

The muscle shape is manually modeled using two different kinds of data: a collection of pictures used on artistic anatomy and the corresponding action lines that describe the actuation of the *triceps*, as shown in Figure 4. Muscles are modeled by triangle meshes that are subsequently resampled for deformation purposes.

As explained above, we need each point in the muscle surface placed accordingly with the action line position, and in this sense, the modeled muscles we have, does not match our needs. To solve this problem, we have resampled each irregular triangle mesh into a regular grid (Figure 4.c shows an example of a resampled *triceps*). To this end, we have developed a muscle editor [10] where the user can connect the modeled muscle to its respective action line.

4.3. Deformation model

Our deformation model uses a model based on the application of forces over all mass points that compose the mesh, generating new positions for them. Adding all the applied forces, we obtain a resultant force for each

particle on the deformable mesh. For the sake of simplicity, we have considered three different forces: *elasticity force*, *curvature force* and *constraint force*. Then, the resultant force in each particle x_i , in a time t can be calculated as:

$$f_{result}(x_i) = f_{elasticity}(x_i) + f_{curvature}(x_i) + f_{constraints}(x_i)$$

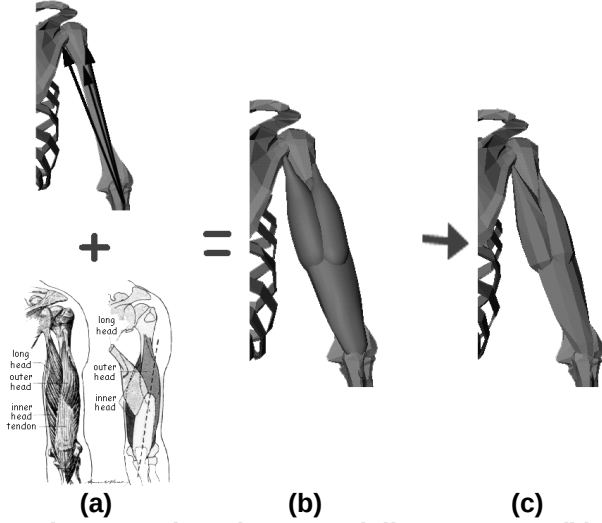


Figure 4. The *triceps* modeling process. (b) shows the 3D muscle shape model and (c) its resampled version. (b) and (c) are obtained from artistic anatomy pictures (a bottom) and the action lines scheme (a top)

To simulate the elastic behavior of the muscle mesh, we have used linear springs. The force that determines the degree of bending of a muscle is called curvature force. As with the elasticity force, this force is also calculated for each mass point over the surface as a function of its four neighbors. The physical simulation of these effects is designed towards the use of a new kind of linear spring which we call *angular spring*. The difference between both kinds of springs to simulate elasticity is the way they are attached. Angular springs are also used as a technique to control the muscles volume.

The geometric constraints are developed to improve the response to the different conditions not formally explicit in our internal force model. The implementation of the major part of the constraints force is done by using inverse dynamics. We would like to emphasize, that the methodology used to satisfy constraints allows the inclusion of new ones without the need to modify the physical model.

In order to reduce calculations, we have decided to consider only the representation of muscle surfaces. More complex models are described by Maurel *et al.* [9]. In fact, we believe we can simulate muscle deformation

without directly considering their volume characteristics. The surface is composed of a set of particles with mass density m . Their behavior is determined by their interaction with the other particles that define the muscle surface. In correspondence with the geometric structure presented before, each point of the mesh corresponds to a particle in the physical model. More details about our muscle model can be found in [10].

4.4. Deformation procedure

The design of a new muscle and its motion characteristics is a hard task. We need to intuitively find the best parameters for the simulation, apply these parameters over a geometric shape and visually test whether they are suitable or not. For this reason, we have developed a software called *mms* (**M**uscle **M**odel **S**imulator), that reads a file with a muscle shape, as well as some simulation parameters. The user can simulate the muscle deformation interactively and in real-time, by compressing or extending its action line with the aid of a slider.

We use the following parameters for the deformations: two elasticity coefficients, two curvature coefficients, the muscle mass and a damping factor used during the motion simulation.

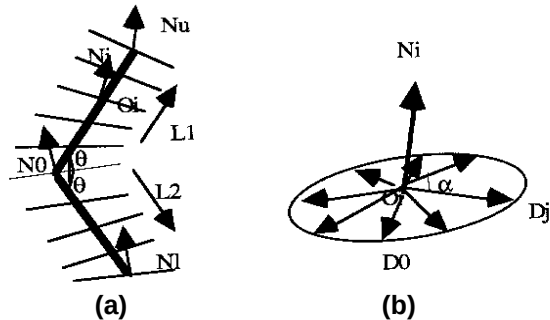
5. The skin

To generate the skin that covers all the bones and muscles, we used a surface sampled using ray-casting on semi-regular cylindrical grids. These sample points are used directly as cubic B-spline control points to smoothen the skin surface. Individual B-spline patches are triangulated, and these triangular meshes are stitched together to connect different parts of the human body for final rendering and output.

This approach takes advantage of the fixed topology of the human skeleton. Human limbs exhibit a cylindrical topology and the underlying skeleton provides a natural centric axis upon which a number of cross-sections can be defined. Each limb link is associated with a number of contours (Figure 5.a). The cross-sectional skin contours can automatically be extracted using the ray casting method. We cast rays in a star-shaped manner for one contour, with ray origins sitting on the skeleton link. For each ray, we compute the outermost intersection point with the muscles and bones surrounding the link. The intersection is a sample point on the cross-section contour (see Figure 5.b).

However, some postures could produce errors on the skin generation while using the method described above. An example is when a leg or an arm of a character is bent. In the case of the arm, our algorithm will generate the skin recovering on the same time (as an unique piece) the

upper and lower part of the arm. Using the same principle, we could also have an only piece of skin recovering the two legs of the character, when the actor have the two legs joined. To solve this problem, we have decided to assign each primitive (a bone or a muscle) to a group. Each group will blend with primitives in its own group or in the root group. Fifteen groups were defined covering whole body. Each primitive is assigned to a group according to its attachment to the skeleton. Some primitives, located on special positions (for example, a muscle that covers a joint), can fall into several groups simultaneously, as they may have contributions to multiple groups. To sample a contour, we only need to consider the primitives in its associated group.



an instance called *mms* (**M**uscle **M**odel **S**imulation data - see Figure 8) and attached to action line segments. A portion of the action line defined by two points is called a segment. Each point in the action line is related to a joint.

In Figure 8 we can see an example of an *instance model* of the muscle type. Each muscle has a name, is associated to one or more groups and is defined by one or more action lines. Each extremity of the action line is attached to a joint, and each segment can either be related to a muscle or not. It is made by indicating the *mms* index. Each *mms* instance contains the muscle shape file name and the parameters required to perform the deformation.

```
inst model 297 {
  name      "right_triceps",
  type      muscle,
  group     r_arm_upper r_arm_lower r_shoulder,
  origin joint r_clav_abduct position -52.0 117.0 -34.0 mms 1,
  insertion joint r_shoulder_abduct position -5.0 137.0 -13.0,
  origin joint r_clav_abduct position -52.0 117.0 -34.0 mms 2,
  insertion joint r_shoulder_abduct position -5.0 137.0 -13.0,
  origin joint r_clav_abduct position -52.0 117.0 -34.0 mms 3,
  insertion joint r_shoulder_abduct position -5.0 137.0 -13.0,
};

inst mms 1 {
  file      "triceps_Lportion.iv",
  degree_of_subdivision_on_x 10,
  degree_of_subdivision_on_y 5,
  elasticity_horizontal 0.0,
  elasticity_vertical 5.0,
  curvature_horizontal 0.0,
  curvature_vertical 5.0,
  total_mass 20.0,
  damping 0.5,
};
```

Figure 8. Extract of a model file with the definition of a complex muscle

The fourth step of the process is the skin generation and it is made automatically by *Body Builder Plus*. We can also consider another intermediate step, if the user desires to model a part of the body by metaballs. It could be made interactively and this procedure is at the same level as the muscle definition step.

6.1. Action lines motion motor

The lowest level in our muscle simulation system is the action line. We first simulate the action line motion and then, the muscle deformation. In this way, the muscle compression or extension depends directly on the action line. However, the final deformation depends also on other parameters. In fact, action lines are attached to bones that move in turn of the joints. When an articulation angle changes, bones move and consequently, muscles attached to these bones also move in the same way.

Currently, there are two ways to perform human motion. The first way consists in picking a joint and performing the motion of this joint interactively, while the

second way consists in loading the motion from an animation file.

The action line motion is produced in a module that, after each movement of the skeleton, detects which action lines are concerned and changes these lengths and/or directions. The deformation process begins for every muscle shape corresponding to the updated action line segments.

6.2. Motion simulation of muscles

The model used to deform muscles is based on an oriented particle system where the interactions between particles are modeled by springs. The movement simulation is produced by applying motion equations over each particle of each muscle, as explained in Section 4.

We have used the Lagrange's equations of motion as presented by Terzopoulos *et al.* [18], using a system of second-order ordinary differential equations. We have used a fourth order Runge-Kutta method [11] to integrate the equations. We have chosen this method because it is more stable than Euler's method while consuming an acceptable level of computation time.

7. Conclusions

This paper has presented a model to design and animate human bodies using an anatomically-based approach where bones are attached to joints and muscles are represented by two layers: the action lines and the volumetric forms. We have presented an automatic method to capture modifications on action lines and to induce deformations. Deformations of muscles are performed by a physically-based model based on a mass-spring system and the movement looks continuous and natural.

The integration of all the layers of our model is achieved. Now, we are working on the design of real muscles for the complete human body, with the collaboration of designers (see Figure 9). Figure 10 shows an example of elbow flexion performed by a body composed of bones and some muscles.

Future improvements were previewed in this work. For the muscle model, we intend to implement a collision detection and response method to solve problems of superposed muscles. Concerning the performance, we are also looking for methods to reduce the calculation time during the animation.

Acknowledgments

We are grateful to Jianhua Shen for the development of *Body Builder* and the skin generation method, Ronan Boulic and Walter Maurel for useful discussions and help and Srikanth Bandi for English review. We also thank

Thierry Michellod for his help and motivation on all muscle's design aspects. This work was supported by CAPES-Brazil and by the Swiss National Foundation for Scientific Research.

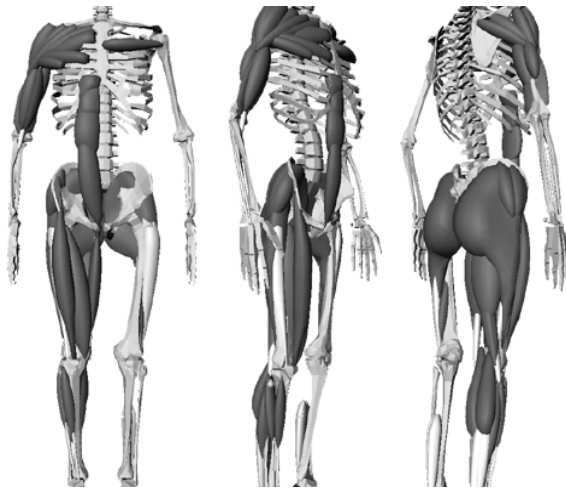


Figure 9. Muscled body

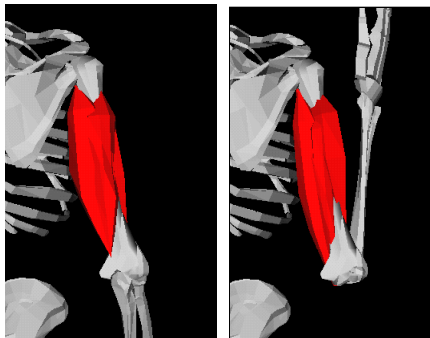


Figure 10. Elbow flexion with muscles deformation

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