Anatomy-Based Joint Models for Virtual Humans Skeletons

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Abstract

This paper describes a new joint model for articulated human skeletons. The model is based in human anatomy and was conceived for use in medical applications. In this model, we try to overcome some limitations of other models used in computer graphics. To validate, we compared a knee modeled with our approach with a simulator, a plastic model of a knee, and images taken during a video-arthroscopy.

1. Introduction

Many computer graphics applications require the creation of models of human bodies, which the complexity and fidelity to the human anatomy vary depending on the application goals. Traditional computerized animation of articulated figures usually do not need to be strongly based in anatomic models unless the realism of movements and appearance are essential for aesthetics reasons. Medical applications dedicated to motion or physiology simulation, however, impose requirements that come from human anatomy. Computer graphics models of virtual humans seldom fulfill such requirements.

The basis of the human body is the skeleton that is composed of approximately 200 bones, all of them connected to each other by joints [1]. Joints or articulations are the structures responsible to allow and constrain the body mobility. The main goal of our work is to create a joint model to represent virtual human skeletons strongly based in anatomic features.

In the next section, we explore human joints from the medical point of view. Section 3 overviews related works on human body modeling and simulation, highlighting the joint issues. In Section 4, we present a new anatomy-based computer model to represent human joints, while Section 5 discusses the results obtained so far. Section 6 contains final comments and future work.

2. Human Joints

Joints can be defined as the union between two or more bones [2]. A joint is the region where the bones meet each other and motion may take place. Many classifications are available for joints. Since the goal of this work is related to movement, we present the following one [1, 2, 3]:

Synarthrodial or Fibrous Joints. Immobile; union of two bones without any kind of motion. These joints are important because they can respond to applied forces, and, thus, absorb shocks. Examples are the sutures between the bones of the skull.

Amphiarthrodial or Cartilaginous Joints. Movable, but still have hard motion constraints due to the presence of a fibro-cartilaginous disc or membrane in the space between the bones, and very rigid ligaments. Provide a good mechanism to absorb shocks, and usually allow a 6 DOF (Degree Of Freedom) motion, which range is very small. Examples are the joints between the vertebras.

Diarthrodial or Synovial Joints. Characterized by the presence of the synovial fluid, which aids in the joint lubrication. They are the most common types of articulation in human motion. The observed motion and the shape of these joints allow classifying them into the following groups:

- **Plane:** A bone slightly translates and rotates against another by sliding its plane and small articular surfaces; up to 6 DOF are allowed. Examples are in the bones of the hands, as well as between tibia and fibula;
- **Uniaxial:** Characterized by the presence of a single rotational DOF. Two subtypes can be considered: hinge, where the motion axis is orthogonal to the bones; pivot, where the axis is parallel to the bones;
- **Biaxial:** Presents two rotational DOFs. The relation between the two axes is arbitrary and the motion range of one depends on the position of the other. According to the groove geometry, we can observe three subtypes: saddle, ellipsoid and condylar. The knee and the wrist are examples;
- **Polyaxial:** Also called ball-and-socket joint due to the bone ends geometry. It presents many rotational DOFs.

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Typically, three orthogonal axes are used to represent this kind of joint. Examples are the shoulders and hips.

Every axis in the last three types of joints mentioned above presents displacements caused by sliding between adjacent surfaces. In general, such displacements have the form of a curved path.

3. Related Work

Computer graphics literature presents many works on computer models for human and animal bodies. However, either they choose to simulate a specific type of joint, like shoulder or hand, or they propose simplifications in joint representation.

Schemes like H3D [4] or APJ [5] were presented in order to provide a mechanism to keep some topological structure. Boulic et al.[4] described H3D (Hierarchy 3D), where each joint has only one rotational or translational DOF. Building a joint like wrist, with two DOFs, requires creating two joints. APJ, the acronym for Axis-Position Joint has been proposed by Zeltzer [5] and extended by Silva [6]. This scheme uses a local reference frame to define position and orientation of a joint in relation to its parent in the body tree.

Wilhelms [7] presents a simplified articulated skeleton to support muscles and the covering of animals' bodies with a flexible surface simulating the skin. The body is considered as segments linked by three rotational DOF joints in tree architecture. Every segment is composed of bones, muscles and skin attachment points, and the joints reference frames hold the relations needed for a correct visualization.

Some works are particularly focused on simulating specific, complex articulated parts of the body. Monheit and Badler [8] presented a spine and torso model applied in the Jack System [9]. Data obtained from medical measurements were considered for building a virtual human torso with an easy way to control motion, suitable for ergonomics applications. In a work focused on the human shoulder, Maurel and Thalmann [10] presented a model based on constraints of scapula movement relative to the thorax. The set of joints in a real shoulder (sternum-clavicle; clavicle-scapula; thorax-scapula; scapula-humerus) forms a cycle, making the hierarchical representation not realistic. Thus, the authors developed a model where the scapula is linked to the thorax by a 5 DOFs joint – three rotational and two translational – while the other three shoulder joints are 3 DOFs joints. The motion is then applied only in the scapulo-thoracic joint, while in the others it is derived from the scapula position.

4. The Joint Model

In this section we describe a new anatomy-based computer model to represent either a whole articulated human skeleton, or just part of it. We try to minimize the anatomic realism loss caused by simplifications found in other models. Nevertheless, since it is intended for medical applications, it requires interaction and real-time rendering. Another issue was motion specification. Motion complexity is hidden from the user (a programmer, in our case) by several layers of abstraction.

4.1 Limitations of Existing Joint Models

Among the existing models (section 3), motion range of the joints is seldom constrained. In some of them, all the joints are equal, which means that they have the same number of DOFs. Such models need a complex motion control system to look like humans.

Another problem concerns the human inability to perform isolated movements. Biomechanics researchers generally try to isolate the motion of each joint and each of its DOFs to easily extract measurements. However, we know that our body works in synergy, and the range of one DOF can be dramatically changed by the status of other joints.

Although models for specific groups of joints (hand, shoulder, column) overcome most of the limitations above, even if we gather them to compose the several parts of a body, we will face an increasing difficulty to control motion.

4.2 Basis of our Model

Our model represents the human body articulated system as a tree where joints correspond to the nodes of the tree. The hierarchical data structure has been chosen because it is close to the human body topology. Every joint in our tree has a 4x4 homogeneous matrix, called LIM (*Local Instance Matrix*), to establish the relationship between a child and a parent joint. Graphic objects, like geometric primitives or polygonal meshes, can be associated to any joint in the tree by means of an object-LIM. These objects represent bones or any other human body structures. When position and orientation of a graphic object in relation to the global reference frame is needed, e.g. for exhibition, they can be obtained by multiplying LIMs of all joints, from the root to the current joint and the object's LIM. This process generates a GIM, the *Global Instance Matrix* of that object.

A generic joint is able to describe any kind of relative motion between two or more adjacent segments of the body. Such motion can be given by: a) a rotation around one axis; b) a composed rotation around two or three axis; c) a translation in one to three Cartesian directions; d) rotations associated to translations; and d) an axis sliding during rotation.

The presence of a DOF or not in a joint, defines if the joint is able or not to allow a specific movement. Joints do not care about what a specific motion means; this work is performed by the Dofs (in minuscule). Besides the joint, Dof is another important structure of this model. Basically, to each Dof corresponds its range of motion and an axis where the motion will be done. To flex a joint, we send it a new flexion parameter (a normalized real value) that is used to determine the new current angle to the joint's flexion Dof. A forward-linear mapping takes place, where 0 is mapped to the minimal angular limit, 1 to the maximal one, and every intermediary values to the corresponding angles.

Dofs are used to make changes in a joint LIM. Every Dof also owns a LIM, which describes a Dof local reference frame. So, the LIM of a joint is regenerated from its Dof's LIMs every time some movement occurs. Figure 1 presents a scheme of the model.

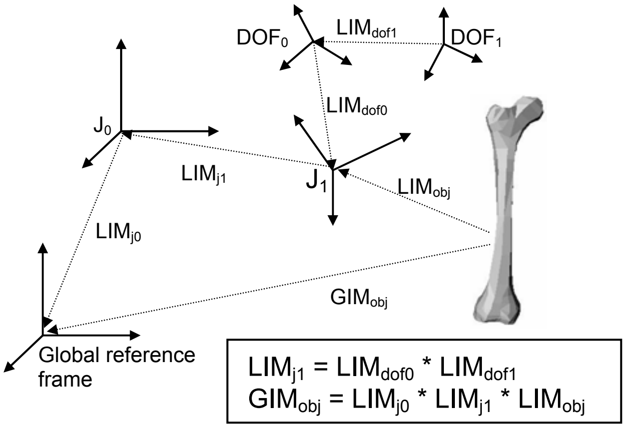

Figure 1. Model scheme. An articulated body composed by two joints (J_0 and J_1) and a bone attached to the second joint (J_1) (DOFs of J_0 not shown). When the rotation angle of one of the J_1 Dofs changes, the bone should also move. This will be achieved by recalculating the LIM of J_1 and, afterwards, the GIM of the object.

4.3 Types of Joints

We propose four basic types that we consider both needed and sufficient to represent any human joint. Once the difference between the two uniaxial human joint types, pivot and hinge, is limited to angular relations between motion axis and bones length axis, both pivot and hinge can be represented by only one ***Uniaxial Joint*** type. In the same way, the three types of biaxial human joints differ only in the bone ends geometry. So, we can represent condylar, ellipsoid and saddle joints by a ***Biaxial Joint*** type. Polyaxial human joints, as well as cartilaginous joints, can be represented by a ***Poliaxial Joint*** type with three rotation DOFs. The last type, ***Plane Joint***, also includes translations, being a six DOF joint type able to represent all human plane joints. A joint of this type can also be used as the root joint of a body to make possible to place it anywhere in a scene.

4.4 The Sliding Axis Case

Here, we describe our approach to solve the problem described in Section 4.1. As the sliding axis move along a *curved* path, we chose to represent it by a standard parametric curve in 3D space. To be sure that the axis will slide *on* the curve, every time the angular parameter of a Dof changes, the same parameter is used in the curve equations to determine its respective point on it. The example in Figure 2 shows a Dof angle and its reference frame position evolving according to the variation of the Dof parameter.

4.5 Relations between Joints Motion Ranges

Another important limitation mentioned in Section 4.3 concerns to the dependency between one joint status and the motion ranges of another joint. Although these relationships can vary from a person to another, we have considered them in our model to increase the correctness of the model and to make simpler the motion control algorithms. We propose that any Dof in the body can be associated to any other Dofs; the latter ones can exert influence on the former one motion range. To each influencer Dof we also associate two functions, one for its effect on the minimal angle of the influenced Dof, and the other for the maximal one. We used a structure called *Modifier* to represent such associations, and curves to represent the functions.

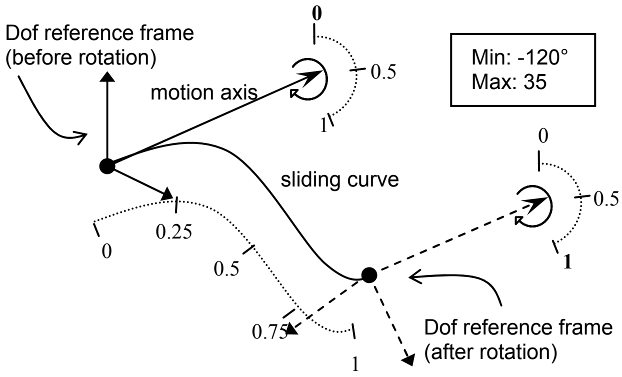

Figure 2. Sliding axis of a Dof.

5. Analysis of the Results

In order to test the model, we developed a system to simulate human joints, the so called BodySim. This system loads a body description and a simple key-frame animation script from a XML file (eXtensible Modeling Language) [11]. This format has been chosen because it is fully extensible, it is human readable, and there are parsers available. After loaded, the body is shown performing the motion defined. Using this platform, we generated some examples of body parts to be used as case studies in tests and validation. They are described in the following sections.

5.1 Topology: Dofs as Components of Joints

The fact that the body parts keep connected along the performance shows that, when Dofs matrices are modified to produce motion, the Joint matrices are correctly recalculated. In addition, the order in which rotations are applied for the two DOFs joints, like wrist (x rotation first and y rotation later, or y rotation first and then x rotation) does not imply in any problem.

5.2 Coupled Dofs

In Figure 3, we show a human forearm, where the wrist, completely abducted, moves from total hyperextension to total flexion. Notice that in extended position (stretched hand), the abduction angle is greater than when the hand is in the extreme angular positions. This constrained movement is due to a variation in the minimal angle for adduction/abduction. This example shows that the model can successfully describe a dynamic change in the range limit of one axis according to the current posture of another.

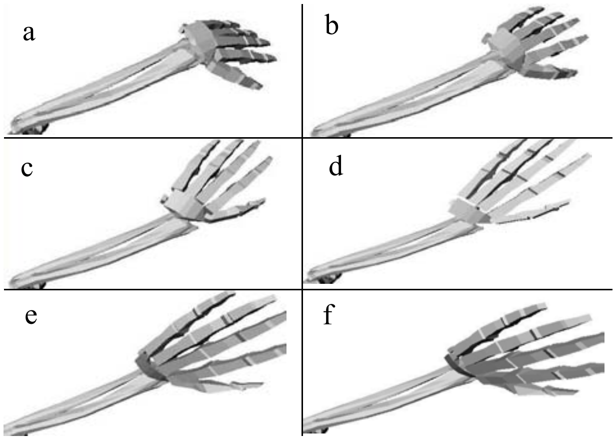

Figure 3. Arm motion using a Dof Modifier. The Modifier constrains the movement applying a variation in the minimal angle for adduction/abduction, which goes from –35° to approximately 0° and back to –35°, as the angular parameter of the flexion/extension Dof ranges from 0 to 1.

5.3 Anatomical Fidelity

In this aspect, we based our validation in the following assumption: if we can validate the model for a particular human articulation that is sufficiently complex, probably it will be also valid for the simpler ones. So, we chose the knee, a complex articulation of large medical interest, especially because of its constant injuries relating sport activities.

We set up the knee properties in the generic model according to medical literature and advice, and specified the motion description to define a complete flexion/extension cycle. Then we looked to compare it with other instances of knees. This comparison was basically visual, and was based in three different experiences. The fourth knee instance, not approached in this work, would be a postmortem dissected knee. In this field, Heegaard et al. [12] have made important measurements, though they do not present visual results.

Simulation system comparison. *SIMM* (Software for Musculoskeletal Modeling) [13] brings a pre-configured human right leg in its demo distribution. In this leg, the knee movement is described such that it seems to be the real knee movement. To compare our knee with the *SIMM* knee, we tried to place the skeleton and the viewer equally in both systems, and we took the shots shown on Figure 4. We can see on the pictures that the postures are very similar.

Plastic knee comparison. A *Sawbones* plastic model created by *Pacific Research Laboratories* is considered very realistic in the orthopedist opinion [14]. With the help of a medical doctor [14], we performed movements with the plastic knee, and recorded several takes. The comparison is illustrated in Figure 5, where we find a great similarity, in particular the *patella* motion (it touches first the lateral *condyle* when flexing), but also the terminal rotation (*tibia* rotates externally in the last 20 degrees of extension) and the flexion/extension axis displacement while rotating.

Internal view of the real living knee. Video-arthroscopy is a surgical procedure that allows the observation of the interior of a living joint. Basically, two or three small cuts are done on the patient knee by means of which the surgeon inserts a mini video camera. The image captured by the camera is shown in a video monitor, where the surgeon can see what is happening inside the knee. An interesting and useful view in the scope of this work, is the view of *patella* motion during an arthroscopy. Figure 6 shows a sequence of takes of the *patella* over and on the *femur condyles*.

6. Conclusions and Final Comments

We presented an anatomically based model to represent joints in articulated bodies. This model will be used in the VPAT – Creating Virtual Patients – project to support medical applications like surgery planning and simulation, prostheses implant preview, measurements in athletic training performance and so on. Features not present in existing models were included in this one to allow higher anatomic correctness and real-time rendering. Some of these features are the ability to represent all types of human joints, sliding axis approach and a mechanism to represent interference of one joint position and orientation in the motion ranges of others.

We also presented a system to test and validate the model. Our validation approach was based in the observation of produced motion in comparison with real and other artificial knees. Videos can be downloaded from the VPAT site at http://www.inf.ufrgs.br/cg/vpat/.

A lack in our validation process was the impossibility of measuring the geometry of the models used in the comparison, and the angles of the performed movements. If that was possible, we could probably reproduce specific geometry and motion for the models, yielding better comparison.

As future work, we intend to create or adapt some existing motion control algorithm, in order to apply realistic movements to our skeleton. We also wish to explore the possibility of attaching muscles and tendons to the joints. With this, more than providing correct motion, the model could also provide correct shape, and shape could be used to parameterize the joint.

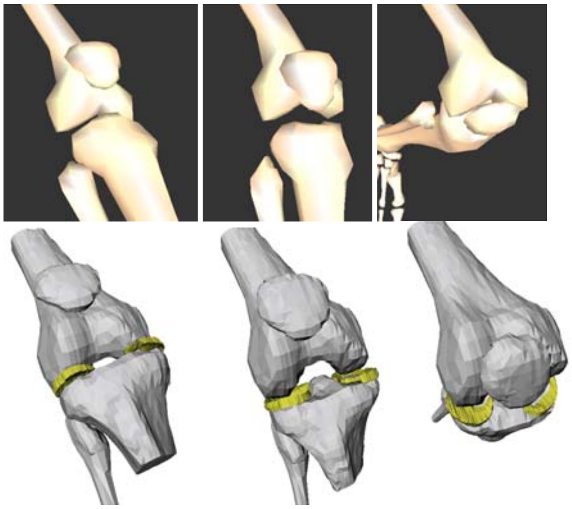

Figure 4. Comparison between SIMM and BodySim knees. The frames on the top show the SIMM knee in 3 stages of flexion. On the bottom, the respective frames captured from our system are shown.

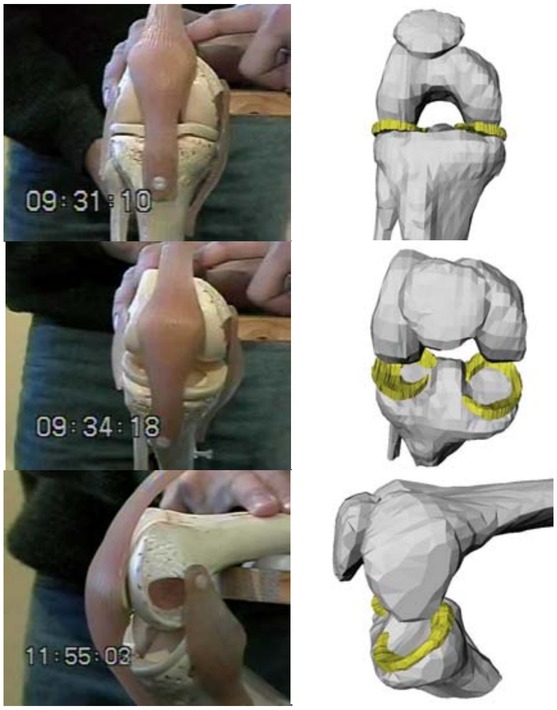

Figure 5. Comparing *BodySim* results and the plastic model. The video frames from the experiments with the plastic model are shown on the left column. Respective frames obtained with our model are presented at the right column.

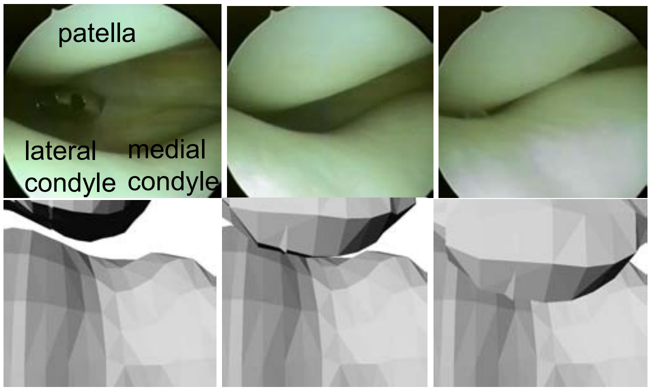

Figure 6. Comparison between a real and the BodySim knees. The top row presents a sequence of arthroscopy takes of the *patella* over and on the *femur condyles*. The first one is in full extension, then in 30 degrees of flexion, and finally flexion of 45 degrees. To compare them, respective takes from *BodySim* are shown in the bottom row. Note that patella touches first the lateral *condyle* and place itself in the fosse only at 45 degrees of flexion.

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