Anatomy-Based Joint Models for Virtual Humans Skeletons

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Abstract. This paper describes new joint model for articulated human skeletons. The model is strongly based in human anatomy and was conceived for use in medical applications, like surgery planning and simulation, prostheses implant or athletic training. In this model, we try to overcome some limitations of other models used in computer graphics. We studied anatomy and biomechanics in order to uncover any specificity, like rotation axes that slide while moving and dependences existing between one joint motion range and other joints status. A knee modeled with our approach was compared to a simulator (SIMM), 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. The complexity of these models and the 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, like in the latest computer graphics movies. Virtual reality environments pose also constraints and requirements in the representation of virtual beings; virtual humans should behave like humans in movement, gestures and expressions. Medical applications dedicated to motion or physiology simulation intending to support ergonomic tests, athletic training, surgery planning and simulation, prostheses implant simulation on orthopedics and plastic surgery, however, imposes 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]. Since joints are fundamental components of the human skeleton, and the structures responsible to allow and constrain the body mobility, we believe that creating a human joint model is the natural first step to be accomplished towards modeling the whole body. Despite the fact that many authors have already addressed the joint problem [4,5,6], especially in robotics and animation, those works did not take into account anatomic features deeply enough to

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be applied in Medicine. 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 briefly explore the human joints from the medical point of view, in order to figure out their anatomic and biomechanical issues, types and motion. Section 3 overviews related works on human body modeling and simulation, highlighting the joint model 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

A joint or articulation can be defined as the union between two or more bones [2]. From the medical point of view, a joint is the region where the bones meet each other and motion may take place. A joint involves the bones, cartilage, tendons, ligaments and muscles, i.e., all the anatomic parts reaching at the bone ends. There are movable and static joints; in those that are movable, the motion is given as a rotation around one or more axis, or translation in one or more directions. Joints can be classified according to their movement, complexity, number of motion axis, geometry, etc. Since the goal of this work is related to movement, we present the following classification [1, 2, 3]:

**Synarthrodial or Fibrous Joints.** Immobile; characterized by the union of two bones without any kind of motion. Nevertheless, 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.** Despite movable, still have hard motion constraints, due to the presence of a fibro-cartilaginous disc or membrane in the space between the bones, and due to very rigid ligaments. Besides providing a good mechanism to absorb shocks, they usually allow a 6 DOF (Degree Of Freedom) motion: rotation around the three coordinate axes, and translation in the three directions. However, the range of motion is very small for all of them. Examples are the joints between the vertebrae, and between the scapula and clavicle.

**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 (Figure 1) allow classifying them into the following groups:

- **Plane:** Joints of this type (Figure 1a) allow a bone to slightly translate and rotate one against another by sliding their plane and small articular surfaces; up to 6 DOF are allowed. Examples are in the carpal, tarsal and metatarsal bones, as well as between tibia and fibula;
- **Uniaxial:** Characterized by the presence of a single rotational DOF. Two subtypes can be considered: hinge (Figure 1c), where the motion axis is orthogonal to the bones; and pivot (Figure 1b), where the axis is parallel to the bones;
- **Biaxial:** Presents two rotational DOFs. The relative position and angle between the two axis 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 (Figure 1d), ellipsoid (Figure 1e) and condylar. The knee and the wrist are examples;
- **Polyaxial:** Also called ball-and-socket joint (Figure 1f) due to the bone ends geometry, it presents many rotational DOFs. Typically, three orthogonal axis are used to represent this kind of joint, and like biaxial joints, the position of one axis can change the range of another. This is the most versatile type of joint and examples are the shoulder and the hips.
Every axis in the last three kinds of joints mentioned above has great ability to move while presenting large motion ranges. In addition to the rotational movements that characterize them, as far as the joint rotates, there are also auxiliary axis displacements caused by sliding between adjacent joint surfaces. In general, such displacements have the form of a curved path.

![Figure 1. Human Joints Geometry](image)

### 3 Related Work

Despite the fact that computer graphics literature presents many works on computer models for humans and animals bodies, they generally propose simplifications in joint representation and concentrate their attention into modeling muscles, skin, hair, motion control, etc. In addition, some of them choose to simulate a specific type of joint, like shoulder or hand.

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. All joints carry matrices representing their relationship with their parents and the root joint of the model, as well as other relations needed to edit and simulate them. 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. In addition, each joint has pointers to its children and allow the creation of branched structures with several DOFs for each joint. Position and orientation of any joint of the tree can be obtained by composing the homogeneous transformation matrices that define the reference frames of each joint.

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, like a hand or shoulder. Monheit and Badler [8] presented a spine and torso model applied in the Jack System [9]. Data obtained from medical measurements of the motion of every individual vertebrae, muscles and ligaments influence, sizes of real bones and cartilaginous discs, and torque and resistance forces, 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. In this model, 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, and some simplifications were made without serious fidelity loss for the resulting motion. Another issue was motion specification. Motion complexity is hidden from the user (a programmer, in our case) since we used object-oriented modeling techniques to provide layers of abstraction, with relatively simple interfaces between them.

4.1 Limitations of Existing Joint Models

Among the existing models (section 3), motion range of the joints is seldom constrained, that is, any rotational DOF is able to rotate 360 degrees. In some of them, all the joints are equal, which means that they have the same number of DOFs. From the medical point of view, such models are not able to perform correct motion and need a complex control system to look like humans. In addition, in those models, joint motion rarely occurs around a fixed axis or point. Actually, as long as rotation movement is carried out around an axis, this axis presents some displacement from its original position. Such a displacement is not large, but is strongly important for anatomic correctness. Even so, the works referenced in Section 3, as many others we found in computer graphics literature, ignore these “sliding process”, considering only fixed rotation axis.

Another problem in joints modeling concerns to the human inability of performing isolated movements. Generally, biomechanics researchers try to isolate the motion of each joint and each of its DOFs, in order to extract motion measurements easily. So, most joint motion range tables presents individual axis values. 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. Nevertheless, we could not find any work in computer graphics literature regarding such relative DOF ranges. To reach natural looking movements, the authors need to develop complex animation control algorithms.

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.
Finally, from the software engineering point-of-view, many models were developed as monolithic blocks, hard to extend, modify, reuse, and integrate to different interfaces and control motion algorithms. Modern software engineering techniques like object-oriented (OO) modeling and UML [11] (Unified Modeling Language) representation should be applied in order to change this situation. Despite we have modeled the joint model using UML and implemented it in an OO programming language, this will not be presented in this paper.

4.2 Basis of our Model

Our model represents the human body articulated system as a tree where joints (the main structures of the model) correspond to the nodes, and the body segments are the edges 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), in order to establish the relationship between a child and a parent joint in the data structure. Therefore, each joint is defined in its parent reference frame, except the root joint, which is defined in the global reference frame. Graphic objects, like geometric primitives or polygonal meshes can be associated to each joint in the tree. These objects carry a LIM that defines its position in relation to the joint, and are intended to represent bones or any other human body structure that changes accordingly to the joint position. 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 must be 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, two, or three Cartesian directions; d) rotations associated to translations; and d) an axis sliding during rotation.

Then, we can say that, in our model, a joint represents a set of possible movements that are defined according to its degrees of freedom. The presence or not of a DOF in a joint, defines if the joint is able (or not) to allow a specific movement. A two DOFs joint, for example, determines two kinds of movement, e.g. flexion/extension and adduction/abduction. But what does flexion/extension mean? What does adduction/abduction mean? Joints do not care about it; this work is performed by the Dofs (in minuscule). Besides the joint, Dof is one of the most important structures of this model. Basically, to each Dof structure corresponds: its rest position, its maximal, minimal and comfortable angular limits; and the axis where the motion will be done. To flex a joint, we should send it a new flexion parameter (a floating-point normalized value) that is used to determine the new current angle to the joint flexion Dof. A forward-linear mapping takes place, where 0 is mapped to the minimal angular limit, 1 is mapped to the maximal one, and all intermediary values are mapped to the corresponding angles. Figure 2 shows an example of one Dof joint flexion movement. In this specific example, when the flexion parameter is equal to 0.5, the joint Dof will be at –42.5 degrees.

As a joint LIM describes a reference frame positioned and oriented in relation to the parent of the joint, moving a joint is the same as modifying its LIM. In order to make the desirable changes in a joint LIM we use its Dofs. Every Dof also owns a LIM, which describes a Dof local reference frame and is based in the parent Dof. For the first Dof of a joint, which does not have a parent Dof, the LIM describes a Dof local reference frame based on its parent joint. So, the LIM of a joint is regenerated from its Dof’s LIMs every time some movement occurs.
Figure 3 shows an example of the scheme required to represent an articulated body composed by two joints (J₀ and J₁) and a bone attached to the second joint (J₁). When the rotation angle of one of the J₁ DoFs changes, the bone should also move. This will be achieved by recalculating the LIM of J₁ and, afterwards, the GIM of the object (as shown on Figure 3).

4.3 Types of Joints
In Section 2 we presented a classification for the movable human joints defining seven types of joints for the freely movable joints, and one type for cartilaginous articulations. Analyzing the ability of those joints to move, we propose four basic types that we consider both needed and sufficient to represent any human joint. A Uniaxial human joint is represented by a joint with only one rotational DOF. The difference between pivot and hinge joints is limited to angular relations between motion axis and bones length axis. Then, once the model can be fully configured, 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, with two rotation DOFs. Polyaxial human joints, as well as cartilaginous joints, which move in many axis, can be represented by a Poliaxial Joint type. It would be noticed that three standard axis are enough to describe motion in any other axis, thus, poliaxial joints present three rotation DOFs. The last type, Plane Joint, also includes translation DOFs, being a six DOF joint type able to represent all plane human joints. A joint of this type can also be used as the root joint of a body to make possible to place the body anywhere in a scene.

4.4 The Sliding Axis Joint Case
In Section 4.1, we presented the sliding axis issue as a limitation of the other computer joints models. Here, we describe our approach to solve that problem. As the sliding axis move along a curved path, we chose to represent them by a standard parametric curve in 3D space, called evoluta (Figure 4). In order to be sure that the axis will slide on the curve while the joint moves, we used the following approach: every time the angular parameter of a Dof changes, the same parameter is used in the curve equations to determine its respective point on the curve. Then, the axis is translated to the calculated
point. The example in Figure 5 extends the one presented in Figure 2 and shows a Dof angle and also the changing of the Dof reference frame position according to the variations on the angular parameter.

![Figure 4. The evoluta represents the sliding curve of the human knee](image)

### 4.5 Relations between Joints Motion Ranges

Another important limitation that was mentioned in Section 4.3, concerns to the relationship 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, since it increases the correctness of the model and makes the motion control algorithms simpler. 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 one for its effect on the maximal angle. In our model we used a structure called Modifier to represent such associations and curves to represent the functions, what is shown with more details in the Figure 7.

![Figure 5. DOF Sliding axis.](image)

![Figure 6. DOF Modifier](image)
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 uses the SGI Open Inventor API [12] to perform the visualization and loads a body – or body segment – description and a simple key-frame animation script from a XML (eXtensible Modeling Language) file [13]. This format has been chosen because it can be fully extensible, it is human readable, and there are parsers available, simplifying the data charge. After the charge procedure, the body is shown performing the motion. It is also important to say that we did not use any high-level motion control algorithm; it is not the goal of this work. The motion is simply generated from a set of instructions that determine the postures each joint should achieve in some given instants of time. The postures of each joint are then linearly interpolated.

Using this platform, we generated some examples of body parts connected by joints 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

Figure 7 shows a human skeleton with 4 joints of the left arm moving. Regardless the number of bones involved, the motion occurs in real-time, since only the position of movable parts need to be recalculated and redrawn. The fact that the limbs 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 latter, or y rotation first and then x rotation) does not imply in any problem.

![Figure 7. Six frames of a complete skeleton in motion](image)

5.2 Coupled Dofs

In Figure 8, we show a human forearm, where the wrist, completely abducted (oriented towards the ulna), 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 8. Arm motion using a Dof Modifier. The Modifier constrains the movement applying a variation in the minimal angle for adduction/abduction, which goes from $-35^\circ$ to approximately $0^\circ$ and back to $-35^\circ$, 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 chosen the knee, a complex articulation with 3 contact surfaces, 3 bones and its respective cartilages, the menisci, and 3 different coupled motion types. Another reason to choose the knee is the large interest of medical doctors in this joint, especially because of its constant injuries relating sport activities. As a consequence of this, we could find many references in the literature and could get medical participation during this validation process.

We started setting up the knee properties in the generic model, as shown in Figure 9. Axis positions, motion ranges, sliding curves and coupling between axis have been configured according to medical literature and advice. The bones and menisci geometric information are triangle meshes read from Open Inventor (iv) files, in turn, reconstructed from the Visible Human Dataset [14]. Finally, we specified the motion description defining a complete flexion/extension cycle.

Once the knee model was built, we looked to compare it with other instances of knees. This comparison was basically visual, and was based in three different experiences. From the more to the less realistic one: a real knee, both in the surface and internally (by means of video-arthroscopy records); a very realistic plastic model; and a widely known virtual simulation system, called SIMM (Software for Musculoskeletal Modeling) [15]. The fourth knee instance, not approached in this work, would be a postmortem dissected knee. In this field, Heegaard et al. [16] have made important measurements, though they do not present visual results.
Figure 9. Schema of the knee designed to perform the model validation. This configuration is probably not the ideal one, but is easier to manually describe in a XML file. We considered 3 joints: femur_tibia, with 2 coupled Dofs (one for flexion/extension and the other to terminal rotation) and a hook-like sliding curve; femur_menisci, to move the menisci forward and backward when the condyles press them; and femur_patella, which is coupled to the flexion/extension Dof of femur_tibia, and results on the patella movement on the condyles.

Simulation system comparison. SIMM 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. It includes non-fixed and coupled axis. However some limitations exist. Those are the absence of some motion axis (only one is considered), the absence of menisci, and the very low resolution of the mesh that represents the bones. 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 10. We can see on the pictures that the postures are reasonably similar.

Plastic knee comparison. Metal, wood or plastic models has been used for years to simulate or replace parts of the human body. A Sawbones plastic model created by Pacific Research Laboratories is considered very realistic in the orthopedist opinion [17]. This model is an articulated reproduction of the human right knee. It presents, besides the 3 bones, the 4 main ligaments, the menisci, and a detachable patellar tendon. With the help of a medical doctor [17], we performed movements with the plastic knee, and recorded several takes with a digital video camera. Later, we chose a set of the most representative frames in the video to reproduce in our model the same knee gestures and camera positions. The comparison is illustrated in Figure 11, in which 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.
Figure 10. 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. The motion is very similar, except for the menisci motion and the terminal knee rotation, both absent on SIMM.

**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 during the knee arthroscopy, by means of what the surgeon inserts a mini video camera and a tool to work in a possible damaged internal structure. The image captured by the camera is shown in a video monitor, in which the surgeon can see what is happening inside the knee. The image is very sharp and clear, allowing the doctor to detect and fix existing pathologies. An interesting and useful view in the scope of this work, is the view of patella motion during an arthroscopy. With it, we can get a better understanding of this motion and its role within the joint motion. Figure 13 shows a sequence of arthroscopic takes of the patella over and on the femur condyles. The first one in full extension, then in 30 degrees of flexion, and finally in 45 degrees flexion. Respective takes from BodySim are also shown, allowing us to compare.

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 the implementation of 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, which we considered as satisfactory for the goals of this work. Such motions can be observed at the VPAT site (http://www.inf.ufrgs.br/cg/vpat/). By comparing with SIMM we verified that important features of this representative simulation system are present in our model. The comparison with a plastic knee model showed fidelity to the motion of the main internal knee elements. Finally, the arthroscopic view added details of the natural movement that can not be observed in plastic models, where many structures are not represented.

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.

Currently, we are developing a modeling system to help assembling bodies that can be further saved in XML file format to be load into BodySim. It will allow us to build more complex bodies avoiding the need to write complex XML files manually.

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. We also believe that the object-oriented design used in the model will make easier the process of extend it.

References

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Figure 12. The upper line 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 in 45 degrees. To compare them, respective takes from BodySim are shown behind. Note that patella touches first the lateral condyle and place itself in the fosse between the condyles only at 45 degrees of flexion.
Figure 11. Comparison of 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.