Automatic modeling of knee joint motion for the Virtual Reality Dynamic Anatomy (VRDA) tool

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Abstract A system for automatic modeling of anatomical joint motion for use in the Virtual Reality Dynamic Anatomic (VRDA) tool is described. The modeling method described in this article relies on collision detection. An original incremental algorithm use this information to achieve stable positions and orientations of the tibia on the femur for each angle considered between these two components on the range of motion. The stable states then become the basis for a look-up table employed in the animation of the motion of the joint. The strength of the method lies in its robustness to animate any "normal" anatomical joint, given a set of kinematic constraints for the joint type as well as an accurate 3D geometric model of the joint. The demonstration could be patient specific (based on a person's real anatomical data from an imaging procedure such as CT scanning) or scaled from a generic joint based on external patient measurements. The modeling method has been implemented on a generic knee model for use in the VRDA tool.

Index Terms- Augmented Reality, physically based modeling, 3D anatomical atlases, anatomical joint motion, optical see-through 3D display.

1 INTRODUCTION

Realistic modeling of joint motion is essential for the design and implementation of the Virtual Reality Dynamic Anatomy tool (VRDA). The VRDA tool is an augmented reality visualization tool for teaching the motion of anatomical joints [1][2]. The VRDA tool will enable a user manipulating the joint of a subject as depicted in Figure1, to visualize a virtual model of the inner bony anatomy superimposed on the limb. This will be achieved using tracking and real-time rendering of a virtual model of the inner components of the knee using an optical see-through 3D display.

Understanding the 3D relationships of internal anatomical structures and the significance of body part movements is essential for clinical examination of patients, understanding normal and pathological conditions, and treatment planning. However, most students in medically related studies currently learn anatomy with a variety of limited formats including two

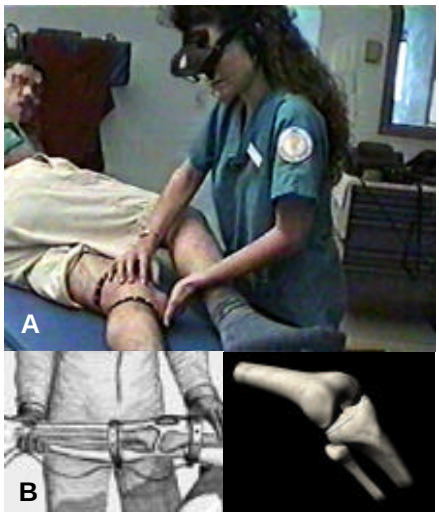

Figure 1: (a) The VRDA tool allows superimposition of virtual anatomy on a model patient. (b) Illustration of the user's view (Courtesy of Andrei State). (c) Rendered knee-joint bones

dimensional printed photographs, slides, labeled drawings, and cadaver dissection labs. Medical education, in particular, includes clinical examination of patients and radiographic correlation with gross anatomy and pathology. Traditional methods often do not allow simultaneous visualization of both internal and external structures. Interactive videodisc, multimedia presentations, and computer dissection simulations have been implemented and evaluated successfully. Video and computer-based demonstrations of dissections are infinitely reversible and repeatable, but they do not integrate the palpation of external anatomical landmarks. In addition, electronic tools do not provide the spontaneous feedback involved with living human models.

Because of the limitations of these traditional approaches to anatomy instruction, students may have artificial limits on their ability to quickly understand and apply the concepts. Direct visualization of scaled internal 3D anatomical structures in motion superimposed on the body such as it will be done with the VRDA tool could help. We anticipate that students will form more accurate mental models of the joint motions in shorter time periods compared to current learning processes [1].

Early versions of the VRDA tool may not simulate some of the more complex movements and elastic tissue deformations with a high level of precision. However, it has certainly a level of accuracy sufficient to provide an effective demonstration of the 3D nature of joint motions. Compared to traditional 2D or static models, the VRDA tool offers distinct educational advantages. One of them is that the user interacts with the whole live model while positioning rather than reducing the study of anatomy to one isolated disarticulated limb at a time. This provides more holistic approach to learning,

We developed an automatic modeling of the kinematics of a 3D geometric model of the knee joint for the VRDA tool. The method allows one to model the motion of any generic joint without creating gaps or intersections of the components (e.g. tibia, femur, menisci) throughout the whole range of motion considered.

2 BACKGROUND

Most current knee-joint models are dynamic because loads are considered. These models are generally created either to simulate dynamic movement [3] or to estimate parameters that cannot be measured in-vivo (e.g. ligaments' reference strain, [4]). These models deal with rigid body dynamics and ligaments and muscles forces but do not take into account the exact geometry of the joint. However, because the implementations of rigid body dynamics are typically non-stable and computationally intensive, the models are typically computed assuming a quasi-stable state and the results are dependent of the intial conditions. In order to reduce the complexity of the computation, planar models or mathematical approximations of the contacting surface are often considered [5]. An example is the sphere or spiral approximation of the condyles of the femur [6], or the planar approximation of the tibial plateaus [7], from which one induce the trajectory of the components of the knee. Yet, another approach is to utilize experimental motion curves from the motion of real joints for use with generic geometric models. Such models typically induce modeling errors that can be readily observed because the motion curves do not correspond to the exact geometry of the joint components.

While all the approaches cited were adopted for meeting specific purposes for given applications, none of them emphasizes the visualization of a given geometrical model in three dimensions. Consequently, collision or gap can occurs between the elements of the model, which we judged unacceptable for use in the VRDA tool.

The only method that considers geometry is a technique that has been employed on 3D models of digitized knee bones. To find the attitude of the femur relative to the tibia, the method minimizes the distances between two contact points [8]. This technique is only valid because the meniscus is not included in the geometrical model and the contact is reduced to two contact points. Another recent approach is to segment volumetric magnetic resonance imaging (MRI) data over multiple angles of various motions (e.g. flexion-extension) [9]. This work is in progress and may provide a pratical approach in the future.

3 METHODS

The method we developed is general in the sense it can be applied to all anatomical joint types because it uses the geometry and the actions of ligaments of the modeled joint rather than external data. The strength of our approach is that it yields no gap or intersection between the bones on the overall range of motion, regardless of the bone geometry used. The joint is assumed to be under no load because the user of the VRDA tool manipulates it. The menisci slide as the knee is flexed and participate to the support of the load with the tibia. However, since their behavior is not well known because it was recently discovered and few data are available, they are considered rigid and attached to the tibia during the modeling. Using our approach, a model with three-dimensional motion capabilities that include flexion and screw-home angles can be generated.

3.1 Kinematic modeling

The ligaments and the contact surfaces are considered to constrain and stabilize the bones in their equilibrium relative positions and orientations. In the knee joint for example, the anterior cruciate, posterior cruciate, and lateral ligaments constraint the femur, and the tibia to a stable configuration. We consider in this model that the ligaments produce a resulting force whose direction, called Δ, is assumed constant. This direction is taken along the main axis of the tibia, however it could be modified without lost of generality. During the use of the VRDA tool, a user will manipulate the knee of a subject that can thus be considered under no load. Since a tracking system will detect the flexion angle of the knee of the subject and we will drive our model accordingly, we only model the kinematic constraints. During the modeling, collision detection is employed to detect the contact points between the bones and the menisci. An original incremental algorithm determines for each given attitude of the joint (i.e. flexion and varus-valgus angles) the optimal relative position and orientation of the bones as if one were pushing them together along this specific direction.

3.2 Collision Detection

Exact collision detection determines which polygons forming the geometric models are intersecting in a given attitude. The modeling algorithm uses the normal at the contact point to make the joint elements slide against each other in a final stable position and orientation [10][11]. A C library called RAPID developed at the University of North Carolina (UNC) is used to solve the problem of finding the collisions [12]. This library returns the list of the intersecting triangles of the colliding geometric rigid-body models. By processing the colliding triangles, the contact points can be extracted. The normals to the model's surface at the contact points are used to give the directions of the reaction forces that appear when collision occurs between two rigid bodies.

3.3 Optimal Positioning Paradigm

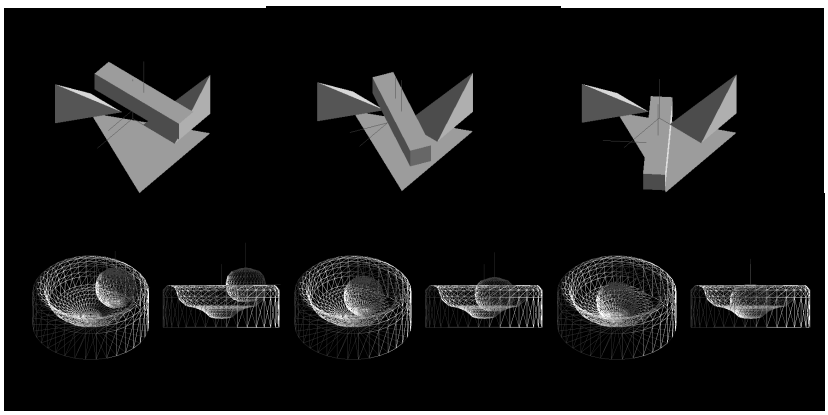

Figure 2: Two test objects to validate the algorithm. A torque is correctly produced on a bar falling between two pyramids (top). A ball falling above a dish converges correctly toward the center of the dish (bottom).

Generally stated, one of the rigid bodies, called the reference, is fixed in space. The other rigid body slides and rotates against the reference in order to reach an optimal position and orientation given that the motion is constrained along some degrees of freedom. In the case of the tibiofemoral joint, the femur is the reference, and the tibia is moved toward the femur to reach a stable state. The motion toward this stable state is constrained so that the flexion and varus/valgus angles are kept constant during the search for stability.

The motion of the moving rigid body is initially set to the estimated direction Δ of the resulting force that would be produced by the ligaments. A first translation allows placing the solids in preliminary contact. Then, at each step, the procedure verifies if there were collisions during the last motion, which could have been a translation or a rotation. If no collision occurred, the original direction of motion is reestablished. If there was collision, exact contact is made along the last performed motion.

At this point three scenarios can happen: the solid can rotate due to a torque, translate, or adopt an equilibrium position. The moving solid can only translate along Δ, the direction imposed by ligament forces, and in the plane orthogonal to Δ, and can only rotate around Δ, the other orientations being fixed for a specific given attitude. The translation along Δ is performed when no collision occurred at the last step. The translation in the plane orthogonal to Δ is performed if no rotation around Δ because of a torque is possible.

To demonstrate the convergence of the algorithm toward a stable position when only translation is involved, the convergence of a ball toward the center of dish is shown in Figure 2. In this example, the direction Δ was set to be vertical to simulate the gravity of the Earth. Another example, showing the automatic generation of torque on a bar falling between two triangularly shaped pyramids is shown also in Figure 2. These test objects were one of those selected to test the functions of the algorithm.

3.4 Algorithm Convergence

Cycle detection has been implemented to eliminate problems of convergence when large modeling steps are employed or computational errors of the result occur in the case of the translation. The procedure verifies if the current computed attitude of the solid is at an attitude similar to a previous step. The difference in angle, in this case, is less than the angular resolution, and the difference in position is less than the translation resolution. If such a case occurs, a cycle is detected and the modeling step size corresponding to the last motion for either orientation or translation is divided in half. The step size is reset to its original value either if the original direction of motion is re-established following a rotation, or if a torque is produced after a translation. When collision occurs during the last computed motion, reducing the step size allows the resulting motion to become finally smaller than the required resolution. This allows the algorithm to converge effectively to a stable position.

The cycle detection also allows the solution of a problem that could occur when a torque should be produced, but does not occur as a consequence of the solid moving step-wise.

Consider the bar falling between two surfaces shown in Figure 4. When the bar touches both surfaces, it rotates as a consequence of a torque. The original position of the bar and the modeling step size can be such that the bar never touches both surfaces at the same time, but rather oscillate between both. However, in such a case, a cycle would be produced and the step size would be regularly decreased, bringing the solid slowly toward a position where both surfaces touch and consequently produce a torque on the object. The method we developed allows motion using modeling steps within the size of the object for fast convergence without unstable behavior.

4 RESULTS

Figure 3: The animated textured knee-joint bones used in the VRDA tool. These snapshots of the automatically animated knee joint during flexion extension show multiple views of the joint with both condyles touching along the flexion/extension.

The method was implemented on an SGI Onyx Deskside with two processors at 150 MHz. We used a high-resolution geometric model from Viewpoint Inc. that includes geometric models of the bones, the meniscus, the ligaments, the tendons, and the muscles. Each polygonal model was transformed in triangle primitives for suitability with the collision detection engine. The model was described in the extension position, vertically, with the patella in front. In this configuration, all the bones had their origin at the same location and in the same orientation. We considered two degrees of freedom, the flexion and the varus/valgus angles, as entry to our model for the modeling. For both orientation and translation, we used a modeling step ten times larger than the associated resolution. The resolution of the human eye is one arc minute, and the viewing distance of the model is typically 0.5 m in our application. The maximum resolution in translation resolvable by the human eye was thus 0.145 mm. We set 0.1 mm as the translation resolution and 1 mm as the translation step during modeling. To obtain the corresponding resolution for the rotation, we accounted for the tibia being enclosed in a circle which radius was 30 mm. Thus, an arc length of 0.145 mm must be produced by an angle of 0.27°. We set the orientation resolution to 0.1°, and the modeling rotation to 1°.

The curve of the translation produced by the Anterior-Posterior drawer effect (AP-drawer) as a function of the flexion angle showed some discontinuities that were also observed during simulation in two places at all varus/valgus angles. We understand that these discontinuities are due to the discrete nature of the geometry of the model using polygons. The polygon roughness prevents the motion of the tibia during a range of flexion angles, whereas at a certain angle the motion is possible because one stopping edge is favorably oriented. We

elected to perform a least-square polynomial surface regression to smooth the discontinuous motion curves. By using a polynomial of degree 6 for the two translations and the rotation curves, a smooth motion model was rendered without perceptible collision. Snapshots of the final rendering the smoothed model animated with a flexion-extension motion are shown in Figure 3. Various snapshots acquired during the full cycle of flexion-extension from various viewpoints are shown. The lookup table used to animate the joint was constructed such that the condyles touch for every value of the flexion-extension angle.

5 CONCLUSION

A new method based on collision detection and biomedical knowledge for automatic modeling of the motion of the bones of the knee joint is reported. This work is a milestone in the development of the VRDA tool. The method was described and applied to the motion modeling of the flexion-extension of a generic model of the bones of the knee joint. A motion model can take months to construct if the bones are manually placed. By comparison, the automatic approach to modeling permits one to scale and animate a joint or some of its components within a couple of hours. The technique employed offers advantages over other techniques for our specific application because of its simplicity and the conformity of the results to the model used.

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