Computer Graphics Based Approach as an Aid to Analyze Mechanics of the Replaced Knee

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***Abstract*—A computer graphics based approach is being developed as an aid for orthopedic surgeons to learn engineering mechanic. As an application of this approach, a planar mathematical model of the human knee is used for analyzing the mechanics of the joint after replacement with artificial implants. Graphic representation is used for the bones, prosthetic components, fibers of ligaments and the lines of various forces. Using computer programming, motion and force data is generated for a large number of joint positions, which is then utilized to simulate the knee mechanics during flexion / extension. The simulations show very clearly during motion the bones relocating in relation to each other, different fibers of the ligaments becoming straight or slack and the muscle and ligament forces changing their direction and position. The simulations can also be used for analyzing the effects on joint mechanics of changing the implant design or of surgical errors.**

Keywords—Modeling and Simulation, Graphics Based Model, Knee Mechanics.

I. Introduction

Healthcare professionals like surgeons and physiotherapists often need to develop an understanding of the basics of engineering mechanics to be able to appreciate the implications of certain decisions in terms of patient outcome. For example, the selection of an implant for joint replacement by an orthopedic surgeon depends on several factors including the extent of damage to the articular cartilage as well as the availability of intact and functional load bearing soft tissues surrounding the joint [1]. To make the task of learning the basic concepts of engineering mechanics by the healthcare professionals more interesting, easier and effective it is important to develop techniques and tools which help in visualization rather than using mathematical methods which normally are not used by such professionals.

This paper presents a computer graphics based planar mathematical model of the human knee joint after replacement with an artificial implant. Mechanics of the joint is analyzed using realistic representation of joint structures from anatomical studies and simulating basic tests that are used in professional practice. The outcomes of such tests can be visualized using the model graphics as determined by the mathematical model.

II. Methods

Three major steps were used in the development of the present interactive computer graphics based mathematical model of the knee in the sagittal plane.

Step-1. The initial mathematical modeling involved defining the anatomical parameters, material properties of ligaments, dimensions of prosthetic components, conditions of geometric compatibility and the conditions of mechanical equilibrium [2,3].

Step-2. Developing computer programs for calculating motion and force data for a large number of knee positions during flexion / extension or during a simulated antero-posterior test at a fixed position of the joint [2–5]. These programs were written in C++ programming language.

Step-3. Developing computer programs in Matlab for a graphical interface to simulate the joint motion using the data produced from step 2 above.

The anatomical parameters and the material properties of ligaments were obtained from previous experimental studies [2,3], while dimensions of the prosthetic components reproduced features of a similar design available in the market, that is, a spherical femoral component, a flat tibial component and a congruous mensical bearing [6,7]. Line representation was used for net muscle forces. The ligaments were divided into a large number of fiber bundles which developed forces when stretched and remained buckled when slack [5]. For a more realistic appearance of the model knee, the bony outlines were digitized and scaled from a radiograph of a patient with a similar implant [7].

Since the emphasis here is on the use of computer graphics as an aid for learning, the details of mathematical modeling and the validation of results have not been discussed in this paper. Elsewhere, the results from mathematical modeling of an intact knee or a knee with prosthetic components have been shown to be in general agreement with the experimental observations from radiographic (in vivo) and cadaveric (in vitro) studies [3,4,6,8–13].

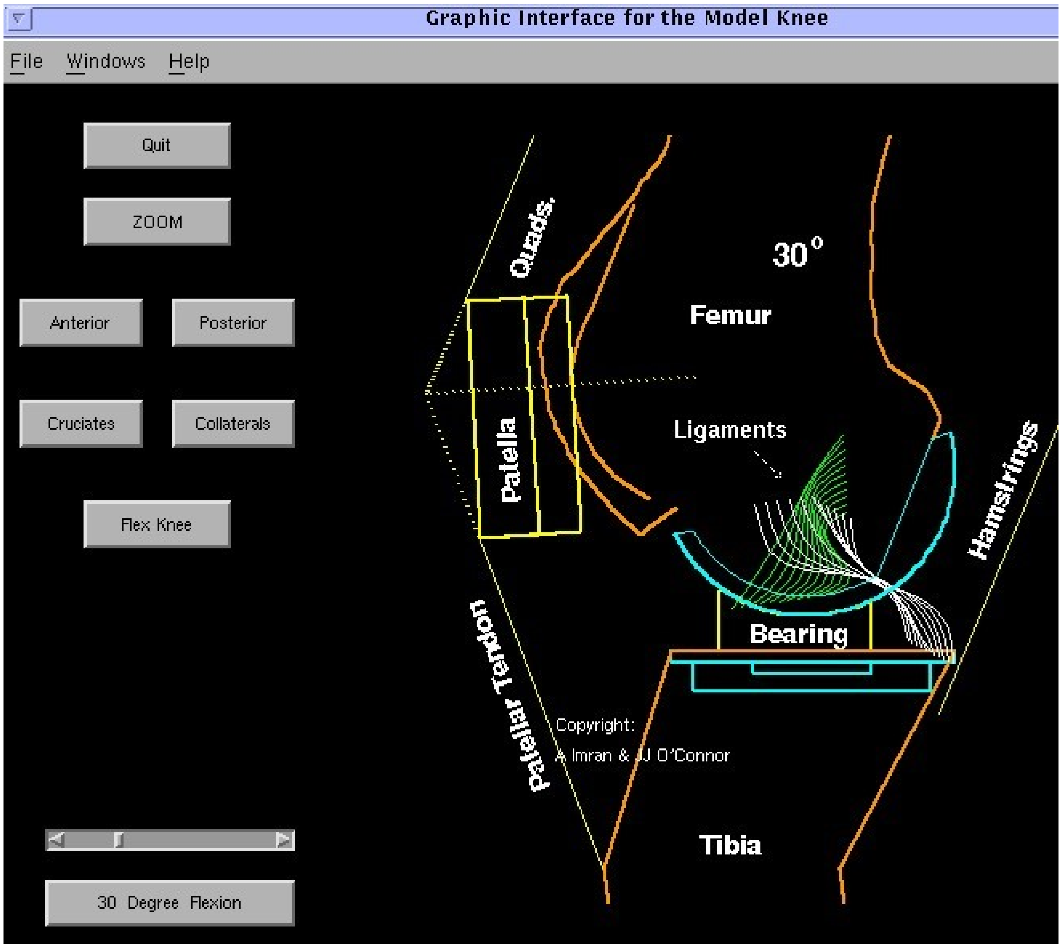

Fig. 1. An image from the graphic interface of the model knee with various elements marked.

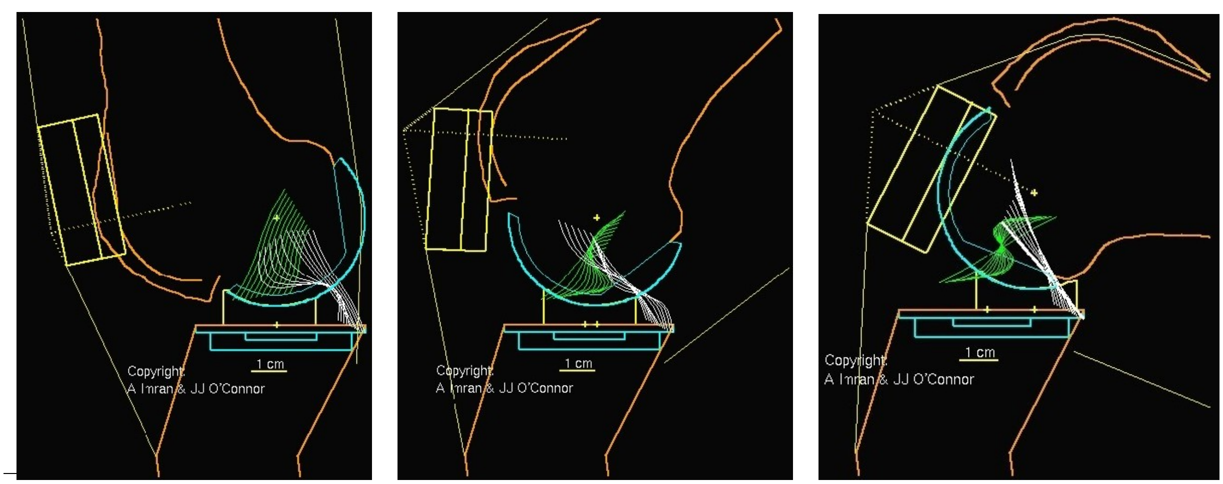

Fig. 2. The model knee shown at 0º, 60º and 120º flexion.

I. Results and Analysis

Fig. 1 shows graphic interface for the model knee at 30º flexion with various elements marked. The control buttons provide various options like simulating flexion / extension, selecting a specific flexion angle, hiding or showing specific pairs of ligaments (that is, cruciate ligaments and/or collateral ligaments), simulating anterior or posterior tests at a fixed flexion angle. The fibers of the ligaments were shown by curves when slack, by thin straight lines when ready to stretch [5] and by thick straight lines if stretched developing forces.

Fig. 2 shows the model knee in three different positions at 0, 60 and 120 degree flexion. While the lower bone or the tibia is shown fixed, the upper bone or the femur is shown to rotate as well as translate posteriorly during flexion suggesting that the

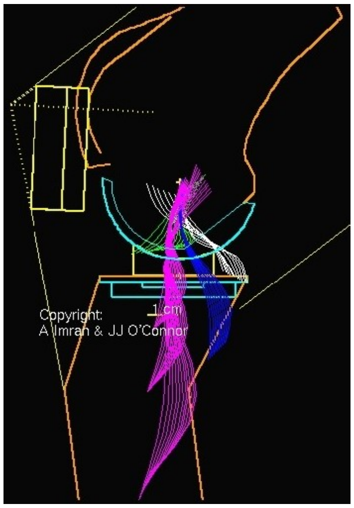

Fig. 3. The knee shown with all the modeled ligaments.

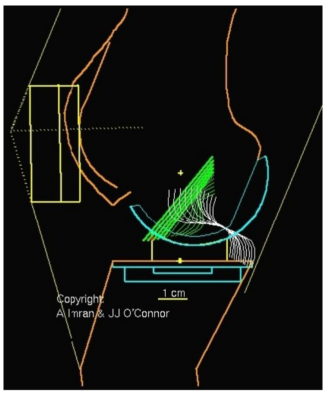

Fig. 4. Effects of a simulated test with anterior force on tibia resulting in stretched fibres of the anterior cruciate ligament.

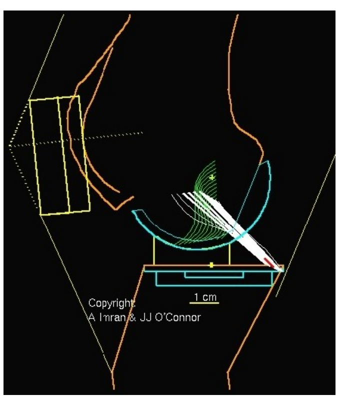

Fig. 5. Effects of a simulated test with posterior force on tibia resulting in stretched fibres of the posterior cruciate ligament.

replaced knee did not act as a simple hinge joint. Notice that the selected placement of the prosthetic components on the bones did not stretch the ligament fibers in any flexion position – they were either slack or just ready to stretch. This behavior has clinical significance [7].

The lines representing muscle forces changed their orientations during flexion. In addition, the ligament fibers became straight or slack. The slackness in the fibers depended on the joint position.

The meniscal bearing inserted between the femoral and tibial components translated on the tibia and allowed femoral rotation while maintaining congruency in all positions of the joint.

Fig. 3 shows the model knee with the cruciate and collateral ligaments with different attachments on the bones. The medial collateral ligament was modeled in three layers. Fibers from these layers may be removed as per surgical practice during replacement. The model allows analysis of the joint mechanics with the ligaments sacrificed either partially or fully.

Fig. 4 and Fig. 5 show the effects of a simulated antero-posterior test whereby the joint laxity is assessed by holding one bone and translating the other antero-posteriorly at a fixed flexion angle. The model shows how the ligament fibers are recruited and forces are developed as the bones translate relative to each other.

These are some of the several features of the model that can be utilized to study the joint behavior. A lot more can be learnt from this graphic approach. For example, the model can be used to analyze the effects of choosing a bearing either thicker or thinner than the one shown here resulting either in stretched ligaments or in increased joint laxity respectively – both of these effects have clinical consequences. Similarly, the effects of mal-placement of the prosthetic components, or the effects of prostheses of altogether different designs can be studied. Other clinical / laboratory tests can also be simulated.

II. CONCLUSIONS

The computer graphics based model presented here can be used as an aid for learning without going into the mathematical details or calculations involved in analyzing the mechanics. The model simulates the knee joint mechanics after prosthetic replacement. Certain features of the model have been presented here showing the effects of joint motion on positions and orientations of various structures as well as the effects during a simulated laxity test. Though limited to the sagittal plane, the model results have shown general agreement with the experimental observations available from literature. It can be a useful tool to gain insight into the mechanical behavior of the joint after replacement with different prosthetic designs, the effects of the surgical decisions like sacrificing or retaining certain ligaments as well as the effects of surgical errors in the placement of components.

ACKNOWLEDGMENT

The author would like to acknowledge Professor J. J. O'Connor for support, guidance and feedback.

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