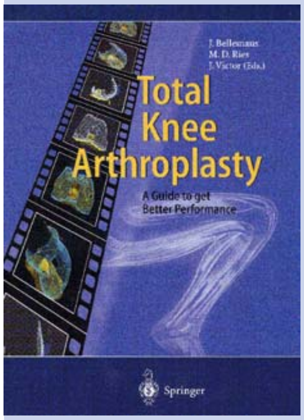

24 The Virtual Knee

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Summary

The Virtual Knee is a 3-D, dynamic, physics-based software that simulates in vivo functional activities for the purpose of evaluating the kinematic and kinetic performance of TKR designs. Implant models are virtually implanted onto a lower-leg Oxford rig-like knee simulator that is driven through activities including gait and deep knee bend using active quadriceps and hamstring actuators. The surrounding soft tissues, including LCL, MCL, and capsule, are modeled. By varying parameters such as implant geometry, ligament tensions, component positioning, and patient anthropometrics, this complex system can be understood, which allows the design of better-performing implants.

Introduction

The typical engineering design process for most complex mechanical systems is illustrated in Fig. 24-1. This process is followed by many industries including the aerospace, the automotive, and of course the orthopedic industry. In this process, virtual testing and physical testing design-iteration loops are employed, both of which are important methods for arriving at a final design that meets the design inputs.

The virtual testing loop uses computational methods to evaluate performance before physical components are ever made. Although virtual methods cannot perfectly model the physical world, the advantages of this method are that many design iterations can be evaluated quickly and cheaply. Moreover, all variables are controlled, and quality measurements can be extracted for nearly everything modeled in the system. Virtual testing is a powerful method for characterizing the system and understanding how specifically varied parameters affect the results. With the exception of finite element analysis, the orthopedic industry has generally been without a robust, dynamic analytical testing method. Consequently, total knee replacement design has relied heavily on physical testing methods.

Although the physical testing loop measures real-world performance, it is time consuming and expensive. Drawings must be prepared and tooling and gaging must all be designed and manufactured just to produce a high-fidelity prototype implant. The physical testing machines for TKR performance evaluation include servohydraulic machines (e.g., MTS and Instron), wear simulators [1, 2], and Oxford/Purdue-type knee simulators [3, 4]. But these machines have their shortcomings. They often generate insufficient data because inline force transducers provide only force magnitude and not direction, multi-degree of freedom transducers are large and expensive, and multiple transducers add complexity. Some testing machines oversimplify the real-world conditions. Often derived resultant forces are applied to the implants, leaving out major stability-contributing tissues (e.g., quadriceps, hamstrings, collateral ligaments, and capsule). Also, the nonlinear properties of these tissues are hard to replicate and

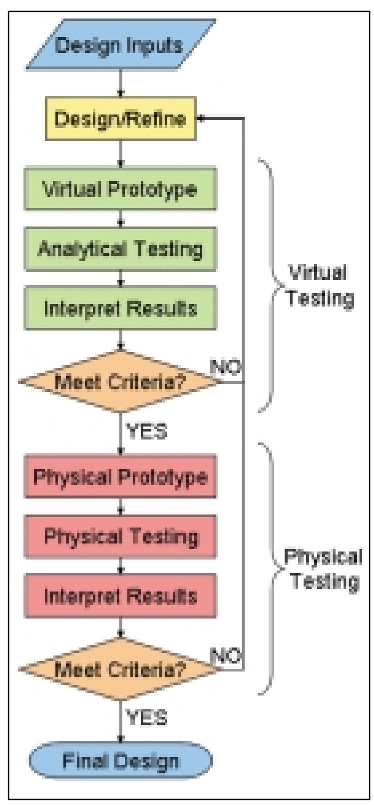

Fig. 24-1. Engineering design process for complex systems

they are difficult to attach to testing fixtures. The simulations are generally limited to less demanding activities like walking, stair climbing, and deep knee bend because of inertia, fixture interference, and limited actuator stroke. More demanding activities (e.g., running, tennis, and skiing) are too challenging to replicate. When cadavers are used, they are variable in size, shape, and location of anatomical landmarks. In addition, great care must be taken to minimize implantation alignment errors.

Because of high cost and long lead times, the number of physical design iterations is severely limited. In addition, the confounding factors of the physical testing machines make it difficult to interpret the results and make educated decisions about design changes. As a result, TKR design has evolved slowly, and the kinematic and kinetic performance has not been optimized. Recently, an analytical tool called the Virtual Knee (Biomechanics Research Group, San Clemente, Calif., USA) has been used to address the shortcomings of the physical testing phase, and it has the potential to greatly advance TKR design.

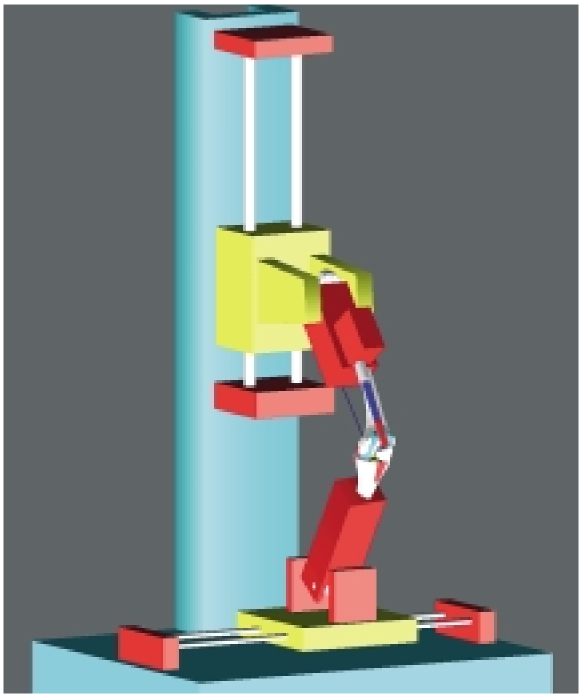

Fig. 24-2. The Virtual Knee simulates lower leg in vivo functional activities for the purpose of evaluating the kinematic and kinetic performance of TKR designs

Materials and Methods

The Virtual Knee is a 3-D, dynamic, physics-based software that simulates in vivo functional activities for the purpose of evaluating the kinematic and kinetic performance of TKR designs. Every parameter during the simulation is controlled and can be kept identical between trials. By comparing the results between design iterations, changes in kinematics and kinetics can be directly attributed to changes in the articular geometry, allowing designers to more easily meet performance design goals.

The Virtual Knee models a lower limb mounted to a Purdue-like knee testing rig (Fig. 24-2). Anatomically accurate 3-D bone models of the femur, tibia, and patella with the desired anthropometrics are mounted to the rig and serve as reference for implant placement, joint line position, scale, and ligament/muscle attachment.

The constraints imparted on the simulation include the hip and ankle joint, passive soft tissues, intrinsic geometric contact constraint, and active muscle elements. The hip joint is modeled as a revolute joint, parallel to the flexion axis of the knee, and is allowed to slide vertically. The ankle joint is modeled as a combination of several joints that combine to allow free translation in the ML direction and free rotation in flexion, axial, and varus/valgus directions. Passive tissue constraints are modeled as spring/damper elements and are attached to the virtual bones at their respective anatomical locations [5]. The mechanical properties of the tissues were obtained from Woo [6]. The LCL is simulated with a single constraint element, and the MCL is modeled with two separate constraint elements to simulate the anterior and posterior fibers (Fig. 24-3). For posterior cruciate-retaining knees, a PCL element is added and attached at the respective anatomical locations. The final soft-tissue constraint is the general capsule force, which simulates the general soft-tissue reactions of the knee capsule. This force is directed such that it draws the femur and tibia together in a similar manner to the capsular tissues in the actual knee.

Intrinsic geometric constraints are imparted by the conformity of the TKR models, which includes stick/slip friction and stiffness characteristics. A contact algorithm models the articular surfaces, which are discretized into quadrilateral elements, as a bed of springs with the stiffness characteristics of polyethylene. The method allows for intermittent contact, contact pressure, and center of pressure determination. This algorithm is used to model contact of the patellofemoral joint, the tibiofemoral joint, between the cam and post, and between the quadriceps tendon and femoral component.

The active, driving elements in the model are the quadriceps and hamstrings muscle forces. The quadriceps muscle attaches to the quadriceps tendon and is discretized into six components which conform to the distal head of the femur or anterior flange of the femoral component, permitting proper force transmission to the femur and patella. The patella is attached to the tibial tubercle through the patellar ligament, which conforms to the polyethylene insert component. The simulation is driven by a controlled actuator arrangement similar to the

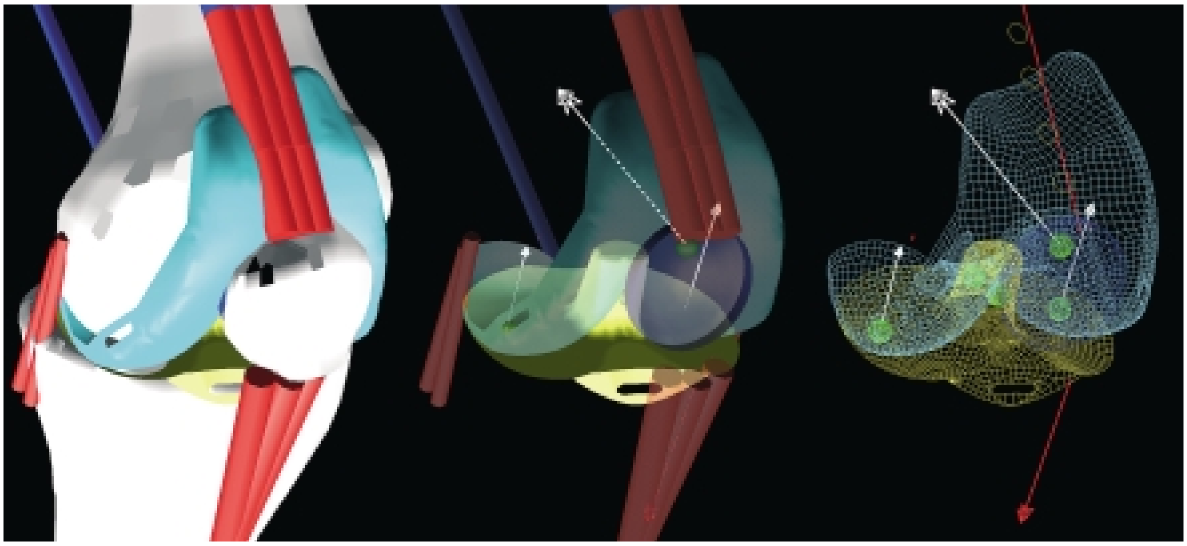

Fig. 24-3. Bones, passive soft tissues, active muscles, and component contact are modeled

physical machine. A closed-loop controller is used to apply tension to the quadriceps and hamstring muscles to match a prescribed knee flexion vs. time profile. No large antagonistic forces are modeled. Ground reaction forces are applied as varus/valgus forces and internal/external torques during the cycle using time history data derived from force plate experiments [7]. Two main activities are simulated, a complete cycle gait, and a 0°-160°-0°-160° double deep knee bend cycle. The double cycle is performed so as to capture the inertial loading conditions at full extension (the second 0°).

Three different reference frames are utilized for the reporting of data. These reference frames are rigidly attached to the femur, tibia, and patella at the respective interfaces where the implant models meet the bone models, so as to easily resolve the interface forces and moments. In the simulation, most kinematic and kinetic data are reported relative to the reference frame fixed in the tibia. Kinematic and kinetic data for the patella are also reported with respect to the femur. Component orientation is reported using a three-cylindric model of knee motion similar to Grood and Suntay [8].

Data are reported via graphical animations and numerical results. The graphical animations serve as a powerful communicative tool to design teams and surgeons. Bones, muscles, soft tissues, and implants can all be selectively displayed during the animations. The center-of-pressures for articular contact are displayed as spheres, and all contact forces and tissue forces are displayed as scaled force vectors (Fig. 24-3). Currently, 84 data time-histories are reported for each simulation. These include patellofemoral and tibiofemoral kinematics, soft-tissue forces and locations, actuator forces and locations, contact forces and center-of-pressure locations, contact area, interface forces and locations, and all externally applied forces and locations. All the data are post-processed in a custom in-house spreadsheet, allowing graphical comparative analysis between trials.

The Virtual Knee has been validated in a variety of ways including mechanical, cadaver, and live subject tests. Mechanical tests have been used to tune the performance of the contact force algorithm for both the shear component (friction/stiction) of the force and the normal component of the force. The shear component of the contact force was tuned by comparing the Instron test machine results for the ASTM 1223 component laxity test with a virtual model of the laxity test. The normal component of the forces was tuned by comparing the resulting contact area of virtual compression tests with the contact areas reported from Instron-Fuji film tests. With the current set of contact parameters, the contact algorithm has consistently delivered results within 10% of mechanical tests [9]. Cadaver tests have been used to tune the soft tissues (attachment locations and mechanical properties) and the system controller function comparing the virtual rig results with physical machine results. Human tests have been used to compare kinematic trends between the virtual simulation and in vivo data derived from fluoroscopy [10].

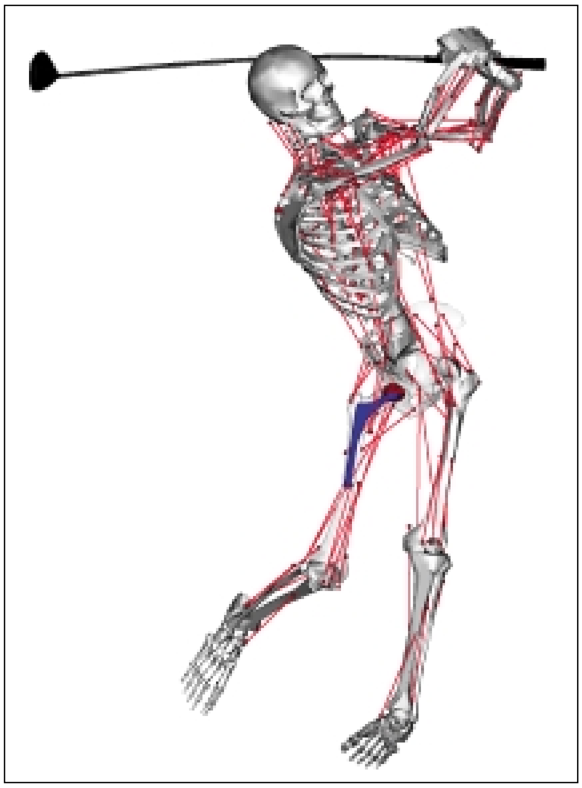

Fig. 24-4. Full-body muscle-driven skeletal model for evaluation of a wide variety of activities

and control the factors affecting the TKR system, analyze the factors using these statistical tools, and subsequently understand how to manipulate the factors to optimize performance.

Factors of particular interest to surgeons are those that affect stability and performance (and which can be variably controlled during simulation) including ligament tension, muscle strength, component alignment, surgical technique, patient anthropometric variability, implant selection, size mismatch, and material selection.

Future analytical functional simulation of TKR systems could involve the use of full-body muscle-driven simulations (Fig. 24-4) rather than the single-leg simulation of the Virtual Knee. In these simulations, motion capture data drive the skeletal model in displacement control, and the muscles are "trained" to perform the activity. After applying forward dynamics analysis, the muscles then drive the motion, and implant performance is evaluated. These simulations are not limited to the standard gait, stair climbing, and deep knee bend movements, but instead allow for more demanding activities.

With the addition of other active and passive tissues, normal knee kinematics and kinetics could be compared with those of the replaced knee for various functional activities, possibly defining new TKR performance testing methods and measures that are more closely correlated to in vivo performance. Furthermore, the Virtual Knee does not have to be limited to TKR design. Patellofemoral and unicondylar designs could all benefit. In addition, awareness of implantation alignment sensitivities can also drive improved instrument design.

The current state of the art in computer modeling, analytical simulation, and statistical analysis offers exciting opportunities for the designing surgeon and engineer. All of the key ingredients now exist to enable a revolution in TKR design. Parametric 3-D CAD models of implants can now be precisely controlled and quickly manipulated in a manner that allows for optimization of the geometry. Reverse-engineered CT and MRI knee scans can provide the geometry required to optimize implant shape, fit, and size. Analytical tools such as the Virtual Knee can accurately model knee function, provide critical measures not possible with physical testing, and reduce cost and lead times. The resulting kinematics measured from the Virtual Knee can be used to drive dynamic finite element analyses [11], providing an enhanced picture of polyethylene stresses, which may be used as a predictor of in vivo wear performance [12]. Finally, proven statistical methods can be used to effectively consider the many factors affecting TKR performance, allowing optimization of those factors to create the desired performance envelope. In the end, the patient will benefit the most by receiving thoroughly tested and optimized knee replacements implanted by surgeons who are more aware of the factors that most affect the desired results.

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