DEVELOPMENT AND VERIFICATION OF A VIRTUAL KNEE SIMULATOR FOR TKR EVALUATION

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Relevance To Musculoskeletal Conditions Evaluation of joint replacement components before any clinical use is important in assuring device safety and efficacy. Computer-aided engineering can play a major role in analysis and development of improved medical devices.

Introduction Joint kinematics and kinetics are to a large degree responsible for the performance and long-term function of total knee replacements (TKR). A number of experimental knee simulators have been developed in order to study cadaveric and implanted knees under physiological loading conditions. As typical experimental evaluations generally require a great deal of time, expense, and expertise, the objective of this research was to develop and verify a virtual knee simulator capable of estimating six degree-of-freedom tibio-femoral kinematics and kinetics for various activities. Unlike experimental cadaveric evaluations, the virtual simulator will provide a consistent test-bed for TKR examination without variable soft-tissue balance or inconsistent implantation. Virtual prototyping of new designs will allow examination of many designs and features from CAD models only, and result in optimal knee prosthesis geometries.

Methods A six-degree-of-freedom bearing surface contact algorithm was incorporated into a custom ADAMS (Mechanical Dynamics, Inc., Ann Arbor, MI) solver to model tibio-femoral and patello-femoral articulations [1]. The surface contact force calculates the forces of penetration and traction between discretized representations of the joint components. The contact force is based on the mechanical properties of the interaction, including the stiffness, damping, and static and dynamic friction values [1]. The contact algorithm was initially used to develop a simulation of the ASTM F1223 laxity test.

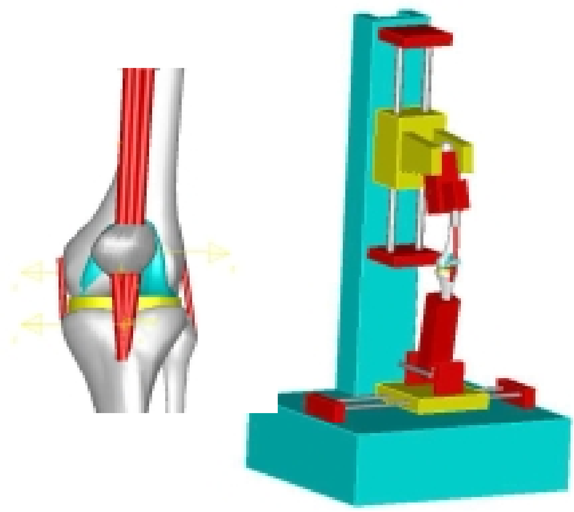
After completion of an experimental verification of the laxity test, a mechanical system simulation of an experimental electro-hydraulic knee simulator (Figure 1a and 1b) was created. Basic geometry and mass properties of the experimental knee simulator and TKR were imported into ADAMS. Cruciate and collateral ligaments were positioned at average insertion points. All the soft tissues wrap appropriately around hard obstructions to permit proper force direction.. The 4-axis knee simulator uses actuators to impart a vertical load at the "hip", and tibial torque and varus-valgus forces at the "ankle". A quadricep force balances the vertical load through the patellar tendon. Input load and motion profiles were developed from simultaneous 3D motion and force plate data to represent gait and stair ascent/decent activities. Knee kinematics are described using a 3-cylindric model of knee motion similar to Grood and Suntay [2].

After development of the virtual simulator, gait simulations were performed for verification using the experimental rig with the same knee components. Six degree of freedom kinematics were compared.

Results Results from the experimental verification were compared with the ADAMS virtual knee simulation for six-degree-of-freedom tibio-femoral kinematics during gait loading. Experimental and virtual analyses compared well overall. Flexion-extension and abduction-adduction correlated well in magnitude and time scale (Figure 2). All rotations and translations agreed within 3 degrees and 2 mm, respectively.

Discussion The development of a virtual knee simulation will allow tremendous reduction in the development and evaluation cycle time. Creating a reproducible test bed permits comparison of TKR components based on design features alone. Good correlation was found between the experimental and virtual simulators.

The bearing surface contact algorithm could be used as the basis for developing other dynamic loading conditions of interest, such as rising from a chair. In addition to TKR design and analysis, the simulator may be used to develop input profiles for displacement-based experimental wear simulators, or to study a host of other issues, such as the effects of ligament balance, joint line position, or other surgical parameters.



(a) (b)

Figure 1. (a) Virtual knee with TKR and soft tissues, and (b) emulation of knee simulator.

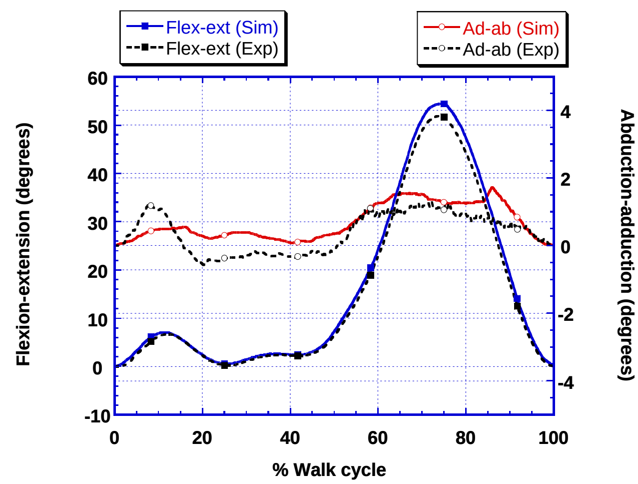


Figure 2. Experimental verification of virtual knee simulator: Flexion-extension and abduction-adduction as a function of walk cycle for simulation and experiment..

References [1] Essinger *et al*., J Bmch, 22:1229-1241, 1989. [2] Grood and Suntay, J Bmch Eng, 105:136-144, 1983.

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