COMPUTATIONAL MODELING OF A DYNAMIC KNEE SIMULATOR FOR PREDICTION OF JOINT LOADING

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INTRODUCTION

Dynamic knee simulators produce complex, controlled forces and motions for simulation of dynamic knee loading and kinematics during activities such as walking or rising from a chair. These tools load knee prosthetics and cadaver knees with simulated physiological conditions allowing for the evaluation of knee implants, surgical techniques, and biomechanical study of natural knee tissue. Modeled after the Purdue Knee Simulator: Mark II [1], a five-axis dynamic knee simulator has been built at the University of Kansas (Fig. 1). The objective of this work was to develop a three-dimensional computational model of the Kansas Knee Simulator for prediction of joint forces and moments produced by the five axes of the machine.

MATERIALS AND METHODS

Kansas Knee Simulator (KKS)

There are five axes of control on the KKS, each actuated through a hydraulic cylinder with servo valve control. Both position and force are measured at every axis allowing for either position or load control. The resultant loading and motion at the knee are reactions to applied loads at simulated hip and ankle joints, and from a simulated quadriceps muscle. The quadriceps actuator is often operated in position control of knee flexion-extension and the remaining four actuators operate in load control to simulate dynamic loading.

Computational Model of KKS

A three-dimensional computational model was developed for the purpose of predicting dynamic loading at the knee due to forces generated by the actuators of the knee simulator. The model was developed in the computer aided engineering package, MSC.ADAMS (MSC Software Corporation, Santa Ana, CA). The basic 3-D structures of the machine were built into the model to replicate the proper line of action of the five actuators. Four revolute joints and three translational joints were used to describe the degrees of freedom of the KKS and vector force elements represented the forces generated by the five hydraulic cylinders. The mass of all components along with the center of gravity and inertia about the center of gravity were measured empirically from constructed parts of the knee simulator and included in the model.

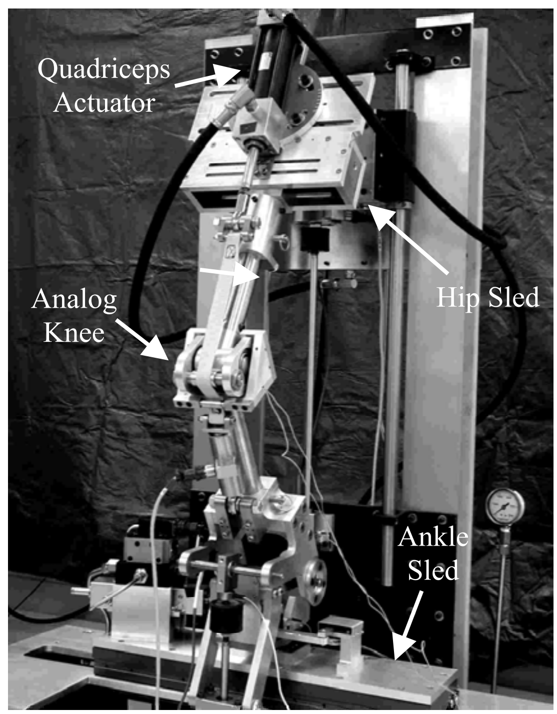

Figure 1. Photograph of the Kansas Knee Simulator.

Flexion–extension of the model was achieved through PID control of the vector force element representing the quadriceps actuator. An error signal between the desired flexion extension angle and the calculated angle was sent to the PID controller with the output used as the force vector amplitude for the next calculation step. The remaining four force vectors were assigned amplitude values equivalent to desired loading on corresponding axes of the knee simulator.

Model Verification

To verify that the model accurately represents the forces generated by the actuators of the Kansas Knee Simulator and the transfer of loading to the knee joint from these forces, a mechanical analog knee was designed and built (Fig. 2). The analog knee was designed with simple geometry and accurately modeled in MSC.ADAMS. In addition, the analog knee was instrumented with force transducers to measure tibial axis compression and posterior forces at a simulated tibio-femoral joint. The analog knee included two bearing surfaces to accommodate loading applied by the quadriceps actuator. A one-inch wide Kevlar strap attached to the quadriceps actuator and wrapped around the anterior of the top bearing and posterior of the bottom bearing, connecting to a load cell at the distal tibia of the KKS. In the model, the Kevlar strap was represented as a series of stiff non-linear springs embedded with small spheres. Three-dimensional contacts between the spheres and outer cylinder of the bearing simulated the strap wrapping around the bearing surface.

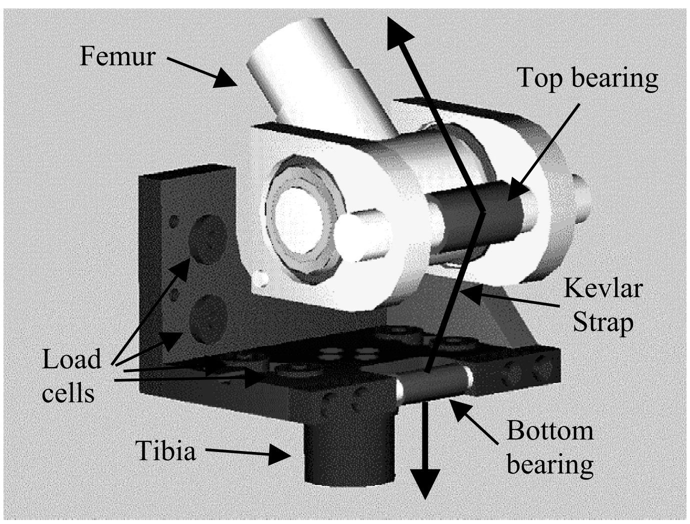

Figure 2. Exploded view of the analog knee.

A series of tests were implemented with the analog knee positioned in both the KKS and model of the KKS. For these tests the quadriceps axis was controlled to follow a sinusoidal flexion-extension of ± 17 degrees while the remaining axes applied various constant forces. The applied loading included a no load condition, vertical compression and tension loads applied to the hip sled, flexion-extension moments applied to the tibia, and adduction and abduction loads applied to the ankle sled.

RESULTS

Predicted and measured loading agreed well (Fig. 3). Shown is the measured compressive force from one load cell and the predicted loading at that position during one ± 17 degree flexion-extension cycle while 111 N (25 lbf) of tension is vertically applied to the hip sled. A comparison between the measured and predicted average load over one cycle of testing also correlated well for all tests (Fig. 4). The average one cycle load was calculated at four combined sensor locations. The two sensors measuring tibial axis compression on the medial side were combined as well as the two on the lateral side. The sensors measuring posterior load were combined in a similar manner.

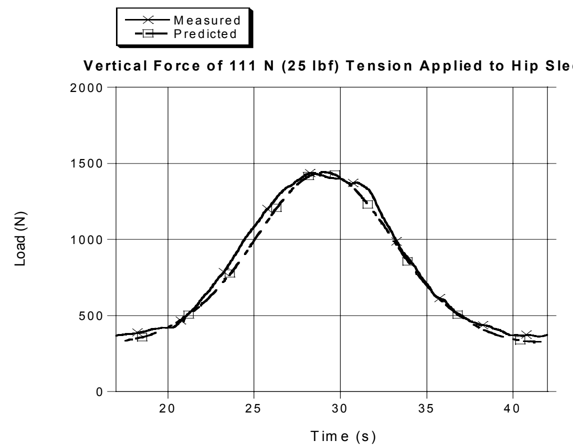

Figure 3. One cycle measured and predicted loading at anterior medial sensor position.

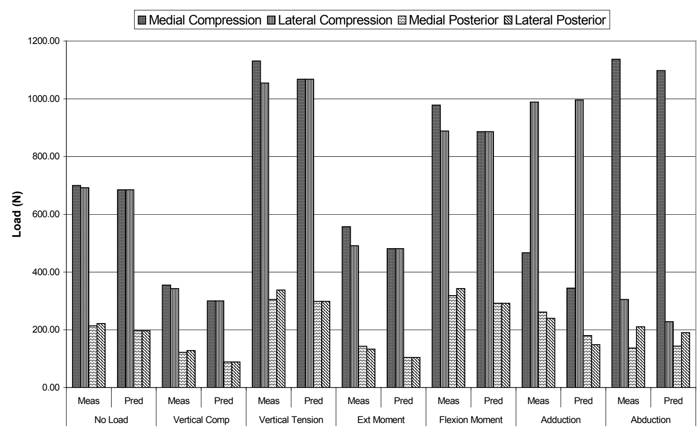

Figure 4. Comparison of one cycle average of measured and predicted load for all verification tests.

The mean percent error between predicted and measured one cycle average load for all sensor positions and verification tests was 13%.

DISCUSSION

Good correlation was found between the predicted and measured loading at the analog knee. This work serves as a basis for further model development that will include predicting control profiles for the five axes of the simulator to produce desired forces and moments at the knee. The enhanced model will enable the KKS to reproduce dynamic three-dimensional knee loading from such activities as walking or rising from a chair. Future work will also include replacing the analog knee with a prosthetic knee for better prediction of actuator profiles required for dynamic load reproduction during experimental testing. Limitations of the model include representing the hydraulic cylinders as ideal force vectors, not including friction at the load cell contacts, and simplifying the load applied by the quadriceps actuator by having the simulated Kevlar strap wrap around only the top bearing surface.

REFERENCES

1. Maletsky, L.P. and B.M. Hillberry, *Loading Evaluation of Knee Joint During Walking Using the Next Generation Knee Simulator*. Advances in Bioengineering, 2000. **Vol. 48**: p. 91-92.