Effects of Variation in Surgical Technique on Range of Motion in Total Knee Replacement

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ABSTRACT

Surgical technique is an important factor that may limit range of motion (ROM) following total knee replacement. The purpose of this study was to use computer simulation to study the effects of resecting too little bone on knee ROM. Dynamic computer simulations of a supine ROM test were performed in order to determine the effects of these variations on ROM, as indicated by the force required to flex the knee, soft-tissue tensions, and articular contact forces.

INTRODUCTION

Total knee replacement (TKR) is a reliable and widely used surgical procedure that involves removal of diseased articular surfaces at the knee joint and replacement of these surfaces with prosthetic implants. According to the American Society of Orthopaedics Surgeons (AAOS), nearly 402,000 patients have undergone TKR in 2003. The number of procedures is predicted to increase nearly 475,000/year by 2030 due to more innovative designs and technological improvement leading to decreased failure rates in TKR.

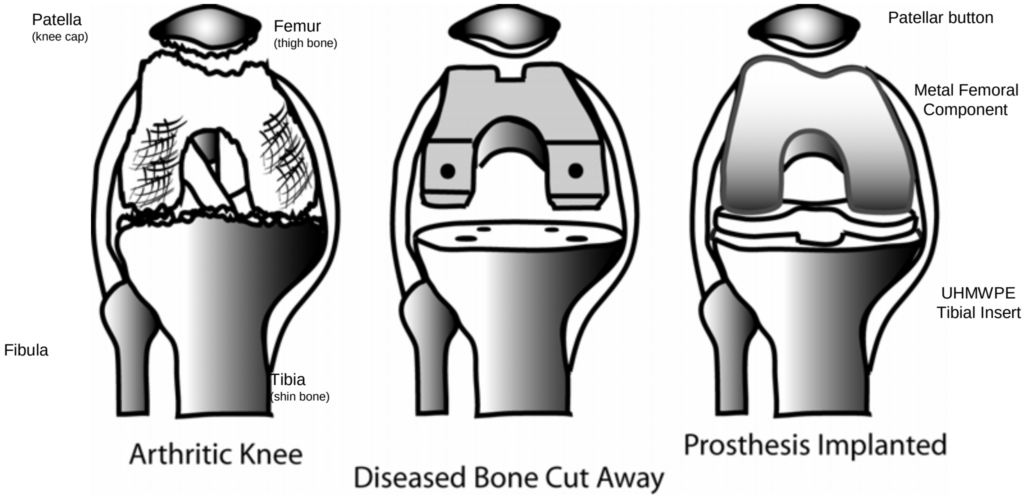

Fig 1. Diagram of “The Process of Total Knee Replacement” (Drawing by Mr. Ryan L. Landon).

Despite being generally accepted as an excellent treatment for osteoarthritis, total knee replacement is not free from problems. One of these problems, complications related to joint line restoration, has become an issue under frequent investigation[1,2,3,4,5,6,7]. The anatomical joint line consists of appropriate positioning of TKR bones with respect to ligament lengths. Previous research has shown that restoration of ideal knee geometry is most desirable and may lead to higher ROM following TKR[1,2,5]. Therefore, an improper joint line can lead to inadequate ligament balancing, abnormal tracking and increase in patellofemoral and tibiofemoral contact forces [3,4,5]. It has been reported that increase in overall patellar thickness leads to higher surface strain and contact force resulting in poor mobility [2,3]. Other studies showed restriction in extension and flexion mechanisms due to tightened collateral ligaments which were a result of minimal tibial cut or a thicker tibial component replacement [7]. This study utilized forward dynamic simulation and musculoskeletal modeling to investigate effects of "overstuffing" the knee by removing too little bone on knee ROM. The following component alignment variations were investigated:

- Femoral component moved inferiorly by 0-3 mm.
- Tibial component moved superiorly by 0-3 mm.
- Patellar component moved posteriorly by 0-3 mm.

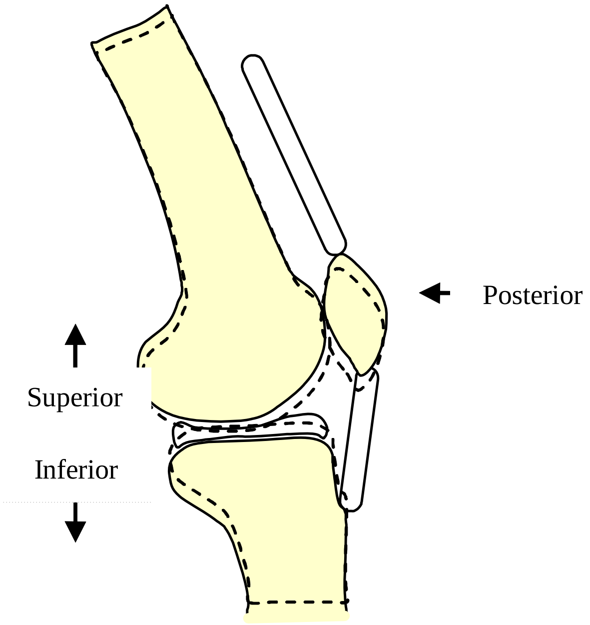

Fig 2. Overstuffing tibiofemoral and patellofemoral compartments.

METHODOLOGY

Preoperative TKR Testing

Preoperative testing of TKR is an integral part of maximizing knee ROM. Some tools available for evaluating implant designs include finite element analysis (FEA), multi-body dynamic simulations, and cadaver studies [8]. Drawbacks for these techniques are as follows:

Technique	Time Consuming	Expensive	May Not Be Reliable	May Not Measure All Variables of Interest
Cadaver Tests	✓	✓		✓
Multi-body Dynamic Simulations			✓	
FEA	✓		✓	✓

Table 1.Comparison of Preoperative Testing Techniques.

Multi-body dynamic simulations, as shown in Table 1, are an attractive alternative to cadaver studies and FEA for investigating knee replacement mechanics. A simulation in which acceptable modeling assumptions are made can provide a means for investigating TKR mechanics that is realistic, fast, and relatively less expensive[8]. This study utilized multi-body dynamic simulations to predict implant motions for a commercially-available TKR system under various surgical techniques.

Pre-Processing

CAD models of a commercially available TKR were obtained from a manufacturer. These models were created using ProEngineer, a 3D solid modeling software. Next the Pro/E models were used to create bone and IGES files necessary to conduct this study. TKR geometries, obtained from these IGES files, were utilized to place virtual springs on articular surfaces of bones. Afterwards, a forward dynamic simulation, where motion is predicted by forces, was implemented to calculate contact force and location between tibiofemoral and patellofemoral compartments using a Kelvin-Voigt model: $F=K*x+B*(xdot)$. The following figure is an example of a tibial component with springs placed on articulating surfaces.

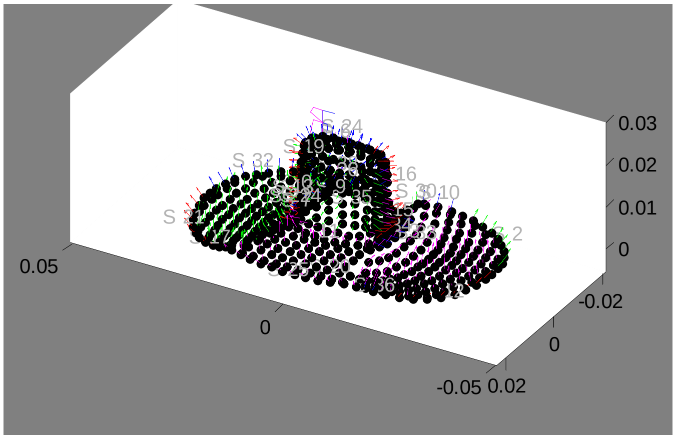

Fig 3. Springs placed on a tibial component.

Post-Processing

Implants with springs on articular surfaces were surgically implanted on a digitized lower extremity model using SIMM. SIMM (Software for Interactive Musculoskeletal Modeling) is a software system that enables users to create and analyze graphics-based models of the musculoskeletal system. In SIMM, a musculoskeletal model consists of a set of bones that are connected by joints. Muscle-tendon actuators and ligaments span the joints. The muscles and ligaments develop force, thus generating moments about the joints[9]. The following figure shows a placed TKR using a SIMM leg model.

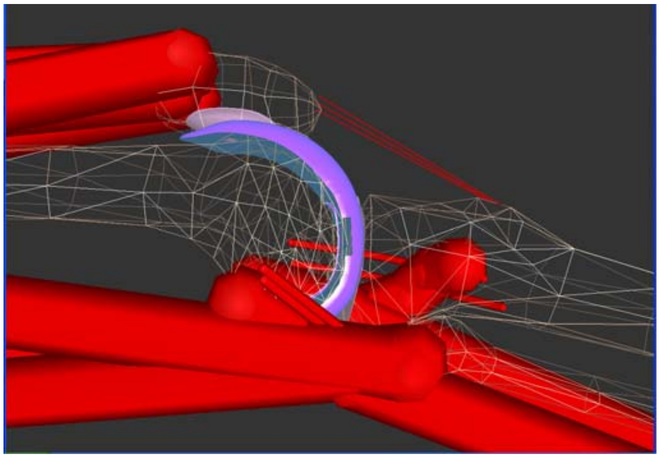

Fig 4. TKR placed on digitized leg model using SIMM.

A supine ROM test, during which a patient is lying on their back and a force is applied to the ankle to flex the knee, was simulated with placed implants. Dynamics Pipeline, a suite of software routines that help SIMM users build dynamic simulations of musculoskeletal structures, was utilized to conduct the rest of the study[10]. Finally, simulations with various overstuffing scenarios were simulated using SIMM and a forward dynamic model. Soft tissue tensions, force required to flex the knee, and articular contact forces were calculated from simulation output. The following figure shows the supine ROM test conducted using SIMM.

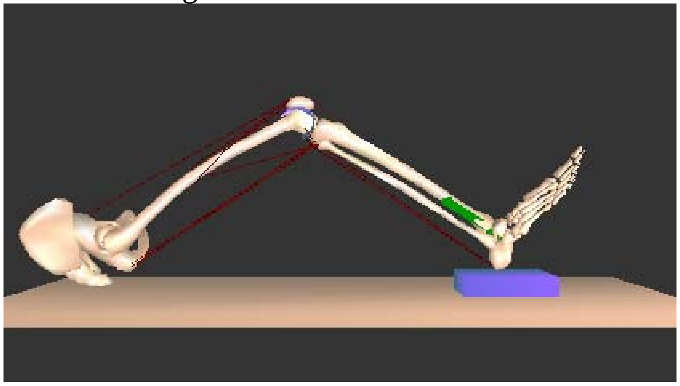

Fig 5. Supine ROM model using SIMM.

RESULTS

The knee extensor mechanism, located anterior to the femur, consists of the quadriceps muscles, the patella, and the patellar tendon. This mechanism becomes tight in deep knee flexion and is an important structure that determines post-operative knee ROM. Cutting away more of the patellar bone is one solution to loosen the extensor mechanism; this study however looked at effects of less bone resection on knee ROM. Another possible technique is partial resection of muscle belly and the tendinous from portions of the quadriceps[2]. The following results show the different components of the extensor mechanism with variations in the amount of overstuffing throughout supine ROM.

Forces on Quadriceps Muscles During Knee Flexion

The quadriceps femoris are located on the front of the thigh. These muscles consist of: the vastus lateralis, vastus intermedius, vastus medialis, and rectus femoris. During the supine ROM test, the quadriceps muscles produce a passive knee extension moment that resists the applied motion. The plot below is the sum of the vastus lateralis, vastus intermedius, and vastus medialis forces during the simulation.

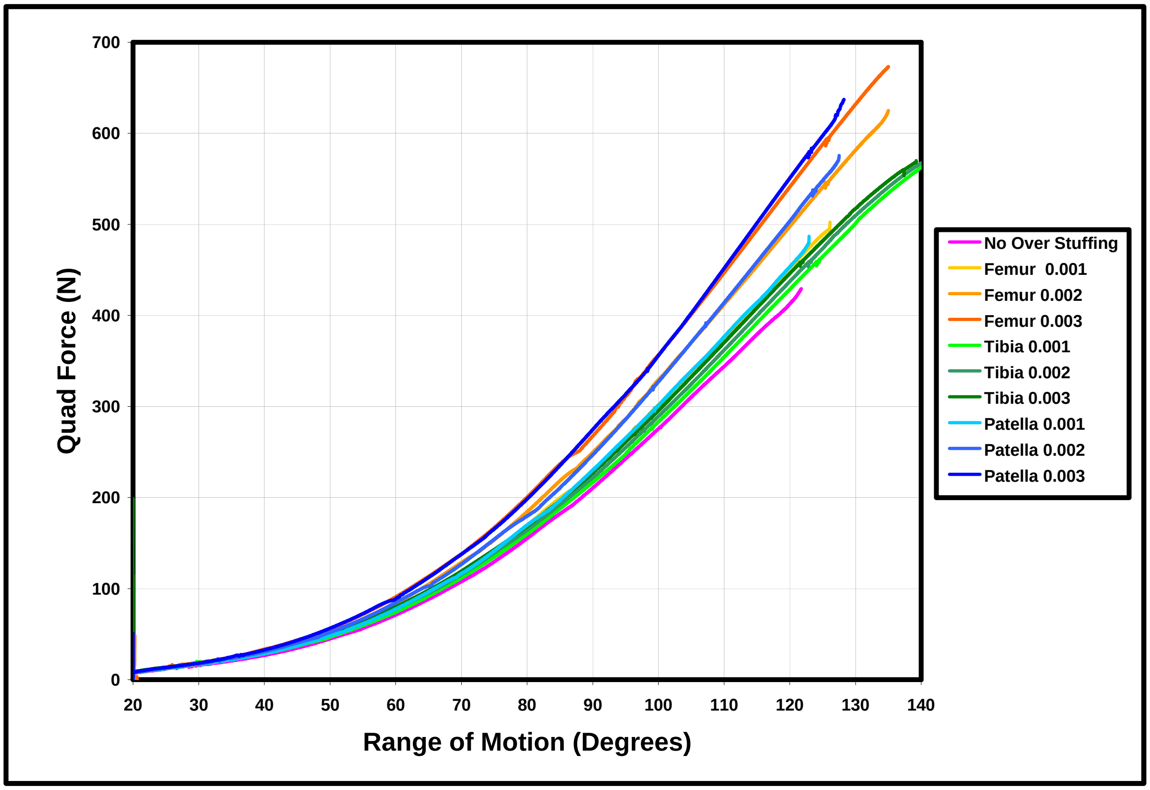

Figure 6: Summed quad force (N) as a function of ROM (degrees), for each surgical variation. The general trend was, as overstuffing increased from 0 to 3 mm, the quad force also increased. One other observation was, overstuffing the tibial component produced much higher ROM with less quad force applied throughout supine ROM.

Forces on Patellar Ligament During Knee Flexion

The patellar ligament, sometimes called the patellar tendon, is located on the anterior (front) part of the tibia. The ligament connects the patella to the tibia bone. During the supine ROM test, the patellar ligament also produces a passive knee extension moment that resists the applied motion. The following is a summary of the forces in the patellar ligament during the simulation.

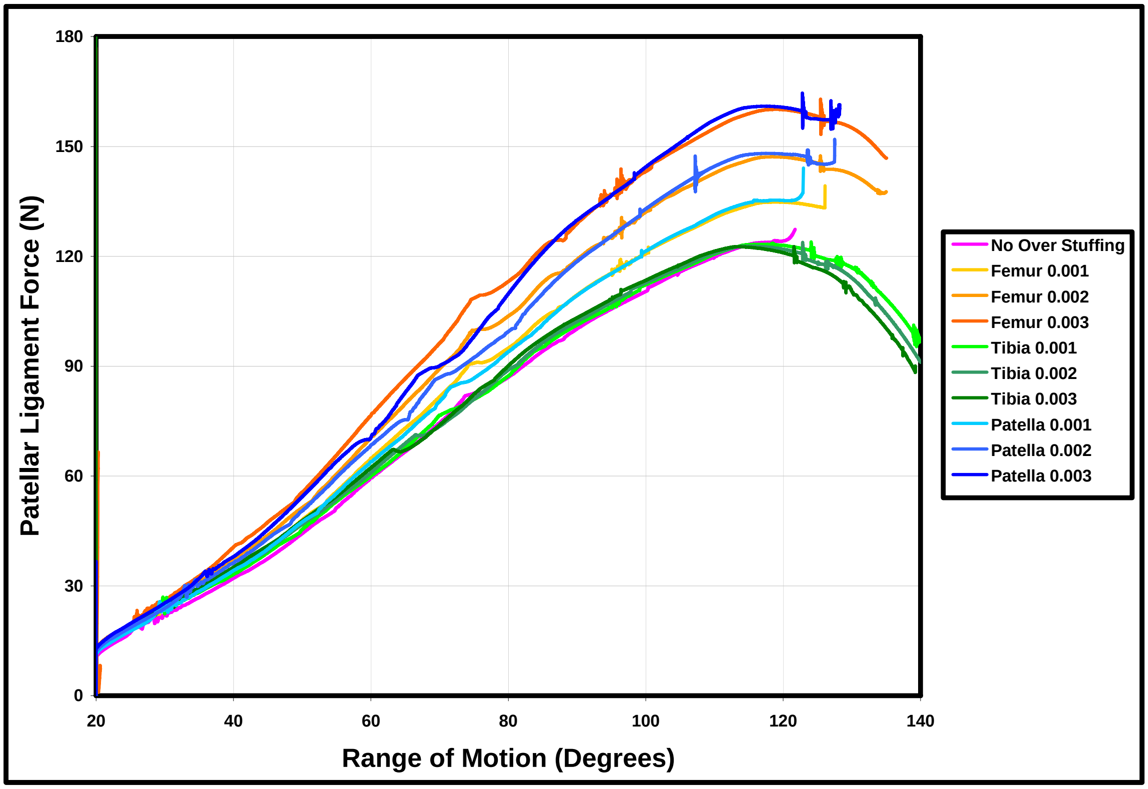

Figure 7: Patellar ligament force (N) as a function of ROM (degrees), for each surgical variation. The general trend present was, as overstuffing in the patella and femur increased from 0 to 3 mm, the force in the patellar ligament also increased. Another observation made, overstuffing the tibial component and no overstuffing produced relatively the same amount of force throughout knee ROM.

Patellofemoral Contact Force

The patellofemoral joint, located on the anterior (front) portion of the knee, plays a crucial role in ROM. As the name suggests, this joint is the contact location between the femur and patella bone (kneecap). Development of high contact forces at this joint may lead to pain and wear of the components following TKR. The following plot is a summary of observations of contact force throughout supine ROM.

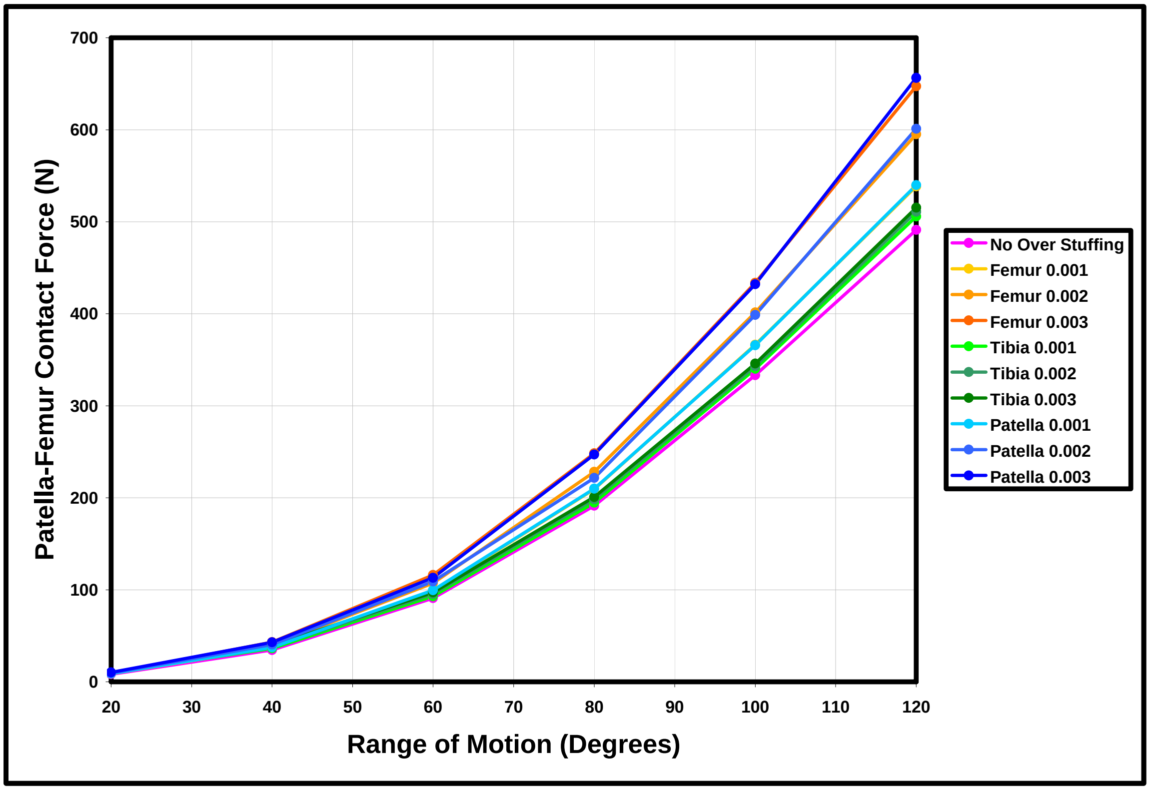

Figure 7: Contact force (N) in the patellofemoral compartment as a function of ROM (degrees), for each surgical variation. Some observations made were: overstuffing the patella or femur produced relatively the same amount of contact force and tibial overstuffing produced less contact force in the patellofemoral compartment.

The supine range of motion test requires a superiorly-directed force applied to the ankle to flex the knee. This force would ordinarily be applied by a surgeon examining a patient at the post-operative stage. In this study the author observed the amount of force required at the ankle to determine if any significant changes have occurred due to TKR overstuffing. The following plot is a summary of the force required to flex the knee with each surgical variation.

External Force Required to Produce Knee Flexion

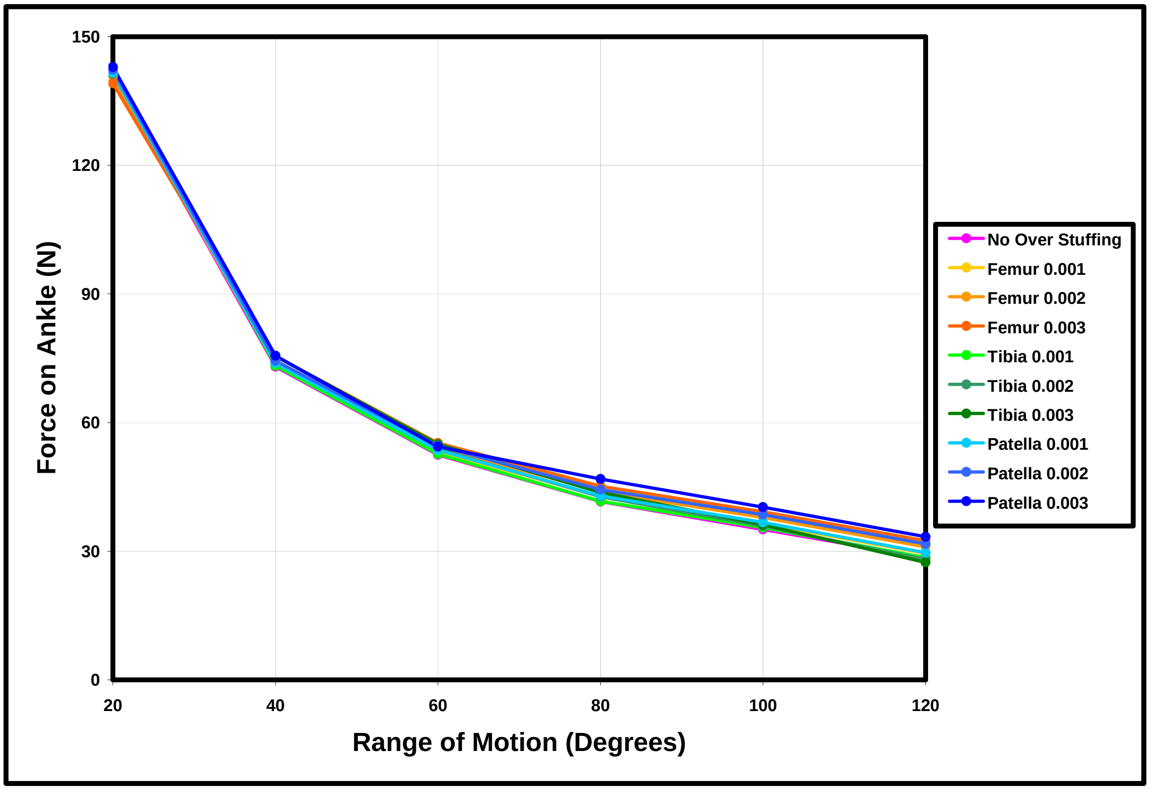

Figure 8: Force applied to the ankle (N) as a function of range of motion (degrees) for each surgical variation. No substantial changes were present from overstuffing each TKR component. However the tibial component required less force to flex the knee when overstuffed.

DISCUSSION

Knee kinematics after total knee replacement influence its long term outcome and quality [1]. Maintaining the anatomical joint line is recognized as one of the most important factors in maximizing knee ROM[1,2,3,4,5,6,7]. The present study investigated variations in joint line geometry also called overstuffing and its effects on knee ROM. Analysis showed that 3mm of tibia overstuffing improved ROM nearly 10 degrees while maintaining suitable anatomical ligament characteristics and contact forces. These outcomes are contrary to those published by Jiang 1993, who found that a 4mm to 10mm increase in the collateral ligaments produced a loss of 0 to 15 degrees in knee ROM [7]. This discrepancy may have resulted from no observations being made exceeding 3mm of overstuffing. Therefore, 3mm might be the threshold before significant variances in ligament lengths and forces are present.

Femur or patella overstuffing were found to improve ROM but resulted in higher contact forces in the patellofemoral joint and higher forces in the quadriceps muscles. Results of patella overstuffing are similar to those described in Jiang 1993 and Stiehl 2001 where increased patellofemoral contact pressure was shown to occur for thicker patella following TKR[6,4].

Some implications that may arise from this study are: tibial overstuffing might improve knee ROM but only when the tolerance is less than 4mm. Also as shown in previous studies, maintaining the patellofemoral joint line is crucial for successful TKR.

Limitations

The author would like to emphasize that these trends may have resulted from improper surgical placement of the components before overstuffing. Another item to acknowledge is that the normal knee motions used to define ligament properties and placement may have been unrealistic. One final point to make is that this study was done on only one type of TKR. Therefore, these results are specific to this design and may not be generalized.

Conclusion

Range of motion (ROM) is a key outcome measure used in the design and evaluation of total knee replacements. An ideal human knee is capable of reaching nearly 165 degrees ROM in full flexion. TKR designers and surgeons are constantly trying to discover better and more innovative ways to achieve higher ROM following TKR. Higher ROM will allow patients the ability to perform more day to day activities without constraints from TKR[11,12]. The overall goal is to design components that are capable of reaching nearly the same range of motion as in the natural human knee. Until this goal is achieved, investigations like the present study provide surgeons and designers with information on how to achieve better ROM with a model currently available on the market.

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