Computational Framework for Determining Patient-Specific Total Knee Arthroplasty Loading

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The purpose of this work is to describe a computational framework for predicting total knee arthroplasty loads which are necessary for accurate preclinical testing of implant designs. Inputs required include patient knee joint kinematics, and implant type, size, and physiological alignment. Computational models used in the framework include the calculation of knee joint kinematics and kinetics, prediction of the contact path, a model to determine muscle forces, and a force model to obtain parametric solutions for implant forces. The resulting knee implant forces have been validated in two studies, and in both the model accurately predicted differences in knee joint loading. To date, implant contact forces have been predicted for 35 patients with four different implant types. Forces have been calculated for walking, chair, and stair activities. [DOI: 10.1115/1.4025765]

Introduction

The demand for total knee arthroplasty (TKA) is increasing steadily. In 2007, Kurtz et al. [1] predicted that TKA procedures would increase from 402,100 in 2003 to 3.48 million by 2030. Recent US national inpatient survey data have borne out these trends [2,3]. Furthermore, demand is growing fastest in people younger than 65 [4]—patients who will need their implants to last the longest. Preclinical TKA testing is performed with knee wear simulators under generic walking conditions, and efforts are ongoing to improve the physiological relevance of current testing standards. The purpose of this work is to describe a computational framework for predicting TKA loading for populations of TKA patients. Accurate TKA loading is an essential input for preclinical wear tests.

Computational Framework

Inputs to the computational framework include patient knee joint kinematics, and TKA type, size, and physiological alignment. Computational models used in the framework include: 1) inverse dynamics to obtain knee joint kinematics from marker trajectories and forceplate data collected during gait analysis, 2) a mathematical model to predict the path of contact between the tibial and femoral TKA components, 3) musculoskeletal lower limb model to predict maximum muscle forces, and 4) a parametric force model to determine TKA forces.

The first step is to obtain patient-specific knee joint kinematics and kinetics using marker-based motion analysis and inverse dynamics. Markers are tracked with an optoelectronic video-based measuring system (Qualisys North America Inc., Charlotte, NC, USA), and a multicomponent force plate (Bertec, Columbus, OH, USA) measures foot-ground reaction forces.

The second step is to determine the path of contact between the tibial and femoral TKA components. Inputs to the model include the knee kinematics and measurements from radiographs taken during postoperative follow up. The radiographs are used to anatomically position the TKA components in relation to the bones.

To determine the contact kinematics, a point cloud of the femoral component is transformed by the knee kinematics. At each time point during gait, the lowest (inferior-most) point on the femoral component is located, with the assumption that the lowest point is first to contact the tibial plateau. The respective contact point on the tibial component is defined as the tibial point with the shortest linear distance to the identified lowest femoral point.

The third step is to use a musculoskeletal model of the lower limb to determine maximum lower limb muscle forces that correspond to the patient-specific kinematics and kinetics. The model is implemented in OpenSim.

The fourth step is to compute 3D contact forces through the knee joint [5] using equilibrium equations. The model includes muscle forces from 15 muscles crossing the knee joint acting along their physiological lines of action. Parametric variation of relative muscle activation levels results in a solution space or envelope of calculated knee joint forces representing different muscle activation strategies a person may use while performing the activity. The model has been validated in two studies [6,7]. The first compared the model to four patients with instrumented TKAs and the second was a blinded model validation competition. In both studies, the model accurately predicted differences in knee joint loading due to different patient-specific walking patterns. In the blinded competition, the model also accurately predicted knee joint loading for a learned “medial thrust” gait pattern.

Discussion and Future Outlook

The computational framework accurately predicts TKA contact forces. To date, TKA contact forces have been predicted for 35 patients with four different implant types [6–8]. Forces have been calculated for walking, chair, and stair activities. Future plans include extending the framework to include finite element modeling to evaluate design specific characteristics, polyethylene stresses, and eventually potential implant failure modes. Additional TKA population characteristics that can be investigated include electromyography muscle activity data, and activity level data. The goal of the framework is to generate accurate knee loads for TKA populations and new insights for preclinical testing. This will help delay or avoid revision surgeries which are risky for the patient, technically difficult for the surgeon, and expensive.

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