IN VIVO MEDIAL AND LATERAL TIBIAL LOADS DURING GAIT, STAIR, KNEEL, AND LUNGE ACTIVITIES

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INTRODUCTION

Asymmetric loading between the medial and lateral compartments of the knee has been hypothesized to contribute to the development of knee osteoarthritis (OA). In artificial knees, asymmetric forces exerted on the tibial insert may contribute to mechanical failure as well as loosening of the implant. Studies using statically determinate muscle models, video-based motion analysis, and external force measurements have predicted larger contact forces on the medial than on the lateral side of the knee during gait. Furthermore, the predicted medial-lateral load split showed considerable variation over the course of the gait cycle. However, the actual *in vivo* distribution of tibial contact forces and pressure during a variety of activities remains unknown.

This study uses an instrumented knee implant capable of measuring the *in vivo* tibial axial loads, along with fluoroscopic motion analysis and a dynamic contact model, to determine *in vivo* medial and lateral contact forces and pressures on the tibia during gait, step-up/down, kneel, and lunge activities. The reliability of the calculated medial and lateral tibial loads is evaluated based on the contact model's ability to reproduce the experimentally measured medial-lateral (ML) and anterior-posterior (AP) center of pressure (CoP) locations.

METHODS

Data were collected from one patient with instrumented knee implant (male, right knee, age 80, mass 68 kg) eight months after surgery. Institutional review board approval and patient informed consent were obtained. *In vivo* tibial force data were recorded simultaneously with fluoroscopic motion analysis data during treadmill gait, stair, kneel, and lunge activities. For the gait activity, the motion cycle was defined to begin at right heel strike, which was determined using synchronized tibial force and ground reaction force data collected during separate overground gait trials.

Figure 1. Dynamic contact model of the instrumented knee implant.

Dynamic contact models (gait and stair) and static contact models (kneel and lunge) of the patient's knee implant were constructed to predict *in vivo* contact forces, pressures, and areas on medial and lateral contact surfaces of the tibial insert. The models were implemented within the Pro/MECHANICA MOTION simulation environment (PTC, Waltham, MA) (Fig. 1) and used a deformable contact model utilizing elastic foundation theory. Linear elastic material properties (Young's modulus = 463 MPa and Poisson's ratio = 0.46) were used for the polyethylene. A 6 degree-of-freedom (DOF) joint between the fixed femoral component and moving tibial insert was used to measure relative (i.e., joint) kinematics for contact calculations. Femoral AP translation, internal-external rotation, and flexion-extension were prescribed to match the fluoroscopically measured kinematics while the other three DOFs were predicted via forward dynamic simulation (gait and stair) or static analysis (kneel and lunge). The location at which the axial force was applied to the tibial tray was prescribed to match the CoP measured experimentally. The medial and lateral contact forces acting on the tibial insert were calculated from the contact pressures acting across the surfaces. The CoP location in the ML and AP directions was also calculated from the model for comparison with the experimentally measured CoP locations.

RESULTS

The contact model was able to match the experimentally measured CoP over most of the gait cycle and the entire stair cycle. Without changing any fluoroscopically measured motion inputs, the contact simulations reproduced the ML location of the CoP extremely closely for all activities with root-mean-square (RMS) errors of 0.6 mm for gait and 0.0 mm for stair, kneel and lunge. In contrast, the AP location of the CoP was matched well for gait only during the stance phase, with an RMS error of 4.8 mm over the entire gait cycle. The corresponding RMS error for the stair motion were 1.3 mm. When the fluoroscopically measured AP translations were adjusted within their range of experimental error (± 1 mm), RMS errors in the AP CoP location were reduced to 3.5 mm over the entire gait cycle, 0.5 mm during stance phase, and 0.5 mm for stair.

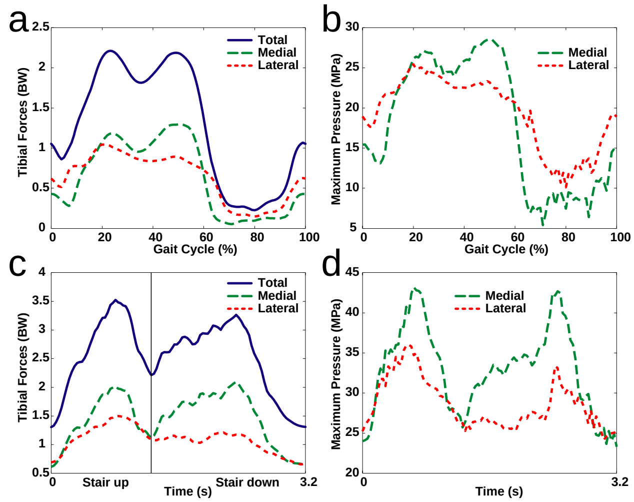

Fig. 2. Medial and lateral contact forces and maximum contact pressures calculated by dynamic contact models during (a, b) gait and (c, d) stair.

When medial and lateral forces were calculated by the contact model (Fig. 2 a and c), the ratio of medial to total force ranged from 18.0% to 60.4% for gait and 46.9% to 64.6% for stair. Medial and lateral maximum contact pressures (Fig. 2 b and d) followed similar trends to medial and lateral contact forces. For kneel, medial and lateral maximum contact pressures were 15.7 and 20.5 MPa, while for lunge they were 37.0 and 67.0 MPa. Table 1 shows the medial force ratio and AP CoP error at the maximum load for all activities.

Table 1. Medial to total force ratio and AP CoP error at maximum load

	Maximum Load (BW)	Medial/Total Force (%)	AP CoP Error (mm)	
			Original	Adjusted
Gait	2.2	53.4	2.8	1.1
Stair	3.5	56.0	0.3	0.1
Kneel	0.3	57.0	11.6	10.4
Lunge	1.6	57.7	2.9	1.7

DISCUSSION

For all activities, the load split was close to equal. The gait results challenge the belief that the majority of the load passes through the medial compartment during mid-stancein a well aligned knee. Even for the high weight-bearing stair activity, the maximum medial/total force ratio was still less than 65%.

Given that the CoP locations measured by the instrumented implant are accurate to within ± 2 mm, the errors in the predicted CoP location were small apart from the AP direction during swing phase and kneel. The experimental CoP calculation involves dividing by the total axial load, and the error in predicted AP CoP location for gait was highly correlated with the inverse of the applied load ($R^2 = 0.80$). Thus, sensitivity of the experimental CoP calculations to small errors in the measured axial load may help explain the large AP CoP errors during activities or phases of activities with only light loading.

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