



Direct comparison of measured and calculated total knee replacement force envelopes during walking in the presence of normal and abnormal gait patterns

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ABSTRACT

Knee joint forces measured from instrumented implants provide important information for testing the validity of computational models that predict knee joint forces. The purpose of this study was to validate a parametric numerical model for predicting knee joint contact forces against measurements from four subjects with instrumented TKRs during the stance phase of gait. Model sensitivity to abnormal gait patterns was also investigated. The results demonstrated good agreement for three subjects with relatively normal gait patterns, where the difference between the mean measured and calculated forces ranged from 0.05 to 0.45 body weights, and the envelopes of measured and calculated forces (from three walking trials) overlapped. The fourth subject, who had a “quadriceps avoidance” external moment pattern, initially had little overlap between the measured and calculated force envelopes. When additional constraints were added, tailored to the subject’s gait pattern, the model predictions improved to complete force envelope overlap. Coefficient of multiple determination analysis indicated that the shape of the measured and calculated force waveforms were similar for all subjects (adjusted coefficient of multiple correlation values between 0.88 and 0.92). The parametric model was accurate in predicting both the magnitude and waveform of the contact force, and the accuracy of model predictions was affected by deviations from normal gait patterns. Equally important, the envelope of forces generated by the range of solutions substantially overlapped with the corresponding measured envelope from multiple gait trials for a given subject, suggesting that the variable strategic processes of in vivo force generation are covered by the solution range of this parametric model.

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1. Introduction

Detailed knowledge of in vivo knee contact forces and the contribution from muscles, ligaments, and other soft-tissues to knee joint function is essential for evaluating total knee replacement (TKR) designs. Laboratory tests and computational models of TKRs and natural knee joints require accurate force inputs in order to physiologically replicate in vivo conditions. If available, patient-specific knee contact forces and muscle forces could be used to determine testing protocols that are truly representative of specific TKR designs, design rehabilitation protocols or predict the safety of recreational activities, and monitor recovery progress after surgery.

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Knee joint forces are difficult to obtain; currently, in vivo force data from instrumented total knees are only available for a few subjects for walking, chair rising/sitting, stair ascent/descent, and other activities (D’Lima et al., 2008, 2006; Heinlein et al., 2009; Kutzner et al., 2010; Mündermann et al., 2008). Consequently, computational models are necessary to bridge the knowledge gap between the available data from the few patients with a specific implant type to patient-specific knee joint contact forces for a larger patient population and multiple TKR designs. Numerical models can be used to calculate muscle and passive structure forces simultaneously with contact forces, and thus allow a more comprehensive and systematic evaluation of knee joint loading.

The unknown validity and sensitivity of modeling assumptions to different gait patterns is illustrated by results from previous models where calculated knee joint contact forces range from 1.7 to 4.3 body weights during walking (Komistek et al., 1998, 2004, 2005; Morrison, 1970; Paul, 1976; Wimmer and Andriacchi, 1997). With the recent availability of data from instrumented TKRs, direct comparisons to numerical models are now possible. We have

previously developed a numerical model which calculates a range or envelope of possible three-dimensional contact forces for both the medial and lateral compartments of the tibial plateau (Lundberg et al., 2009). The force envelope is intended to represent the natural physiological variability in gait, as any number of strategies could be used to balance the external moments and forces measured during gait analysis. The purpose of this study was to test the validity of the knee joint contact forces predicted by the parametric numerical model. Model validity is tested by direct comparison of the predicted contact forces to measurements from four subjects with instrumented TKRs during the stance phase of gait. Model sensitivity to abnormal gait patterns is also discussed.

2. Methods

Contact forces were calculated for four subjects (Table 1) with instrumented TKRs during the stance phase of three level walking trials (Mündermann et al., 2008). Kinematics and kinetics (Fig. 1) were measured simultaneously with telemetric force data during gait analysis. A previously developed mathematical model was used to calculate TKR contact forces (Lundberg et al., 2009). The mathematical model is fully three-dimensional (Fig. 2) and calculates six contact force components in total, three for the medial side, and three for the lateral side of the tibial plateau using equilibrium equations. For equilibrium, internal moments and forces from contact forces, muscles, and passive structures were equal to external moments and forces measured during gait analysis. Inputs to the model included the subject kinematics and kinetics measured during gait analysis, the maximum physiological lower limb muscle forces from a musculoskeletal model (Delp et al., 1990) implemented in OpenSim 1.9.1 (Delp et al., 2007), and the path of contact between the tibia and femur during gait. The parametric model calculated a solution space or “envelope” of possible contact forces for a particular gait trial resulting from the parametric variation of muscle relative activation levels.

Previous work has shown that the external frontal plane moment is correlated to the medial-lateral force distribution through the knee (Zhao et al., 2007). The model calculated a medial-lateral force distribution through the tibial plateau that was a linear function of the external frontal plane moment (Fig. 1) at each instance of stance. The peak adduction moment during stance predicted the maximum percentage of force passing medially (Erhart et al., 2010).

Table 1

Demographics of the four subjects with instrumented TKRs (Mündermann et al., 2008).

Subject	Age (years)	Height (m)	Weight (N)	Sex (M/F)
1	81	1.70	631	M
2	79	1.74	680	M
3	64	1.64	835	F
4	84	1.79	756	M

The contribution from passive structures was included as a summed transverse passive structure moment (from soft tissue and prosthetic constraints) equal to the difference between the external transverse plane moment (external-internal rotation moment) and the transverse plane muscle moments.

The tibiofemoral contact path input to the model was determined in two different ways. Three-dimensional laser scans of the TKR components were available for one of the four subjects (Kim et al., 2009; Lin et al., 2010). In this case the path of contact between the tibial and femoral components was calculated using the laser scans and previously developed software (Swanson et al., 2007). Briefly, software was developed that used the knee kinematics and point clouds of the tibial and femoral TKR components from the laser scans as input. At each time point during stance the femoral point cloud was transformed according to the knee kinematics. The points on the tibial component that had the shortest linear distance to the inferior-most points on the medial and lateral femoral component were deemed the contact point. For the other three subjects without available laser scans of their prostheses, the path of contact was estimated from the movement of the markers representing the transepicondylar axis, which was previously shown to be a good estimate of the detailed contact path for the stance phase of gait (Swanson, 2007). The absolute positioning of the contact paths on the tibial plateau was unknown, and was initially assumed to be coincident with the position of wear scars measured on retrieved components (Paul, 2004). If no solutions were obtained after solving for the TKR contact forces, the contact path was moved in the direction that improved the efficiency of the lever arm of the agonist muscles until solutions were obtained throughout stance. The contact path was always constrained to stay within the possible contact area of the tibial plateau.

The mean total (medial plus lateral) normal force envelope was compared to the measured force data for each trial at 100 time points during stance. Specific comparisons were made at the first peak total normal force, second peak total normal force, and the local total normal force minimum between the two peaks. “Overall force envelopes,” defined as the minimum to maximum force at each instance of stance for all trials of each subject were also compared.

The entire measured and calculated force waveforms were statistically compared using coefficient of multiple determination (CMD) analysis. The contact forces for CMD analysis were normalized by the maximum occurring force within each respective waveform so that only similarities between the shape of the measured and calculated force waveforms were evaluated. For CMD analysis an

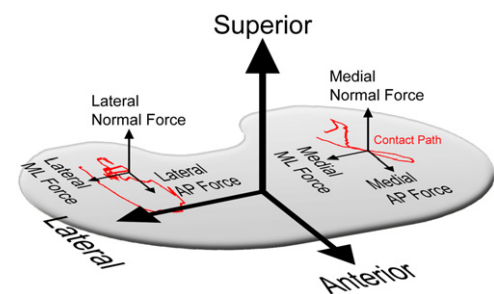


Fig. 2. Three-dimensional numeric contact forces are calculated in an anatomical coordinate system with their Anterior-Lateral plane location specified by the path of contact of the femoral component on the tibial plateau.

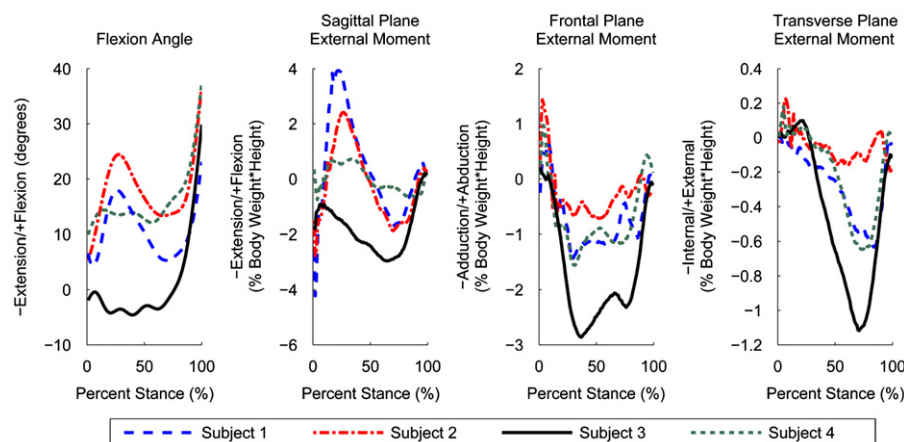


Fig. 1. Knee joint kinematics and kinetics during the stance phase of walking from a representative trial for each of four subjects with instrumented TKRs. Subject 3 has a different pattern of gait compared to the other three subjects including less knee flexion during stance (“stiff knee gait”), an external sagittal plane extension moment throughout stance (“quadriceps avoidance gait”), and a larger external frontal plane adduction moment during stance.

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