

The Influence of Obesity and Frontal Plane Alignment on Tibiofemoral Compartmental Loading

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INTRODUCTION: Obesity, defined as excessive fat accumulation that poses a risk to health and indicated by a body mass index (BMI) of 30 kg/m² or higher [1], affects over 40% of U.S. adults [2] and is a rapidly growing chronic disease. Individuals affected by obesity often move differently than their normal-weight (NW) counterparts, producing distinct knee joint loading patterns that may accelerate KOA progression [3,4] and the likelihood of total knee arthroplasty (TKA) [5]. Despite this, implant designs often overlook obesity-related loading demands, and variable BMI cutoffs remain common, underscoring the lack of obesity-specific biomechanical data to guide treatment. Kinematic findings related to frontal plane (varus-valgus) knee angle are often contradictory [6-8], in part due to the limitations of marker-based motion capture, where soft tissue artifact can obscure true joint motion. The objectives of this study were to 1) use high-speed stereo radiography (HSSR) to accurately quantify six degrees of freedom (6DOF) tibiofemoral (TF) kinematics in people with obesity and NW individuals, and 2) input these data into subject-specific musculoskeletal models to assess the relationship between obesity, frontal plane angle, and TF compartmental loading at the knee.

METHODS: As part of a IRB approved study, ten healthy subjects—five NW (height: 165.1±11.2 cm, weight: 58.9±11.5 kg, BMI: 21.5±2.3, age: 69.2±10.3 years, 3M/2F) and five obese (height: 171.2±6.7 cm, weight: 98.1±9.1 kg, BMI: 33.5±2.8, age: 60.8±8.1 years, 3M/2F)—performed five dynamic tasks of increasing knee flexion: gait, pivot, step-down, step-up, and lunge (Figure 1A, top). All trials were completed with synchronized data collection from an 11-camera motion capture system for full-body kinematics, HSSR for 6DOF right knee kinematics (Figure 1A, bottom), and in-ground force plates. Custom subject-specific musculoskeletal models were developed in OpenSim [9]. Each model implemented a knee joint capable of estimating medial and lateral TF contact forces [10], was scaled using subject-specific medical imaging data (Figure 1B, left), and included prescribed TF contact points in the frontal plane (Figure 1B, right; Figure 1C). Marker trajectories, HSSR kinematics, and force plate data were then used to drive each model through the standard OpenSim pipeline—Inverse Kinematics (for joint angles other than the right knee), Inverse Dynamics, Static Optimization, and Joint Reaction Analysis (Figure 1D)—to quantify medial and lateral TF loading for each activity. Statistical parametric mapping (SPM) was used to determine significant differences in regions of the time-series TF load data between cohorts, and Pearson’s correlation was used for understanding the relationship between the peak varus knee angles and peak medial TF forces for each activity.

RESULTS: The cohort with obesity had higher body weight (BW) unnormalized medial TF forces across all five activities, with significant differences in the identified regions during gait, pivot, and step-down (Figure 3A, top). On average, the peak unnormalized medial TF force was 1.63 ± 0.35 times greater in the cohort with obesity compared to the NW cohort. There were no differences between cohorts for the unnormalized lateral TF forces (Figure 3A, bottom). After BW normalization, the cohort with obesity retained greater peak medial TF forces in pivot (+10%) and step-down (+27%) (Figure 3B, top), but consistently showed smaller lateral TF forces across all activities (Figure 3B, bottom). Consistent with literature, both cohorts exhibited larger medial than lateral TF forces in lower-flexion activities such as gait, where medial forces are typically 2–3x body weight and lateral forces around 0.5x. As flexion increased, the medial-to-lateral force ratio decreased, approaching a more balanced 1:1 distribution (Figure 3B). There was substantial variability in the varus-valgus (VV) angle across activities in both cohorts, as illustrated by pivot (OB = 0.27±3.5°, NW = 3.89±3.4°) and step-down (OB = -1.10±5.1°, NW = 2.87±3.2°). This VV angle remained consistent for each subject across the different activities (Figure 2A). There was a strong, statistically significant relationship between the peak varus knee angle and the peak medial TF force during gait (r=0.91, p=0.0003), but not in the other four tasks. Pivot (r=0.046, p=0.18) and step-up (r=0.57, p=0.11) tasks, however, had moderate correlations approaching significance (Figure 2B).

DISCUSSION: This study employed subject-specific musculoskeletal modeling to quantify the impact of obesity and frontal plane alignment on TF compartmental loading, with the most pronounced relationships observed during the lower-flexion activities of gait and pivot. The cohort with obesity consistently demonstrated higher medial TF forces, a pattern commonly associated with accelerated KOA progression. The VV angle strongly influences compartmental loading, but the variability observed in both cohorts, with varus- and valgus-aligned individuals maintaining consistent alignment across activities, suggests that frontal plane alignment reflects baseline anatomy rather than body mass or task demands. These findings indicate that the group differences in medial loading are not explained by VV alignment alone and are likely also influenced by other movement adaptations and body shape parameters in the cohort with obesity.

SIGNIFICANCE: This work addresses a critical gap by characterizing TF loading across activities spanning increasing knee flexion ranges, providing insight to guide future implant design and treatment strategies for individuals with obesity.

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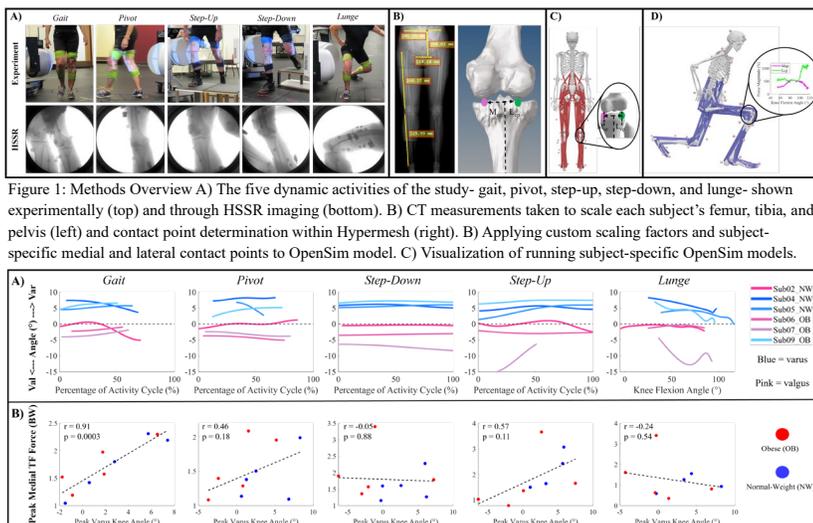


Figure 2: A) Frontal plane (varus-valgus) angle for the three most varus (blue) and the three most valgus (pink) subjects across all five dynamic activities regardless of cohort. B) Pearson correlation between peak medial TF force and peak medial TF force for all ten subjects across all five dynamic activities.

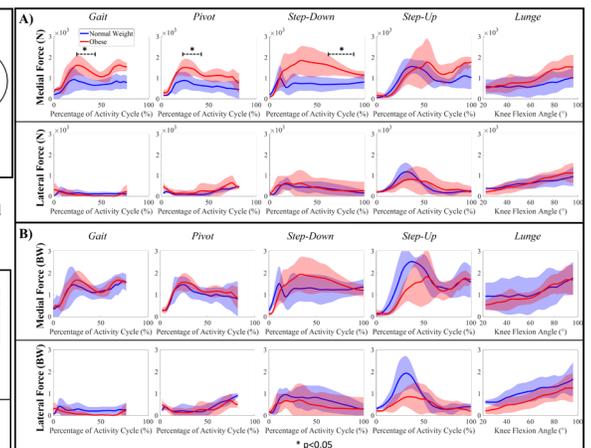


Figure 3: Time-series plots of the tibiofemoral compartmental contact forces over the activity cycles for all five dynamic activities (A) Unnormalized medial (top) and lateral (bottom) compartmental forces in Newtons (B) Corresponding medial (top) and lateral (bottom) compartmental forces normalized to body weight (BW). Arrows indicate regions of significant differences.