

# Different muscle recruitment strategies produce a large range of tibiofemoral forces during walking

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## Introduction

The tibiofemoral (TF) joint is subjected to high loads that affect joint health and function [1,2]. Quantifying TF forces *in vivo* is difficult because direct measurement requires surgical placement of an instrumented implant [3]. Using this approach, TF forces have been measured from a small number of subjects (~11) [3,4,5]. Musculoskeletal modeling provides a noninvasive alternative for estimating TF forces. Previous studies have compared model-predicted TF forces to *in vivo* data during walking [6]. Model-predicted TF forces require estimates of muscle forces, which are usually calculated by assuming a muscle recruitment strategy such as minimization of muscle stress or muscle activity. However, it is unclear how varying muscle recruitment strategies affects TF force predictions. The purpose of this study, therefore, was to quantify the range of predicted TF forces in response to varying muscle recruitment strategies during walking. Specifically, we (1) used various optimization criteria to estimate muscle and TF forces in a model representing a subject and (2) compared these estimates to *in vivo* TF forces measured in the same subject.

## Materials and Methods

We used data [4] that included simultaneous marker positions, ground reaction forces, muscle activations (EMG), and *in vivo* TF force data during walking from a subject (83 year old male, 64 kg, 166 cm tall) with an instrumented total knee replacement (TKR) (Figure 1A). The instrumented TKR measured TF force along the longitudinal axis of the tibia [3].

We calculated full body dynamics, muscle forces, and TF joint forces for the subject using OpenSim [7]. A 3D, rigid-body model consisting of 23 degrees of freedom and 92 muscle-tendon units was scaled to match the weight and segment lengths of the subject (Figure 1B). The model's joints consisted of a ball-in-socket hip joint, an elliptical tibiofemoral joint, a planar patellofemoral joint, and a revolute ankle joint. We determined model kinematics for 5 walking trials by minimizing error between the experimentally measured marker positions and the corresponding markers on the model. The model kinematics were low-pass filtered at 6 Hz. We used an optimization method to calculate muscle activations and forces that reproduced the model kinetics. This method accounted for force-length and force-velocity behavior of muscle when calculating muscle forces. To represent muscle recruitment strategies, we calculated TF forces resulting from optimizing three objective functions: 1) minimizing TF force, 2) maximizing TF force, and 3) minimizing the sum muscle activations squared.

## Results

Optimizations that minimized and maximized TF force resulted in a large range of predicted TF forces during walking (Figure 2A). Maximum and minimum TF force differed on average by 9.0 body-weights (BW) throughout the gait cycle, with the largest difference (11.6 BW) occurring at 47% gait cycle. The model produced an absolute maximum TF force of 13.0 BW at 18% gait cycle, early in the stance phase. We obtained similar results for all 5 trials of walking.

Predicted minimum TF forces were in good agreement with the *in vivo* data (average absolute difference of 0.3 BW) during the first half of stance phase (0-33% gait cycle, Figure 2B). However, predicted minimum TF forces were substantially less than the *in vivo* data (average absolute difference of 0.9 BW) during the second half of stance phase (33-66% gait cycle).

Predicted TF forces corresponding to minimum muscle activity were greater than measured *in vivo* forces, especially between 33-66% of gait cycle when the average absolute error was 0.9 BW (Figure 2A-B, compare solid black and dashed blue curves). During this period, the predicted TF forces were dominated by gastrocnemius muscle forces and were most sensitive to its strength. Decreasing the gastrocnemius strength by 50% altered the optimization solution and reduced the average absolute difference between model-predicted and *in vivo* TF forces from 0.9 BW to 0.3 BW (Figure 2B, compare solid black and dashed red curves).

## Discussion and Conclusion

This study quantifies the range of model-predicted TF forces in response to varying muscle recruitment strategies during walking. The TF forces varied by up to 11.6 BWs, primarily due to differences in co-contraction of the antagonist muscles. The absolute maximum TF forces were as high as 13.0 BW and were limited by the force-generating capacity of the muscles in the model.

The subject's muscle coordination may produce near minimal TF forces during the first half of stance phase, based on the good agreement between *in vivo* data and model predictions (Figure 2B). However, the subject adopts a different muscle recruitment strategy during the second half of stance phase, as is evident from the substantially greater *in vivo* data compared to the predicted minimum TF forces. Our future work will explore a new spectrum of muscle recruitment strategies based on simultaneously or intermittently minimizing muscle activity and TF force. The contribution of this study is new insight into understanding muscle coordination and its effect on TF forces during walking.

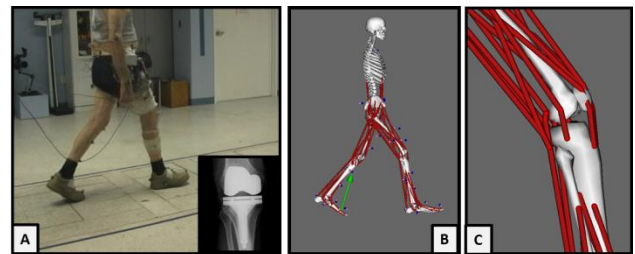


Figure 1. (A) 3D motion analysis of a subject with an instrumented TKR (inset). (B,C) Calculating full-body dynamics of walking with a scaled musculoskeletal model in OpenSim.

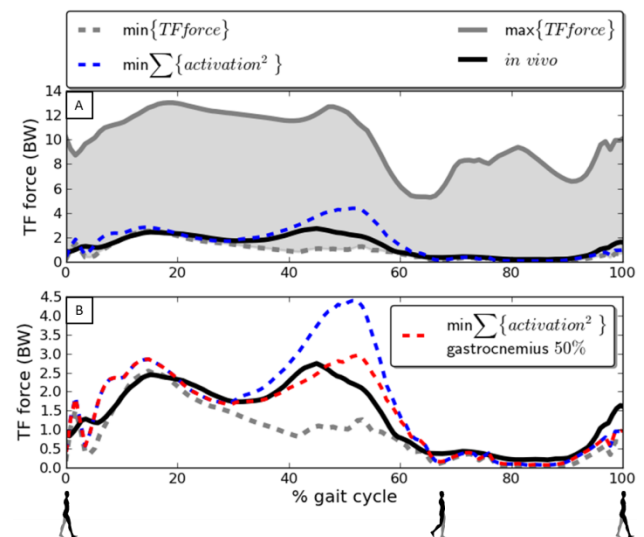


Figure 2. Model-predicted TF forces using different optimization objective functions compared to *in vivo* measurements from a representative walking trial. The grey envelope represents the range of predicted TF forces.

## References

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