Bilevel Optimization Improves Knee Contact Force Predictions from Musculoskeletal Simulation

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Summary

Static optimization can estimate knee contact force (KCF) for knee load monitoring and rehabilitation. To improve KCF estimates, we used bilevel optimization to find the weights in the cost function of static optimization for each muscle crossing the knee that minimized KCF errors during gait. Using cross validation on four individuals with instrumented knee replacements, we found that the bilevel-optimized weights reduced KCF error over stance and at stance peaks for held-out individuals, suggesting that the weights may be generalizable to other individuals with knee replacements.

Introduction

Large knee contact forces (KCFs) during walking relate to accelerated knee osteoarthritis progression [1]. However, in-vivo KCF cannot be directly measured in most cases, so musculoskeletal simulation methods, like static optimization, are used to estimate KCF. In previous studies with instrumented knee replacement measurements, static optimization overestimated KCF. This suggests that the commonly used objective function—minimizing the sum of squared muscle activations—may not accurately represent the coordination patterns of individuals with knee replacements [2-4]. Previous work has tuned static optimization objective function weights for knee-crossing muscle groups manually or with optimization to minimize KCF error for a single individual. These individualized weights outperformed uniform weights but did not generalize well to new individuals [4,5]. Our study aimed to identify generalizable static optimization muscle weights that minimize KCF errors by leveraging bilevel optimization and walking data from multiple individuals with instrumented knee replacements.

Methods

We used 20 overground walking trials for four individuals from the third–sixth knee Grand Challenge competitions [6]. Data processing, musculoskeletal modeling, and static optimization details have been reported previously [3].

We used leave-one-subject-out cross validation to evaluate the generalizability of the optimized muscle weights. The inner level of the bilevel optimization was static optimization, performed at stance peaks (25% and 75% stance) over all trials. The objective was to minimize the sum of squared muscle activations, using separate weights for the gastrocnemius, hamstrings, and quadriceps muscle groups. The outer level optimized these three muscle-group weights by minimizing the difference between the static optimization KCF estimates and measured KCF. Optimized weights were bounded between 0 and 10, and initialized to 7 (gastrocnemius), 3 (hamstrings), and 1 (quadriceps) [5].

For each cross-validation fold, the optimized weights were evaluated by applying them to static optimization for the held-out participant. To compare estimated to measured KCF, we computed stance-phase root mean square error and the mean absolute error at both stance-phase peaks.

Results and Discussion

The average (standard deviation) bilevel-optimized weights over cross-validation folds were 4.30 (0.80) for gastrocnemius, 2.56 (0.28) for hamstrings, and 3.03 (0.42) for quadriceps. The optimized weights reduced the average root mean square error over stance by 0.21 bodyweights (BW), with 0.45 BW error compared to 0.66 BW for uniform weights (Figure 1). The optimized weights reduced the second stance-phase peak error (0.68 BW improvement) more than the first (0.07 BW improvement). The optimized weights yielded an average peak KCF error of 0.33 BW, which is within a clinically meaningful range of peak KCF reductions based on weight loss studies (0.08-0.41 BW) [3].

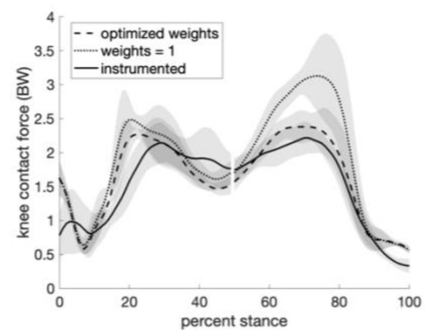

Figure 1: The mean knee contact force in bodyweights (BW) ± standard deviation (shaded) for held-out trials, comparing bilevel-optimized muscle weights (dashed) and uniform weights (dotted) to instrumented knee replacement measurements (solid).

Conclusions

Optimizing the weights of knee-crossing muscles in static optimization improved KCF accuracy on held-out individuals following knee replacement. This suggests that this approach is likely to improve KCF accuracy for individuals with knee osteoarthritis.

References

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