Knee Contact Force Validation Alone Falls Short in Capturing Accurate Joint Mechanics in Musculoskeletal Models

Seyyed Hamed Hosseini Nasab[1], Ning Guo[1], Allan Maas[2,3], Thomas M. Grupp[2,3], and William R. Taylor[1]
[1] Laboratory for Movement Biomechanics, ETH Zürich, Switzerland
[2] Aesculap AG, Research & Development, Tuttlingen, Germany
[3] Ludwig Maximilians University Munich, Department of Orthopaedic and Trauma Surgery, Musculoskeletal University Center Munich (MUM), Campus Grosshadern, Munich, Germany
Email: seyyed.hosseini@hest.ethz.ch

Summary

We used a musculoskeletal (MS) model incorporating detailed representations of knee articular contact and soft tissue constraints to simulate level walking trials. A Monte Carlo simulation with 1,000 variations in muscle activation strategies was conducted and outcomes were analyzed to explore the relationship between the rigor of knee contact force (KCF) validation and uncertainties in kinematic predictions within the MS model. We found that simulations yielding appropriate KCF estimates do not necessarily guarantee precise predictions of joint kinematics.

Introduction

MS modelling plays a crucial role in understanding knee joint mechanics for applications such as surgical planning and implant design. A common validation approach involves assessing the model's performance in predicting KCFs. However, such validation may not necessarily guarantee an accurate reconstruction of joint contact mechanics in the MS model. This study investigates the relationship between the rigor of KCF validation and uncertainties in kinematic predictions of a MS model.

Methods

Skin-marker trajectories, ground reaction forces (GRFs), fluoroscopically measured tibiofemoral kinematics, and telemetric KCFs during five level walking trials were obtained from a 65-year-old subject (1.74 m, 95.6 kg) with a unilateral total knee arthroplasty (Innex FIXUC, Zimmer, Switzerland) as part of the CAMS-Knee dataset [1].

A previously developed MS model (Fig 1; [2]), along with skin-marker trajectories and GRF data, were used as inputs to the COMAK algorithm [3] to predict 12 degrees of freedom tibiofemoral and patellofemoral kinematics. The algorithm also estimated KCFs, muscle forces, and ligament forces during walking. To evaluate the robustness of the knee kinematics predictions under varying internal loading scenarios, we performed a Monte Carlo simulation with 1000 iterations. Each iteration introduced a random penalty factor ($-0.5 < a_i^* < 0.5$, [3]) into the cost function ($\sum_{i=0}^{n}(a_i - a_i^*)^2$).

For each simulation, we calculated the root mean square error (RMSE) between the model's predicted forces and kinematics and their corresponding in vivo data. Simulation with the lowest KCF RMSE was identified and designated as the optimal simulation (KCF_OS). Simulations with RMSEs within 15% BW of the KCF_OS were further categorized into six groups based on increasing RMSE intervals ranging from 2.5 to 15% BW in increments of 2.5% BW. The uncertainty in the kinematic predictions for each category was quantified as the largest 5–95% confidence range of the corresponding kinematic parameters and compared across categories to assess the impact of the permissible KCF RMSE on kinematic prediction accuracy.

Results and Discussion

With kinetic errors remaining below 13% BW and kinematic errors under 1.3 mm and 1.4°, outcomes of the KCF_OS demonstrated strong agreement with in vivo data. However, our findings indicate that allowing slightly larger KCF errors (only an additional 2.5% BW) leads to substantial inaccuracies in kinematic predictions, with uncertainties reaching up to 3° and 3 mm (Fig. 1). Broader permissible KCF RMSEs resulted in increased uncertainty in kinematic estimates, with a more pronounced impact observed in simulations involving less-stable low-conformity implants. Importantly, simulations with a 15% BW KCF error, commonly regarded as a negligible error, could exhibit substantial inaccuracies in kinematic outputs, with deviations reaching up to 8 mm and 10°.

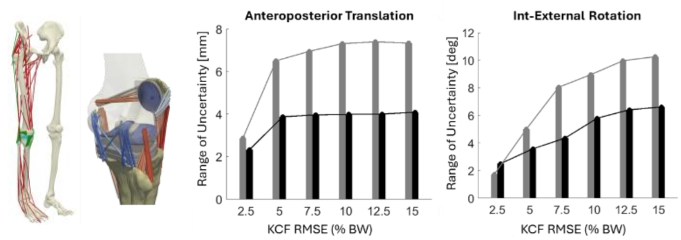

Figure 1: The MS model with detailed knee structures (left). Uncertainty in knee kinematic estimates of the MS model with extended permissible KCF error ranges (middle and right). Results of the INNEX inlay (contact arc radius of 36 mm) are presented in black, while those of the low-conformity inlay (contact arc radius of 72 mm) are depicted in gray.

Conclusion

This study demonstrates that comprehensive validation of MS models, incorporating both kinetic and kinematic data, is essential for reliable predictions of in vivo knee joint mechanics in biomechanical and clinical contexts.

References

[1] Taylor et al, J Biomech, 65:32-39, 2017.
[2] Guo et al, Front. Bioeng. Biotechnol, 12, 1352794.
[3] Febrer-Nafría et al, J Biomech, 161: 111851, 2023.