XVII International Symposium on Computer Simulation in Biomechanics
July 28th – 30th 2019, Alberta, Canada

The Contributions of External Joint Moments and Internal Musculoskeletal Loading to Knee Joint Mechanics during Functional Movements

Colin R. Smith[1], Melissa Bevers[1], S.H. Hosseini Nasab[1], Pascal Schutz[1], Adam Trepczynski[2], Philipp Damm[2], and William R. Taylor[1]

[1]Institute for Biomechanics, ETH Zürich, Switzerland
[2]Julius Wolff Institute, Charité – Universitätsmedizin Berlin, Germany
Email: colin.smith@hest.ethz.ch, Web: www.movement.ethz.ch

INTRODUCTION

A comprehensive understanding of the factors that govern knee joint mechanics during functional movements is important to gain insight into the pathogenesis of osteoarthritis and improve outcomes of total knee arthroplasty (TKA). However, the interactions between external joint moments, neuromuscular coordination, passive tissue forces, and articular contact loading that ultimately determine functional knee mechanics are highly complex.

Experimentally, *in vivo* knee contact forces can be measured using instrumented implants and knee kinematics assessed using video-fluoroscopy. Unfortunately, these datasets are only available for a limited number of patients. Thus, the external knee joint moments, especially the knee adduction moment, are commonly used as surrogate measures of knee loading [1]. However, biarticular muscles that cross the hip and ankle also influence knee loading, these joint moments may also factor into functional knee mechanics.

Multibody musculoskeletal simulation can enable a more comprehensive investigation of internal loading by distributing the external joint moments to muscle and joint contact forces. However, simulation based insights into the role of external movement dynamics in knee loading are often limited by simplified joint representations, uncertainty in model parameters, minimal validation.

The CAMS-Knee datasets provide synchronized *in vivo* measurements that enable comprehensive investigation of the correlations between external lower limb joint moments and internal knee contact forces. We coupled these measurements with a novel musculoskeletal simulation routine to investigate the contributions of external and internal loading to knee joint mechanics during functional movements.

METHODS

Simultaneous tibiofemoral contact forces, tibiofemoral kinematics, motion capture, and ground reaction forces in six patients with TKA during five trials of three gait-like activities (level walking, downhill walking, stair descent) and three squat-like activities (squatting, sit-to-stand, stand-to-sit) were captured within the CAMS-Knee project and used in this study [2]. All patients were implanted with an ultra-congruent INNEX TKA (Zimmer AG). Contact forces were measured using an instrumented tibial implant and kinematics were measured using a novel moving fluoroscope. The medial and lateral contact forces were computed from the implant measurements using force balancing equations.

A generic musculoskeletal model was personalized to each subject in OpenSim based on CT scan data. Inverse kinematics was performed with the knee kinematics prescribed to the fluoroscopic measurements and the hip (3-rotations) and ankle (1-rotation) kinematics calculated from the motion capture data. Inverse dynamics was then performed to calculate the hip, knee, and ankle moments. Linear first and second order regression models were used to determine the correlations between the hip and knee adduction and flexion moments (HAM, HFM, KAM, KFM) and the measured tibiofemoral contact forces and kinematics throughout each activity. Activities were compared using the means of subject correlations based on all trials pooled together.

A detailed knee model was then implemented for each subject. The tibiofemoral joint included 6 degrees of freedom (DOF) and the patellofemoral joint had 1 DOF that allows the patella to track along the trochlear groove. Fourteen ligaments were represented using bundles of nonlinear springs. The attachment footprints were identified relative to bony landmarks from the CT scans using anatomical descriptions from the literature. Articular contact pressures between the femoral component and tibial inlay were computed using an elastic foundation model. The Concurrent Optimization of Muscle Activations and Kinematics (COMAK) simulation routine was used to predict muscle forces, ligament forces, contact pressures, and secondary knee kinematics (tibiofemoral translations, adduction, rotation, and patellar DOF) throughout each activity. COMAK simultaneously optimizes muscle activations and secondary knee kinematics (5 tibiofemoral DOF, 6 patellofemoral DOF, and 12 menisci DOF) to satisfy both whole-body and joint-level movement dynamics, while minimizing a weighted squared muscle activation objective function.

RESULTS AND DISCUSSION

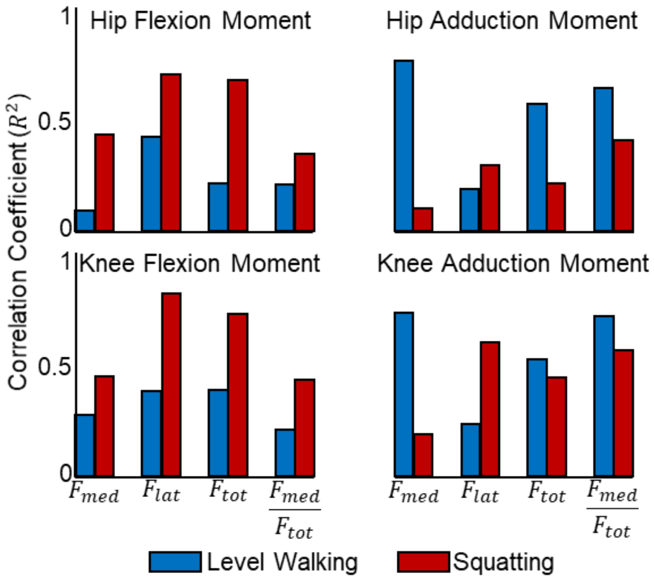

Fig 1: Correlations between the compressive knee contact force and the HAM, HFM, KAM, and KFM for only level walking and squatting. The correlations were calculated over the entire activity cycle.

The correlations between external joint moments and measured contact forces showed distinct differences between gait-like activities and squat-like activities (Fig 1). Gait-like activities showed stronger correlations with the HAM and KAM, while squat-like activities showed higher correlations with HFM and KFM. The hip and knee rotation moments and the ankle flexion moment showed only weak correlations for all activities.

While the relationships between the external joint moments and the joint contact forces were strongly activity-type related, no such activity dependency was observed in the correlations between the external joint moments and knee kinematics.

We are now working towards using the measured *in vivo* tibiofemoral contact forces and kinematics to validate the COMAK simulation predictions. Then, a Monte Carlo analysis will be performed where neuromuscular coordination, TKA component alignment, and ligament properties are perturbed to explore the possible knee contact forces that can result from a given trajectory of external moments.

CONCLUSIONS

The strong correlations observed between knee contact forces and both hip and knee moments were highly activity dependent, possibly driven by active biarticular muscles, but also the inherent coupling between the hip and knee joints. Knee translations were largely determined by the knee flexion angle, which reflects the highly constrained implant design. Importantly, while these data support the use of KAM and HAM as a surrogate measure for determining the internal loading conditions during gait activities, caution should be exercised when applied to squat-like activities. Future musculoskeletal simulations have great potential to provide further insights into the internal musculoskeletal loading that leads to these experimental correlations.

REFERENCES

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ACKNOWLEDGEMENTS

This work was supported by the RMS Foundation and the Whitaker International Program.