An elastic-foundation contact model with balanced ligaments accurately predicts in vivo knee mechanics during different activities of daily living

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Summary

By comparing predicted knee contact forces (KCFs) and local kinematics against *in vivo* measurements from the CAMS-knee datasets during different activities of daily living (ADLs), this study represents the most extensive musculoskeletal (MSK) modelling validation for the prediction of knee mechanics to date. In particular, it shows that an advanced elastic-foundation joint contact model with surgically balanced ligaments can accurately predict joint mechanics across different ADLs and subjects.

Introduction

MSK modelling enables the estimation of internal body loads in a non-invasive manner, yet its use in product design and surgical planning is limited, mostly due to a lack of extensive validation. The CAMS-knee datasets [1] currently represent the gold standard for MSK model validation, as they comprise knee loading data from 6 subjects fitted with instrumented implants and simultaneous local joint kinematics obtained with moving video-fluoroscopy during different ADLs.

Methods

Motion-capture data from the CAMS-knee datasets were used as input for an inverse-dynamics analysis in the AnyBody Modeling System. Personalized models were built starting from the TLEM 2.2 lower-limb model while accounting for subject-specific anthropometrics and radiographic data. Virtual implantation of femoral and tibial components (INNEX FIXUC; Zimmer Biomet) was performed in the MSK models to match subject-specific post-operative implant alignment from CT data. In a first iteration, the implanted knee was modelled as 1-degree-of-freedom (DOF) idealized hinge joint with a flexion axis that matched the implant's geometrical features. Next, a 6-DOF elastic-foundation contact model between implant components was defined and a surgically balanced model of the ligaments derived from in-house cadaveric testing was included. Tibiofemoral kinematics were determined by solving the instantaneous quasi-static equilibrium between external loads, muscle forces, and ligament constraints through force-dependent kinematics (FDK). Predicted KCFs and local kinematics were compared against instrumented implants and video-fluoroscopy data. Five trials per subject per ADL were analysed. Root mean square error (RMSE) was computed across trials for each subject and ADL.

Results and Discussion

The implementation of a 6-DOF knee contact model stabilized by a surgically-balanced ligament model led to improved prediction of both KCFs and local implant kinematics (Figure 1), in agreement with the experimental measurements across ADLs: KCF magnitude RMSE = 0.30–0.47BW; anterior-posterior (AP) translation: RMSE=1.57–2.87mm. However, some variability between subjects persisted (Table 1).

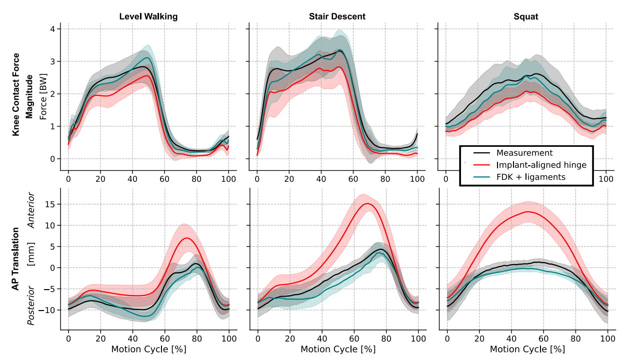

Figure 1: Mean (± SD) KCF magnitude and local knee kinematics, defined as relative AP translations of the femoral component with respect to the tibial baseplate, during different ADLs.

Conclusions

In vivo knee mechanics are governed by the interaction between joint surface geometry, passive soft tissue stabilizing structures, and active (muscular) joint control. The improved predictions obtained with advanced contact and ligament models indicate that these are essential features to accurately model and understand the knee joint. The development and validation of realistic MSK models will enable us to better understand how implant design and surgical planning can influence overall patient satisfaction and mobility during a broad range of real-life activities.

References

[1] Taylor WR et al. *J Biomech* **65**: 32-39, 2017.

Table 1: Mean RMSE (min–max range across subjects) between measured and predicted KCFs and local knee kinematics for each ADL with an elastic-foundation contact model and surgically balanced ligaments.

RMSE	Level walking	Downhill walking	Stair descent	Squat	Chair sit-stand-sit
KCF magnitude [BW]	0.30 (0.20 – 0.40)	0.45 (0.38 – 0.49)	0.46 (0.38 – 0.64)	0.44 (0.19 – 0.89)	0.47 (0.22 – 0.68)
AP translation [mm]	2.07 (1.13 – 2.59)	2.48 (1.99 – 2.91)	2.15 (1.55 – 2.73)	1.57 (0.76 – 2.06)	2.87 (2.31 – 3.68)